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Importance of multi-modal data for predictive rendering

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Abstract

Accurate modeling of material appearance is crucial for achieving predictive rendering. To improve reflection models, databases with measured reflection behaviors of various material and surface types are of great importance. However, current databases provide limited information, focusing either on the spectral or spatial domain and often lack microgeometry details. To address this limitation, a multi-modal database that includes reflection behavior in both spectral and spatial domains, along with comprehensive microgeometry information, is essential. Additionally, scatter information simulated with microgeometry enhances the understanding of light-matter interactions. This paper discusses the importance of multi-modal reflection data in developing more realistic and computationally efficient reflection models for predictive rendering.

CCS Concepts
• ***Computing methodologies*** → ***Reflectance modeling;*** • ***Applied computing*** → *Physics;*

1. Introduction

A primary goal of computer graphics is the physically correct simulation of light propagation in a virtual scene, known as predictive rendering. Current rendering methods deliver photorealistic images that are perceived as realistic but differ from reality. These deviations limit the use of rendered images in color-critical applications such as virtual prototyping, serious games or training AIs.

A major challenge of predictive rendering is the simulation of the light-matter interaction. Although the light-matter interaction is well described in physics, it is still heavily simplified in computer graphics to enable renderings of complex scenes in an acceptable time or even in real time. The reflection models used in computer graphics are usually based on geometric optics, which assume light transport along rays, thus neglecting the wave characteristics of light. This is a good approximation when the surface roughness is clearly above the scale of light wavelengths. But, in reality, this is usually not the case, as Goodman stated in his Book Speckle Phenomena in Optics [Goo07, p. 1]: "In fact, most materials encountered in the real world are rough on the scale of an optical wavelength (notable exceptions being mirrors)."

Therefore, in the real world, we often encounter wave-optical phenomena such as diffraction or interference, which have a great impact on the visual appearance of rough surfaces. This is particularly the case when conductive or dark dielectric surfaces are illuminated by sharp light such as sunlight. To improve the realism and performance of reflection models, databases are of great importance. However, existing databases are limited to the spectral or spatial domain and don't provide microsurface information. Since wave-optical phenomena strongly depend on both domains as well as on the incident and reflection angle, multi-modal reflection data are of great importance for predictive rendering.

2. Related Works

Recent advancements in reflection models have enabled the simulation of wave-optical phenomena occurring on various types of surfaces. Notably, these models enable the representation of interference effects on thin layers and films [BB17], as well as diffraction phenomena on structures like hair and fur [XWM*20, XWH*23], scratches [WVJH17, VWH18], and small repetitive patterns [DTS*14, TG17].

While these models describe wave-optical phenomena on specialized geometries, it is noteworthy that diffraction phenomena also manifest on rough surfaces even when illuminated with partially coherent light. Recent advancements have led to models that physically simulate diffraction on rough surfaces [DWMG16, HP17, YHW*18, SY21, SY22], as well as heuristic approaches that offer computationally efficient solutions suitable for real-time applications [CCFM23, CMF*24].

Diffraction on rough surfaces is a plausible explanation for discrepancies observed between measured data and reflection models based on geometric optics [HP17]. These discrepancies lead to physically implausible extensions, such as specular albedo or multiple lobes [CT81, NDM05, Bur12, LKYU12].

Databases such as the popular MERL [MPBM03] or the RGL Database [DJ18] are very beneficial for analyzing light-matter interaction and for developing and evaluating reflection models. However, both databases measure the reflection behavior only for a

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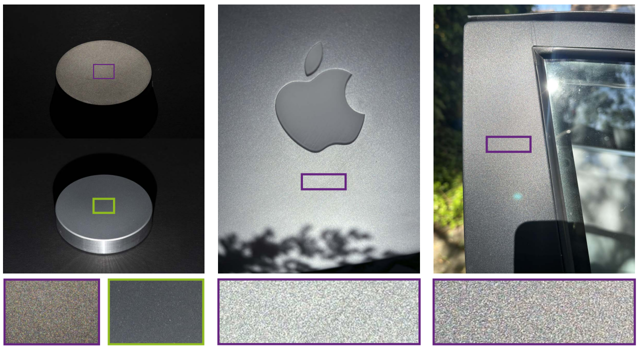

(a) *Al sample* **(b)** *MacBook* **(c)** *Car door*

Figure 1: *Photo (a) depicts a rough aluminum patch illuminated by a standard LED light source, captured in the forward-scattering (upper photo) and backscattering (lower photo) directions. Photos (b) and (c) show a MacBook and a plastic part of a car door illuminated by sunlight.*

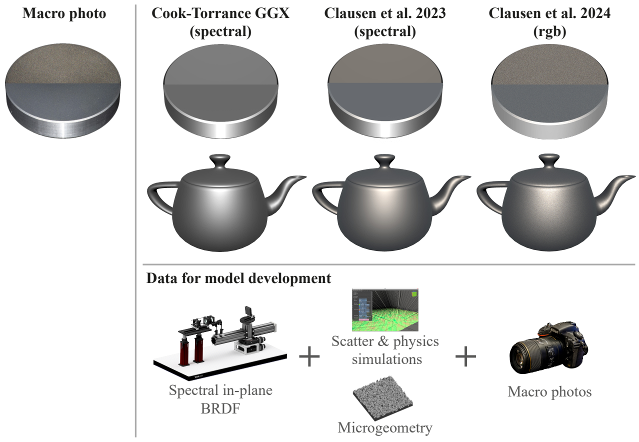

Figure 2: *Upper row: Comparison of macro photos with renderings using Cook-Torance model and our models including diffraction phenomena. Lower row: Required multi-modal reflection data for model development.*

single point. Several works [FV14, WGK14, MHRK19, GARP*23] capture the reflection behavior spatially resolved but are limited to the RGB color space. Datasets that provide the reflection behavior in spatial and spectral dimensions and, at the same time, microgeometry information are missing.

3. Investigation of diffraction phenomena

In the real world, we frequently encounter wave-optical phenomena. In Figure 1, three examples of wave optical phenomena are shown, where (a) is captured in the laboratory and (b) and (c) under sunlight. In all three examples, wave optical phenomena, such as speckle patterns, can be observed.

3.1. Observations

In the course of our research, we first observed wave-optical phenomena on rough surfaces while comparing rendered images with reality [CMF18]. We compared reference data captured from ColorChecker patches within a controlled scene with renderings computed using the Mitsuba renderer [Jak10].

We discovered that the Cook-Torrance model primarily accounts for the discrepancies observed between the measured and simulated data. Our analysis of the fitting error in the spectral domain revealed a novel reflection behavior. Specifically, we identified a linear increase and decrease in the bidirectional reflectance distribution function (BRDF) spectra in forward- and backscattering directions, which cannot be explained by geometric optics.

We investigated the observed color shifts in [CCFM23], fabricating aluminum samples with varying degrees of roughness. As anticipated, the color shifts are more pronounced on rough conductive surfaces, as shown in the macro photo in Figure 2, and diminish as the surface becomes smoother. We captured the microgeometries of all aluminum samples using a confocal microscope. We used these measurements to simulate the reflection behavior with a physical model [YHW*18] and analyzed the scattering behavior with a self-developed virtual gonioreflectometer. The reflection and scatter simulations provided us with interesting new insights. First, the linearly increasing spectrum in forward scattering is also present in the simulation, confirming that it is not caused by measurement errors. Second, the decreasing spectrum in backscattering is not reproduced by the model, which can be attributed to the fact that it does not account for multiple reflections. Third, the scatter simulation indicates that the first and multiple reflections cause the red and blue shifts, respectively.

Based on these insights, we developed a heuristic model to approximate the diffraction-induced color shifts by extending the Cook-Torrance model with a linear shift function. Although our model improves the simulation of wavelength shifts (cf. middle column Figure 2), it still ignores the spatial characteristics of speckle patterns, which significantly affect visual appearance, as the macro photos illustrate.

In our recent work [CMF*24], we present a real-time RGB model taking into account the color shifts and dynamic speckle patterns. We analyzed the spatially varying speckle patterns using macro photos and simulated them by a simplex noise function, where the color distribution is determined by a multivariate distribution function. Finally, we integrate our diffraction model into a popular game engine and introduce specific improvements for the usage in Virtual Reality (VR) applications.

The model is still simple enough to avoid any performance issues while, at the same time, significantly improving the realism of rough metallic surfaces compared to the classic Cook-Torrance model (Figure 2).

3.2. Experiences

The primary experience made during our investigation was that diffraction phenomena influence the appearance of rough surfaces more significantly than previously anticipated. We identified two

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critical diffraction effects – color shifts and speckle patterns – that substantially impact the visual appearance, particularly of rough conductive surfaces illuminated by a sharp light source.

While the color shifts are readily visible for conductors under natural viewing conditions, they are barely noticeable for dielectrics since they primarily occur at grazing angles. However, even for dielectrics, these color shifts become more apparent when fitted with BRDF models based on geometric optics. We observed that the Cook-Torrance model attempts to account for color shifts by adjusting the diffuse albedo, resulting in a reddish-tinted diffuse albedo. The spatially varying speckle patterns observed on rough surfaces also significantly affect visual appearance. The presence of speckles makes rough surfaces appear more dynamic, as the speckle pattern changes continuously with head or light source movement. Additionally, in stereoscopic vision, surfaces with speckle patterns appear much rougher and more metallic due to highlight disparity as each eye perceives a different speckle pattern because the surfaces are viewed from slightly different angles.

Furthermore, two additional observations were made during the analysis of scatter and reflection simulations using measured microgeometry, indicating areas for future research. First, the measured normal distribution function (NDF) is Gaussian distributed and can be well-fitted by the Beckmann distribution. However, when fitting the Cook-Torrance model against the measured BRDF, the GGX distribution provided significantly better results.

Second, in physical simulations using microgeometry, an off-mirror peak was observed toward the normal, which contrasts with the direction observed in the measured data. Previous works by Dong et al. [DWMG16] and Schröder et al. [SDC*11] also noted discrepancies between measured BRDF and simulated results. Both studies suggest that the measured microgeometry might be the source of error, but a thorough investigation of these observed differences remains lacking.

4. Multi-modal Database

Our research in reflection modeling underscores the importance of multi-modal reflection data for the development of accurate reflection models. However, the limited number and incompleteness of available multi-modal data complicates the further development of reflection models. For instance, our dataset includes information on only a few aluminum samples, does not provide the reflection behavior in the spectral and spatial domains simultaneously, and is limited to the in-plane. Furthermore, the data acquisition involved three distinct processes, rendering the measurement process both time-consuming and labor-intensive.

To enhance reflection models, we advocate for the creation of a multi-modal database that captures reflection behavior across spatial, spectral, and angular domains, as well as microgeometry, as illustrated in Figure 3. Besides the measured data, the multi-modal database should also include physics-based simulations that give additional insights into the light-matter interaction.

Measured reflection behavior: The measured reflection behavior is critical for analyzing, understanding, and modeling the complex light-matter interactions of real-world materials and quantifying model realism. Since the light reflection of real-world materials

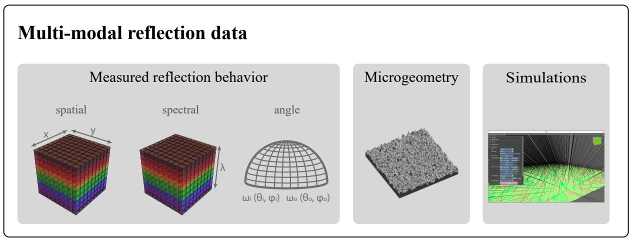

Figure 3: *Layout of proposed multi-modal database*

strongly depends on spatial, spectral, and angular domains, the reflection behavior must be acquired in these domains. This is particularly true for textured materials but also for isotropic surfaces due to wave-optical phenomena.

Microgeometry: The geometry details play an integral role in validating reflection models. Contemporary reflection models, predominantly based on the microfacet theory, assume surfaces are comprised of small facets. Access to geometry information enables surface reconstruction, facilitating the derivation of intrinsic properties as well as BRDF-related terms such as the autocorrelation function, the NDF, and the shadowing-masking function. In this case, the resolution should be small enough to be considered as microgeometry and, hence, as microfacets. If diffraction effects are to be investigated, higher resolutions might be necessary.

Simulations: The scatter simulation should virtually replicate a real-world goniophotometer while being free of some physical limitations, such as calibration errors and limited acquisition directions. Our simulation uses geometric-optics ray tracing techniques, suitable for geometry details larger than the wavelength of the light. Note that using such approaches for resolutions higher than the light's wavelength can yield erroneous results, like inflated roughness values. If wave-optics simulations are necessary, numerical methods like Finite-Difference Time-Domain (FDTD), Finite Element Method (FEM), and Method of Moments (MoM) can simulate electromagnetic wave behavior. Nevertheless, they are computationally expensive and time-consuming. Consequently, current research [YXW*23] still has limitations related to the geometry details that can be effectively simulated.

5. Conclusion

The paper highlights the importance of multi-modal reflection data for the development of accurate reflection models in predictive rendering. We share our observations and experiences collected while investigating diffraction phenomena on rough surfaces, which underscore the great value of multi-modal data. Additionally, we identify open research questions in material modeling that demand multi-modal data. We discuss the limitations of existing databases and advocate for a new database, including measured reflection behavior in the spatial, spectral and angle domains, as well as the microgeometry. Physics simulations provide further insights into the light-matter interaction complementing the database.

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