Reconstruction of sparse hyperspectral BRDF measurements preserving their physical and topological properties

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Abstract

The measurement of hyperspectral bidirectional reflectance distribution function (BRDF) of a material is a key issue in physically based spectral rendering. We present here a device for measuring BRDF, enabling high spectral sampling (sub-nanometric from 450 nm to 1100 nm) with the counterpart of sparser angular sampling. To overcome this problem, we propose an interpolation method that respects the physical and topological properties of the BRDF by construction. The characteristic properties of the material deduced from the interpolated data set correspond to the reference values obtained using dedicated measuring instruments.

CCS Concepts

• ***Computing methodologies*** → *Rendering;* • ***Mathematics of computing*** → *Topology; Interpolation;*

1. Introduction

The measurement of hyperspectral bidirectional reflectance distribution functions (BRDF) is a key element in physically based hyperspectral rendering. While high spectral definition is guaranteed, angular sampling can be more sparse depending on the setup used. Here we propose a method for reconstructing the BRDF $f(\omega_\mathrm{i},\omega_\mathrm{o})$ from scattered data while ensuring that the physical properties, such as non-negativity (Eq. 1a), energy conservation (Eq. 1b) and Helmholtz reciprocity (Eq. 1c) of the BRDF are verified by construction.

$$\forall\,(\omega_\mathrm{i},\omega_\mathrm{o},\lambda), \qquad f(\omega_\mathrm{i},\omega_\mathrm{o},\lambda) \geq 0 \tag{1a}$$

$$\forall\,(\omega_\mathrm{i},\lambda), \qquad \int_\Omega f(\omega_\mathrm{i},\omega_\mathrm{o},\lambda)\,\cos\theta_\mathrm{o}\,d\omega_\mathrm{o} \leq 1 \tag{1b}$$

$$\forall\,(\omega_\mathrm{i},\omega_\mathrm{o},\lambda), \qquad f(\omega_\mathrm{i},\omega_\mathrm{o},\lambda) = f(\omega_\mathrm{o},\omega_\mathrm{i},\lambda) \tag{1c}$$

2. Methodology

2.1. Measurement setup

The setup, whose optical diagram is described in Fig. 1, consists of two controlled arms, one carrying a supercontinuum laser, the other a spectrometer [M*24]. Spectral resolution is less than a nanometer, going from 450 nm to 1100 nm.

The arm carrying the laser has one zenithal degree of freedom, while the arm carrying the spectrometer has two degrees of freedom, one zenithal and the other azimuthal. Blind zones exist when one arm obscures the other. In addition, the measurement time is significant, resulting in much sparser angular sampling.

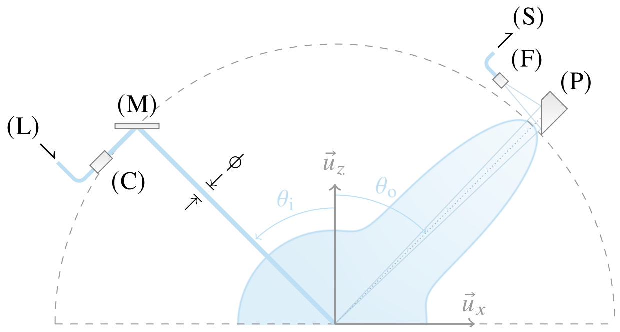

Figure 1: *Optical diagram of the measurement bench. The emitting arm consists of a Leukos STM 250-VIS-IR supercontinuum laser (L) transported in an optical fibre, collimated by a custom-made collimator from Leukos (C) and then redirected towards the sample by a mirror (M). $\varnothing = 5.0\,\mathrm{mm}$. The sensor arm consists of a Thorlabs MPD129-P01 off-axis parabolic mirror (P) that reflects the collected light back to an optical fibre (F) connected to an Avantes AvaSpec HS-TEC spectrometer (S).*

2.2. Interpolation method

Radial basis function interpolation is a suitable tool for our problem, being able to adapt to the topology of the domain and being a meshless strategy.

Let Ω be the domain of $f(\omega_\mathrm{i},\omega_\mathrm{o})$. Let $\mathbb{S}^2_+$ be the hemisphere of unit radius corresponding to the domain of ω_i and ω_o. We can

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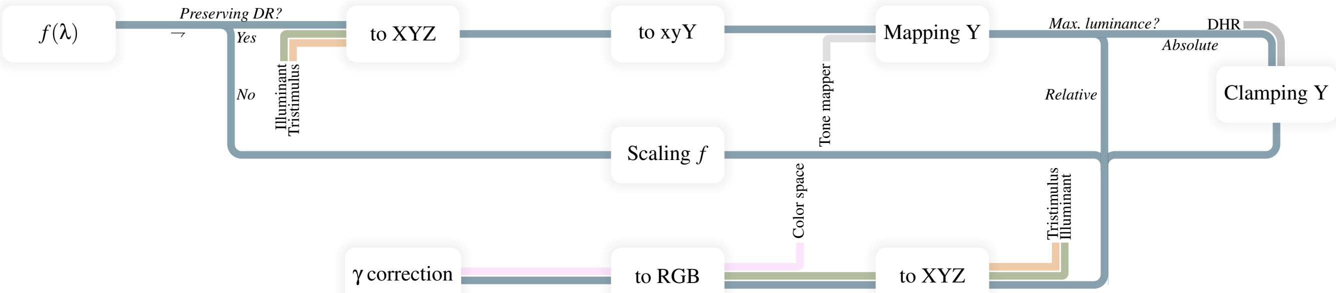

Figure 2: *Diagram of the colorimetric processing chain, listing the stages and inputs required. Several methods are possible, depending on the constraints chosen, written in italics. DR stands for dynamic range.*

express Ω as $\Omega = \mathbb{S}^2_+ \times \mathbb{S}^2_+$ where the symbol $\times$ denotes the Cartesian product. From the metric $d_{\mathbb{S}^2_+}$ associated with $\mathbb{S}^2_+$ as expressed in Eq. 2 (where $\mathrm{hav}(\theta) := \sin^2(\theta/2)$ corresponds to the haversine function) corresponding to the great circle distance, we can express the metric d_Ω associated with Ω as explicited in Eq. 3.

$$d_{\mathbb{S}^2_+}(\omega, \omega') = 2\,\mathrm{asin}\left(\sqrt{\mathrm{hav}(\theta - \theta') + \sin\theta \sin\theta' \,\mathrm{hav}(\phi - \phi')}\right) \quad (2)$$

$$d_\Omega\left((\omega_i, \omega_o), (\omega_i', \omega_o')\right) = \sqrt{d^2_{\mathbb{S}^2_+}(\omega_i, \omega_i') + d^2_{\mathbb{S}^2_+}(\omega_o, \omega_o')} \quad (3)$$

This expression, if it respects the topological properties of the BRDF, can be modified to take account of Helmholtz reciprocity. To do this, we define the metric used in our RBF interpolation d^{Rec}_Ω as the infimum of all possible paths in Ω considering reciprocity.

2.3. RGB visualisation

There are several ways of moving from an unnormalised spectral BRDF to a normalised RGB result: we propose an algorithm based on a decision tree shown in Fig. 2.

3. Results

This method allows us to generate a tabulated RGB BRDF (following the MERL format [MPBM03]) from measured BRDF with 10 incidence angles values, each one having 10 zenith observation angles $\times$ 10 azimuth observation angles. The result used in a rendering engine has given the images shown Fig. 3.

4. Conclusion

The reconstruction method used enables us to obtain a complete dataset that can be used in a rendering engine. The properties of the reconstructed result, such as directional hemispherical reflectance (DHR), are consistent when compared with values measured using a spectrophotometer (Fig. 4).

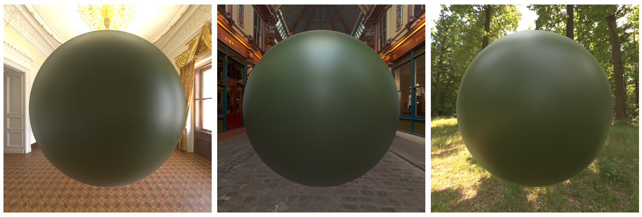

Figure 3: *Results obtained in a rendering engine using the BRDF measured from a green paint sample using setup shown in Fig. 1 after interpolating data from sparse measurements for different environments.*

References

[M*24] Margall F., et al.: Supercontinuum laser-based gonio-scatterometer for in and out-of-plane spectral BRDF measurements. *Optics Express* (2024). 1

[MPBM03] Matusik W., Pfister H., Brand M., McMillan L.: A data-driven reflectance model. *ACM Transactions on Graphics 22*, 3 (July 2003), 759–769. 2

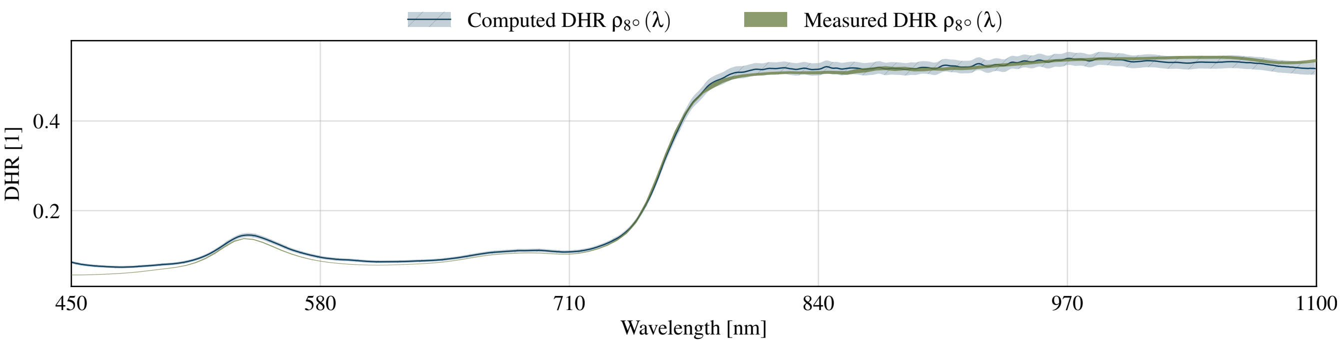

Figure 4: *Computed directional-hemispherical reflectance (DHR) and its uncertainty (lines and hatched areas) as a function of wavelength for the green paint sample with its measured DHR and its uncertainty (green area) obtained using a PerkinElmer Lambda 900 spectrophotometer. The correlation between the results and the reference values validates the approach.*