Grand Challenges in BSDF Measurement and Modeling

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Abstract

Measuring and representing reflection and transmission accurately are core to high fidelity visual simulation of materials. However, state-of-the-art Bidirectional Scattering Distribution Function (BSDF) models do not suggest a general solution for any surface class, from glasses to metals, isotropic to anisotropic materials, and daylight redirecting films. Furthermore, an accurate BSDF acquisition is not a trivial task at especially some specific measurement angles, such as normal incidence and grazing angles. In this paper, we address the problem of finding a general solution for efficient BSDF measurement and representation. We also outline the main issues that do not allow the effective use of current BSDF representations. Finally, we suggest specific solutions that could be investigated in order to address these challenges.

CR Categories: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Color, shading, shadowing, and texture;

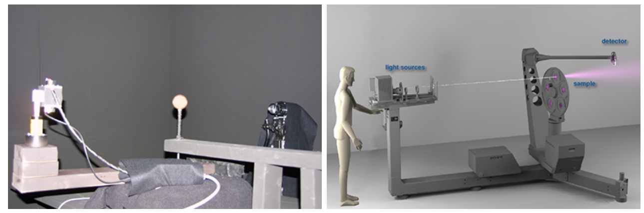
Keywords: BSDF, BSDF measurement, BSDF representation, rendering, global illumination

1 Introduction

Rendering complex scenes requires precise descriptions of materials involved. Some materials, such as papers, glasses, metals and daylight redirecting films, have a unique appearance. To measure these materials accurately, various measurement devices are used [Matusik et al. 2003; Ghosh et al. 2007; Apian-Bennewitz 2014]. After data measurement process, these measurements are represented by Bidirectional Scattering Distribution Function (BSDF), or Bidirectional Reflectance Distribution Function (BRDF) or Bidirectional Transmittance Distribution Function (BTDF) models [Nicodemus et al. 1977; Walter et al. 2007].

Data acquisition process often yields noisy, irregular and sparse measurements, especially when higher dimensional data needs to be measured (i.e, anisotropic measurements). Furthermore, some data acquisition systems [Apian-Bennewitz 2014] do not allow measurements at some specific measurement angles, such as normal incidence and grazing angles. This is an another reason for sparsely measured data. Therefore, representing sparse, irregular and noisy measurements with a material model accurately is an open challenge.

Analytical BRDF representations [Cook and Torrance 1981; He et al. 1991; Ward 1992; Lafortune et al. 1997; Ashikhmin and Shirley 2000; Duer 2005; Edwards et al. 2006; Ozturk et al. 2008; Geisler-Moroder and Dür 2010; Kurt et al. 2010; Xu et al. 2013], BTDF representations [Walter et al. 2007; Dai et al. 2009; de Rousiers et al. 2012; Papas et al. 2014] and BSDF representations [Walter et al. 2007; Dai et al. 2009; de Rousiers et al. 2012; Papas et al. 2014] try to model measurements with a few parameters. However, analytical models fail to fit some material types. Data-driven based representations [Matusik et al. 2003; Lawrence et al. 2004; Öztürk et al. 2010; Bilgili et al. 2011; Pacanowski et al. 2012] are more successful to represent real-world materials. However, data-driven based representations pose some difficulties when measurements are sparse, irregular and noisy.



(a) (b)

Figure 1: *(a) A photograph of Matusik et al.'s BRDF measurement device [2003], (b) An overview of pgII goniophotometer [Apian-Bennewitz 2014] (images from [Matusik et al. 2003; Apian-Bennewitz 2014]).*

In this paper, we focus on the problem of finding a general framework for an accurate and efficient BSDF acquisition and representation. We also summarize the main challenges that do not permit the effective use of state-of-the-art BSDF representations. Finally, we propose specific solutions that could be investigated in order to address these challenges.

2 Grand Challenges

This section can be decomposed to the following two sub-domains: grand challenges in BSDF acquisition and grand challenges in BSDF representation.

2.1 Grand Challenges in BSDF Measurement

One of the most popular BRDF database is the MERL MIT database. BRDFs in the MERL MIT database have been acquired by Matusik et al. [2003]. An image from Matusik et al.'s measurement setup can be seen in Figure 1(a). The MERL MIT database consists of 100 different isotropic BRDF measurements which include highly dense and regular samples. Therefore, this database has been used by many researchers [Ngan et al. 2005; Kurt et al. 2010; Bilgili et al. 2011; Pacanowski et al. 2012; Bagher et al. 2012] for validation, experimental analysis and comparison purposes.

Furthermore, Ngan et al. [2005] measured 4 different anisotropic BRDFs. The renderings of these anisotropic materials using Kurt et al.'s [2010] BRDF model can be seen in Figure 2. Since anisotropic BRDF domain is four dimensional ($4D$) and it's very time consuming to measure whole $4D$ domain, this data set includes noisy, irregular and sparse measurements. Therefore, Ngan et al.'s anisotropic BRDF data set is not suitable for data-driven based representations and it must be preprocessed before it can be represented by a suitable BRDF model. In addition, both Matusik et al. [2003] and Ngan et al. [2005] do not address the light transmission to describe BTDFs which are required to render translucent surfaces.

On the other hand, BME database includes BRDF, BTDF and BSDF measurements. Materials in BME database have been measured by Apian-Bennewitz [2014]. As it can be seen in Figure 1(b), Apian-Bennewitz [2014] used pgII measurement setup. Images of

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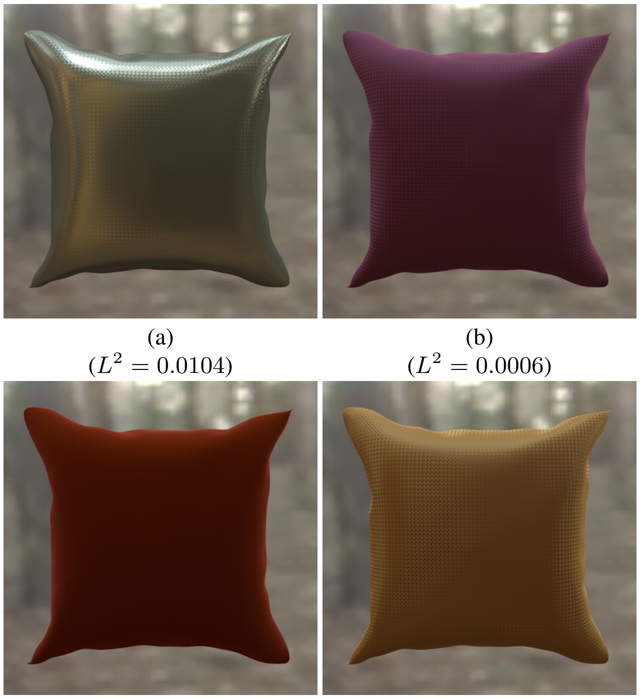
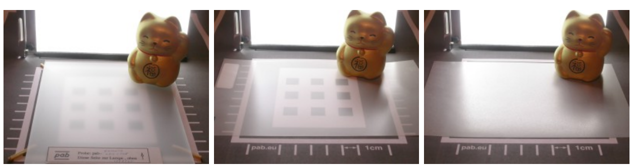


(a) ($L^2 = 0.0104$)
(b) ($L^2 = 0.0006$)
(c) ($L^2 = 0.0003$)
(d) ($L^2 = 0.0014$)

Figure 2: *(a) Brushed aluminum, (b) Purple satin, (c) Red velvet and (d) Yellow satin materials are represented by Kurt et al.'s anisotropic BRDF model [2010]. The L^2 errors of Kurt et al.'s BRDF model are also reported (images from [Kurt et al. 2010]).*



(a) (b) (c)

Figure 3: *Photographs of isotropic translucent materials, which were measured by Apian-Bennewitz [2014]. (a) $L02 - 148$, (b) vk_op10, (c) vk_rms220 materials (images from [Apian-Bennewitz 2014]).*

some measured isotropic translucent materials can be seen in Figure 3. Although, this database includes both reflection and transmission measurements, it has several drawbacks. Firstly, measurements in BME database are noisy, irregular and sparse. Secondly, number of materials in BME database is not enough for a strong validation and comparison. Thirdly, measurements at some important incident angles, such as normal incidence and grazing angles, can not be done by pgII goniophotometer. Because of these drawbacks, measurements from BME database must be preprocessed before representing and rendering measured translucent materials.

2.2 Grand Challenges in BSDF Modeling

Noisy, irregular and sparse reflectance and transmittance measurements can be represented by analytical BRDF models [Cook and Torrance 1981; He et al. 1991; Ward 1992; Lafortune et al. 1997; Ashikhmin and Shirley 2000; Duer 2005; Edwards et al. 2006; Ozturk et al. 2008; Geisler-Moroder and Dür 2010; Kurt et al. 2010; Xu et al. 2013], BTDF models [Walter et al. 2007; Dai et al. 2009; de Rousiers et al. 2012; Papas et al. 2014] or BSDF models [Walter et al. 2007; Dai et al. 2009; de Rousiers et al. 2012; Papas et al. 2014].

Ngan et al. [2005] have experimentally validated that BRDF models, which include Fresnel term [Schlick 1994], can represent the measurements at grazing angles and normal incidence more accurately than its competitors. For example, Ashikhmin-Shirley [2000], Cook-Torrance [1981] and Kurt et al. [2010] BRDF models include Fresnel terms. Therefore, these BRDF models generally give better fitting results than Ward [1992] and Ward-Duer [2005] BRDF models which do not include any Fresnel terms. This result can also be seen in Figure 4. In Figure 4, the Peak Signal-to-Noise Ratio (PSNR) values [Richardson 2002] and difference images are also reported to see differences between the BRDF representations. Although, analytical BRDF models can represent a large number of materials, they can not represent all materials quite well [Ngan et al. 2005; Bagher et al. 2012].

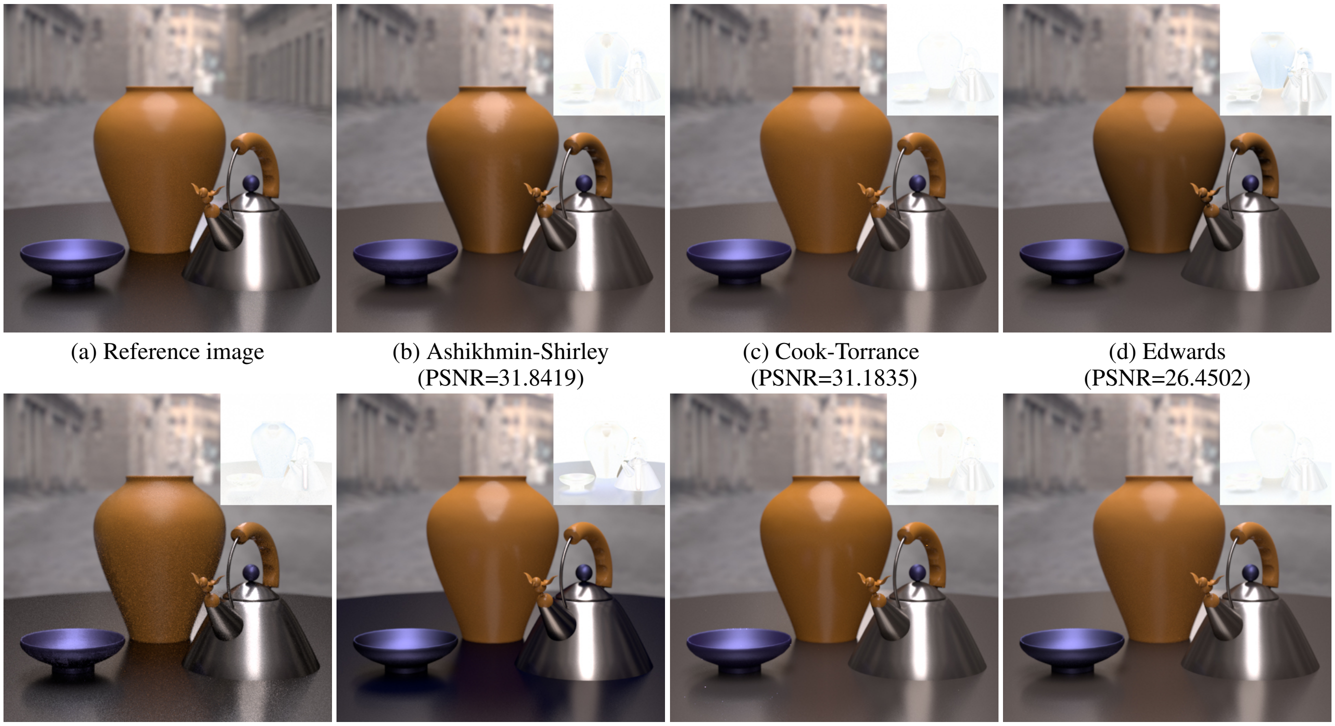
Walter et al.'s [2007] analytical BSDF model is based on microfacet theory and it's for representing rough glass material. In their work, Walter et al. introduced GGX microfacet normal distribution which works extremely well when representing rough translucent materials [Papas et al. 2014]. Recently, Papas et al. [2014] introduced an analytical BSDF model for representing paper material. Papas et al.'s physically-based BSDF representation includes absorption and scattering parameters and accounts for single scattering, multiple scattering and surface reflection. However, none of these BSDF models are suitable for representing custom-designed translucent materials that have unusual scattering properties and/or highly anisotropic structures, such as daylight redirecting films.

Lawrence et al.'s [2004] data-driven BRDF representation uses a Non-negative Matrix Factorization (NMF)-based algorithm and it's also suitable for efficient BRDF importance sampling. Öztürk et al.'s [2010] BRDF model is based on Rusinkiewicz coordinate system [Rusinkiewicz 1998] and uses Copula distributions for representing measured reflectance data. Bilgili et al.'s [2011] factored BRDF representation uses a Tucker-based factorization algorithm to compactly represent measured BRDF data and it allows to efficient BRDF importance sampling. Pacanowski et al. [2012] uses rational functions to compactly represent measured reflectance data. Pacanowski et al.'s [2012] data-driven BRDF representation is based on Rusinkiewicz coordinate system [1998] as this coordinate system helps to represent specular highlights more accurately. However, none of these data-driven BRDF representations can represent noisy, sparse and irregular measurements. Therefore, noisy, sparse and irregular measurements need to be preprocessed before they can be represented with a data-driven based representation.

3 Key Issues

One of the key issues is creating a general framework for sharing and rendering measured BSDFs. Accordingly, Ward et al. [2012] proposed an XML representation and an Open Source C library to support BSDFs in rendering applications. The proposed library allows for the efficient representation, query and Monte Carlo sampling of real-world BSDFs in a model-free framework. The proposed library includes two data-driven based BSDF representations: Matrix-based BSDF representation and Tensor tree BSDF representation.

Matrix-based BSDF representation has advantages for certain matrix operations. On the other hand, Tensor tree BSDF representation has an adaptive density which helps to represent highly peaked data more accurately. As it can be seen in Figure 5, Tensor tree BSDF representation provides a more accurate representation of measured BSDF data than Matrix-based BSDF representation.



(a) Reference image
(b) Ashikhmin-Shirley (PSNR=31.8419)
(c) Cook-Torrance (PSNR=31.1835)
(d) Edwards (PSNR=26.4502)
(e) Lawrence (PSNR=30.3722)
(f) Ward (PSNR=22.2599)
(g) Ward-Duer (PSNR=31.7116)
(h) Kurt et al. (PSNR=32.1210)

Figure 4: *A visual comparisons of various well-known BRDF representations on the Princeton scene. While (e) was rendered at 4096 samples/pixel, others were rendered at 262144 samples/pixel. Insets depict differences between the reference image and the rendered images and darker portions in these difference images imply to higher imparity. Below each image we also report PSNR values (higher is better) (images from [Kurt et al. 2010]).*

Furthermore, Ward et al.'s [2012] proposed library helps to handle advanced schemes such as Complex Fenestration Systems (CFSs) which have been designed to convey daylight in specialized ways, such as prismatic glazings, holographic films, daylight redirecting films and specular louvers.

Simulating CFSs correctly is especially important to modern building designers. As it can be seen in Figure 6, CFSs can be simulated more correctly when the data-driven BSDF representation is used as a proxy for detailed geometry. In this setting, the geometry is used for direct views and shadow testing and the data-driven BSDF representation is used for characterizing light reflected and transmitted by the CFS.

Another key issue is filling noisy, sparse and irregular measurements, as many data-driven based BSDF representations, such as Matrix-based BSDF representation and Tensor tree BSDF representation [Ward et al. 2012], require noise-free, continuous and regular BSDF measurements. Recently, Ward et al. [2014] proposed an interpolation technique for filling a sparse set of incident angle BSDF measurements. The proposed interpolation technique is based on a Lagrangian mass-transport solution [Bonneel et al. 2011] and it fits a set of radial basis functions to each measured distribution, which allows to interpolate between sparse incident directions. The proposed interpolation technique is especially suited for anisotropic BSDFs, because anisotropic BSDF measurements generally include many holes and noise.

As it can be seen in Figure 7, Ward et al.'s [2014] interpolation technique is better than a naive linear interpolation. For efficient rendering and simulation, interpolated data can be converted to a standard BSDF representation, such as Tensor tree representation, and it can be used in a model free framework [Ward et al. 2012].

4 Conclusions

In this paper, we summarized grand challenges and key issues in BSDF measurement and representation. We hope that this short outline of the key issues encourages researchers to focus on these issues. We also hope that this short outline of the key issues helps to advance BSDF measurement and representation.

Indeed, there is a need for a huge database that includes variety of BSDF measurements. We think that both researchers and designers will use such a database for comparison, validation and simulation purposes. In the future, we're planing to help this process by measuring various translucent materials and providing them with a suitable BSDF library. In BSDF representation side, there is a need for an accurate interpolation technique and an efficient BSDF representation. Extrapolating BSDF data at grazing angles and modeling backlit appearance are other big challenges and they should be carefully handled. In the future, we're also planing to investigate an accurate BSDF representation that handles these challenges quite well.

Acknowledgements

We would like to thank all the co-authors of the papers discussed here, as well as other collaborators that have helped when preparing these works.

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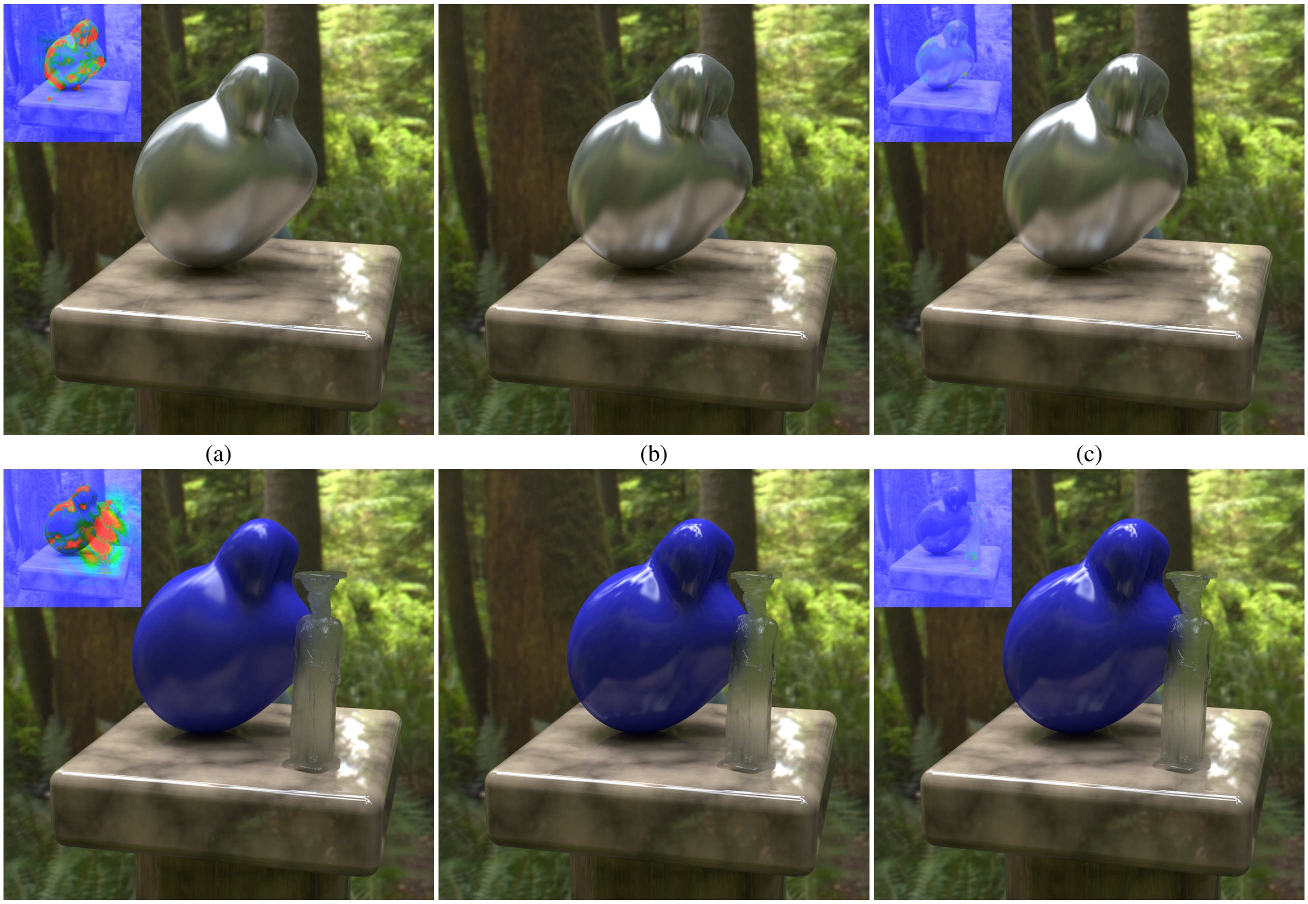

(a) (b) (c)

(d) (e) (f)

Figure 5: *(a),(d) Matrix-based representation. (b), (e) Reference image. (c), (f) Tensor tree representation. Insets show color-coded differences between reference and rendered images [Mantiuk et al. 2011] (images from [Ward et al. 2012]).*

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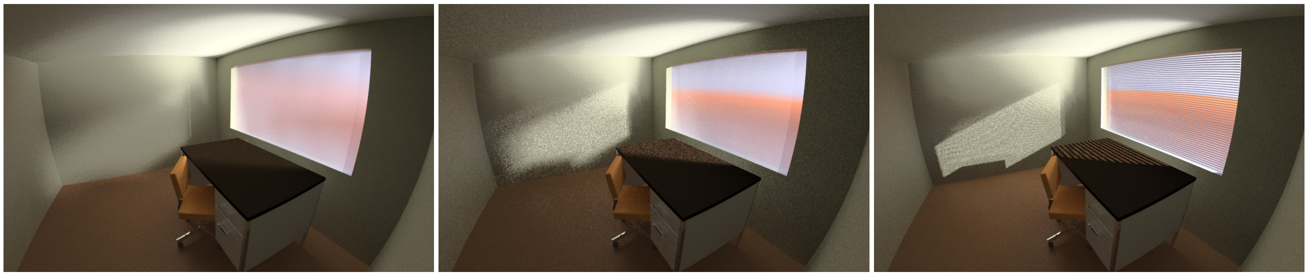
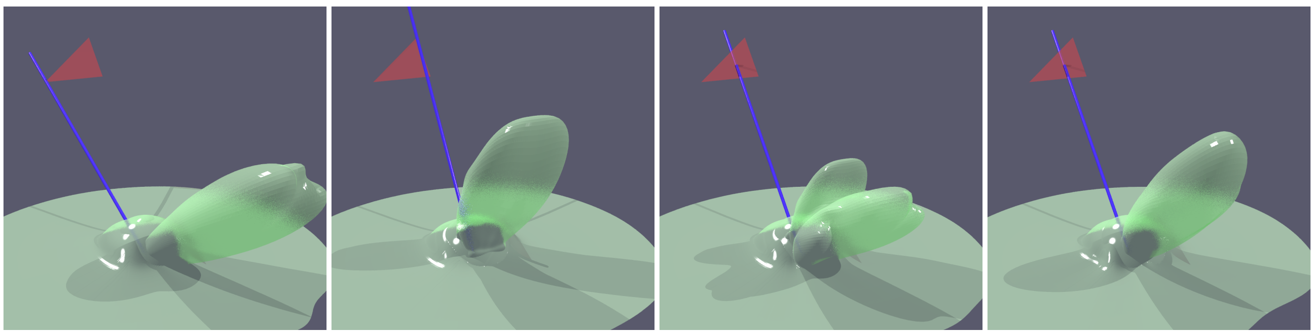


(a) (b) (c)

Figure 6: *(a) A venetian blind system was rendered using a* 145×145 *Klems matrix representation. (b) was rendered using a tensor tree representation with* $3\times$ *the resolution of the Klems matrix data. (c) was rendered using a BSDF surface as a proxy for detailed blinds geometry. We can now see all details and the striped shadows (images from [Ward et al. 2012]).*



(a) (b) (c) (d)

Figure 7: *(a) Measured reflectance distribution at one incident direction. (b) Distribution at another incidence direction. (c) Linear interpolation of three distributions. (d) Lagrangian mass transport based interpolation (images from [Ward et al. 2014]).*

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