Workshop on Material Appearance Modeling (2013)
H. Rushmeier and R. Klein (Editors)

BTF based Material Representations: Current Challenges

Roland Ruiters and Reinhard Klein[†]

Institute for Computer Science II, University of Bonn, Germany

Abstract

The development of Bidirectional Texture Functions (BTFs) has made it possible for a wide range of different materials to acquire their characteristic appearance from a real-world counterpart and reproduce it faithfully in a high-quality rendering, that is hard to distinguish from an actual photograph. However, they have not yet found wide-spread use in practical applications. In this paper, we discuss, from our point of view, the main reasons for this and which unanswered questions and challenges for future research in this area remain. We focus on three different aspects: How can BTFs be measured and represented more efficiently? How can they be edited intuitively? And finally, can we find a perceptual difference metric between materials?

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Color, shading, shadowing, and texture

1 Introduction

During the last 15 years, the development of *Bidirectional Texture Functions* (BTFs) has enabled very faithful reproductions of a large range of different materials. For many materials, it is possible to acquire their characteristic appearance from a real-world counterpart and reproduce it faithfully in a high-quality rendering, that is hard to distinguish from an actual photograph. For example, Figure 1 shows a rendering of a few representative material samples that have been acquired with the Multi-View Dome Acquisition Setup at the University of Bonn (first description in [MMS*04]). Still, these techniques have not yet found wide-spread use in practical applications in computer graphics. This is mainly due to two important reasons.

On the one hand, the acquisition of the datasets remains a big challenge. Even though the measurement devices have improved considerably, the requirements in regard to quality and resolution have risen as well. Thus, the acquisition is still too costly and time-consuming for many practical applications, the size of the datasets remains a challenge even for current hardware and for a number of materials the available angular resolutions are still not sufficient to resolve specular highlights. High angular resolutions are not only a challenge during the acquisition but also with respect to the data representation that is chosen for storing and processing the acquired data. Data-driven approaches are based on a discrete often uniform sampling with limited resolution of the BTF which is incapable of representing the high frequent components of specular reflections of the material. In contrast representing the materials by fitting analytical models to the measured samples is in principle capable of representing also high frequency components but lack the generality to represent the full complexity of effects stored in the Apparent BRDF often resulting in the loss of important effects such as depth perception and interreflections.

On the other hand, the lack of suitable techniques to edit the resulting datasets has limited their application. Though the data-driven approaches are well-suited for the exact reproduction of real-world exemplars, editing the resulting dataset is very challenging due to their size and complexity. Still, in many applications an exact reproduction is not sufficient and techniques for the creative editing of the datasets are desired. This ranges from the generation of tileable materials without clearly visible repetitions, over the creation of spatially varying materials to the actual process of designing new material based on the available measurements.

Apart from rendering, digital material representations could also have considerable impact in industrial applications, such as product design, material procurement, fabrication, and quality control. However, these have not yet been

† e-mail: {ruiters, schwartz, rk}@cs.uni-bonn.de

DOI: 10.2312/MAM.MAM2013.017-020

Figure 1: *Rendering of measured Bidirectional Texture Functions*

Figure 2: *Comparison of a photograph (left, background masked out) with a rendering (right) of an object with an acquired BTF.*

realized. In colorimetry, there exist standardized color systems, such as the PANTONE matching system, measures for the perceptual difference between colors, e.g. CIE94 ΔE^* [CIE95], and suitable devices for color matching and calibration. In contrast, no standardization is available for the appearance of materials. This is probably mainly due to the lack of a suitable perceptual distance measure which could predict whether two materials would be perceived as identical or not. If such a measure, together with suitable lightweight measurement devices, would exist, a similar standardization could also be realized for material appearance.

2 Acquisition and Representation

For the practical applicability of measured material representations, techniques for the fast, simple and inexpensive acquisition from real-world counterparts are required. Although there has been considerable progress in the performance of the acquisition devices, purely data-driven techniques such as Bidirectional Texture Functions will always have to trade of the demand for simple and inexpensive measurement devices with the high spatial and angular resolutions that are needed for high-quality reproductions of the material. The example shown in Figure 2 shows a comparison between a photograph and a rendering of an object with a measured BTF. It illustrates one of the limitations of the purely data-driven acquisition. Most of the object is reproduced quite accurately, but the angular resolution is insufficient to resolve the specular highlights correctly. This happens even though a large number (198) of illumination directions has been acquired and the resulting dataset requires already 165 GB of storage. Further increasing the angular resolution would therefore be very costly.

The only way to overcome this fundamental trade-off is the utilization of a suitable prior to reduce the cost of the measurement without having to sacrifice quality. Although many different priors have already been applied in this context, an open question is whether typical assumptions such as analytical BRDF models, smoothness, low-rank etc. provide the best priors or whether data-driven priors are a superior approach. Given a suitably large set of high-quality measurements, these could provide the necessary prior to reconstruct new materials successfully from a much sparser measurement without explicitly making model assumptions. This idea has already been applied to reconstruct BRDFs [MPBM03b] or SVBRDFs [WWHL07] from a small number of samples and a database of isotropic BRDF measurements. This principle could be extended to a database containing spatially varying reflectance information in the form of BTFs as this would provide additional information in the

Figure 3: *Examples for BTF interpolation sequences.*

form of local neighborhoods. In the area of image processing, this idea has already been successfully applied. In a recent example [SH12], that is very similar to our case, super-resolution is performed by first identifying images showing a similar context in a large database and then synthesizing a high-resolution image from them using the captured low-resolution image as a constraint. Similarly, it might be possible to identify measurements of similar materials in a database and then use constrained BTF synthesis algorithms to create a plausible reconstruction of the presented sample.

Another important question is, whether the currently mostly utilized measurement paradigm has to be overcome. In most of the current approaches, the continuous reflectance function is sampled at discrete points (or more precisely in small regions, if considering that a pixel is actually an integral in the spatial domain and the entrance pupil of the camera and the extent of the light source result in an integral in the angular domain). However, it is very difficult to scale this approach to the angular resolutions necessary to resolve highly specular objects, as these exhibit a very high-frequent reflectance behavior and one is thus fundamentally limited by the Nyquist criterion. An alternative might be to measure weighted integrals of the reflectance function. Area light sources or patterned or gradient illumination can be used to perform those measurements. Again, given a suitable prior, it should be possible to reconstruct the reflectance behavior from these measurements. First techniques reconstructing analytical SVBRDFs utilizing spherical gradient illumination [GCP*09], Gray-Codes [FCMB09] or Spherical Harmonics [TFG*13] have already been proposed. Similar approaches have received much attention lately in the context of compressive sensing, where the measurement is specified in the form of a random measurement basis and the prior as a second basis in which the signal can be represented sparsely. Currently, it is not clear whether the mathematical framework of compressive sensing can be directly applied to the measurement of BTFs. However, even if not, the general idea of performing measurements in a different basis than the currently employed Dirac delta functions and then utilizing a suitable prior to reconstruct the reflectance behavior might be an interesting avenue of future research.

The utilized representation of the material often specifies already a strong prior. For example, using analytical SVBRDFs is a commonly used prior as it specifies extensive knowledge about common materials. It is able to describe specular reflections well, however is not suited to represent the typical complex ABRDF effects like parallax and shadowing. Therefore, other representations that tabulate measured data and use them directly for rendering after a possible data-driven compression are often employed, as they are general enough to represent all these non-local complex effects especially contained in BTFs. However, we want to point out that using a tabulated data representation implicitly enforces a strong prior as well, namely that the functions are band-limited according to the sampling density. Unfortunately, increasing the sampling resolution of current BTF measurements in such a way that even highly specular materials can be represented this way seems not feasible in the near future. Therefore, a representation which is at the same time sufficiently compact, capable of reproducing the appearance of a wide range of materials faithfully, allows for the integration of a suitable prior and is directly applicable during the reconstruction process is required.

3 Editing

Several different techniques for BTF editing have already been proposed. A very promising approach is in our opinion the use of BTF synthesis techniques to interpolate between measured materials. In a recent publication [RSK13], we have demonstrated that it is possible to create interpolation sequences, in which the intermediate materials are still perceived as plausible. See Figure 3 for a few example sequences. The interpolation works even for materials with complex feature topology, spatially varying reflectance behavior and a meso-structure resulting in strong parallaxes. This provides the necessary foundation for and demonstrates the general possibility of a data-driven material design approach. This would provide a very general technique for the design of new materials, which could work with a range of different material classes without the need to use specialized models or choose unintuitive parameters. As this technique is based on BTF synthesis, it could allow for the synthesis of large and repetition free materials and the creation of seamless and distortion-free materials on an objects surface.

However, for a practical application of this design paradigm further questions have to be resolved. The most important challenge is probably the necessity for a considerable speed-up of the interpolation. An intuitive material design can only be realized if an interactive synthesis is possible. It remains an open question whether existing more efficient texture synthesis approaches could be adapted or whether the fact that the interpolated patches are less consistent than the uninterpolated ones results in unsatisfactory results. Furthermore, either more efficient techniques to compute the interpolated patches or a suitable precomputation approach should be developed.

On the other hand, the question how the currently available material interpolation technology is best utilized to enable an intuitive and efficient material design process is still open. Which type of user interface and which design paradigm allows for the most intuitive and efficient design process? It might be that an approach in which the designer is given an intuitive interface to directly interpolate between the measured materials is sufficient. On the other hand, a more indirect approach, such as the one proposed by Matusik [MPBM03a] for BRDFs, in which the measured samples are abstracted and the user instead navigates a material space along perceptual traits, might be more intuitive.

4 Perceptual Distance Measure for Materials

The question how it might be possible to determine the perceptual distance between two materials is mostly unanswered. Though a perceptual distance metric [GMSK09] for BTFs has already been proposed, this metric can only be used to compare an original measurement to a compressed or distorted version of exactly the same measurement as it requires exact one-to-one correspondences. It does not answer the more general question, whether two different material samples (e.g. two samples cut out of the same piece of leather) would be perceived as belonging to the same material. In this context, several different settings can be investigated. If a full measurement of both materials is available, one approach might be to use constrained BTF synthesis to create two samples which are in feature alignment and then use the existing BTF metric [GMSK09] to determine whether the two samples would be perceived as similar.

It would however be even more useful if this decision could also be made if for one of the two samples only a sparse measurement or even a single image is available. This way, after only a sparse measurement, a perceptually equivalent material could be retrieved from a database. In many practical settings, this could enable a simple and fast material acquisition without the need for complex and expensive measurement devices. In the most general setting, the metric would even work for materials captured under general, unknown illumination and complex object geometry. However, it is yet unclear under which conditions these more general questions can be answered and which techniques could be employed. An approach based on BTF synthesis might generalize to a sparse measurement under controlled conditions but it seems very unlikely that it could cope with more complex settings. Here, approaches based on suitable image statistics (e.g. [CD04]) might be more promising.

5 Conclusion

There has been considerable progress in the acquisition, processing, editing and rendering of Bidirectional Texture Functions and we are now at the point that these can provide a very faithful reproduction for a wide range of materials. A more wide-spread adaption in industry is currently probably mainly hampered by lacking standardization of the file formats, suitable shaders for common graphics software, the fact that measurement devices and material databases are not yet commercially available and no easy to use solutions for BTF editing exist. However, there still remain unanswered fundamental questions. Which material representation is both capable of representing materials with complex meso-structures but also high specularity? How could we measure such materials efficiently? How can we provide intuitive and interactive tools to explore the space of materials? Can we find a perceptual material difference metric?

References

[CD04] Cula O. G., Dana K. J.: 3d texture recognition using bidirectional feature histograms. *IJCV 59*, 1 (2004), 33–60. 4

[CIE95] *Industrial Colour-Difference Evaluation*. Tech. Rep. CIE 116-1995, Commission Internationale de l'Eclairage (CIE), 1995. 2

[FCMB09] Francken Y., Cuypers T., Mertens T., Bekaert P.: Gloss and normal map acquisition of mesostructures using gray codes. In *International Symposium on Advances in Visual Computing* (2009), pp. 788–798. 3

[GCP*09] Ghosh A., Chen T., Peers P., Wilson C. A., Debevec P.: Estimating specular roughness and anisotropy from second order spherical gradient illumination. In *Proc. of EGSR* (2009), pp. 1161–1170. 3

[GMSK09] Guthe M., Müller G., Schneider M., Klein R.: BTF-CIELab:A perceptual difference measure for quality assessment and compression of BTFs. *CGF 28*, 1 (2009), 101–113. 4

[MMS*04] Müller G., Meseth J., Sattler M., Sarlette R., Klein R.: Acquisition, synthesis and rendering of bidirectional texture functions. *CGF - Eurographics, State of the Art Reports 24*, 1 (2004), 83–109. 1

[MPBM03a] Matusik W., Pfister H., Brand M., McMillan L.: A data-driven reflectance model. *ACM TOG - Proc. of SIGGRAPH 22*, 3 (2003), 759–769. 4

[MPBM03b] Matusik W., Pfister H., Brand M., McMillan L.: Efficient isotropic BRDF measurement. In *Proc. of EGSR* (2003), pp. 241–248. 2

[RSK13] Ruiters R., Schwartz C., Klein R.: Example-based Interpolation and Synthesis of Bidirectional Texture Functions. *CGF - Proc. of EG 32*, 2 (2013), 361–370. 3

[SH12] Sun L., Hays J.: Super-resolution from internet-scale scene matching. In *Proc. of ICCP* (2012). 3

[TFG*13] Tunwattanapong B., Fyffe G., Graham P., Busch J., Yu X., Ghosh A., Debevec P.: Acquiring reflectance and shape from continuous spherical harmonic illumination. *ACM TOG - Proc. of SIGGRAPH 32*, 4 (2013). 3

[WWHL07] Weistroffer R. P., Walcott K. R., Humphreys G., Lawrence J.: Efficient Basis Decomposition for Scattered Reflectance Data. In *Proc. of EGSR* (2007), pp. 207–218. 2