BRDF Measurement of Highly-Specular Materials using a Goniometer

Jiří Filip

Institute of Information Theory and Automation of the CAS Prague, Czech Republic filipj@utia.cas.cz

Radomír Vávra Institute of Information Theory and Automation of the CAS Prague, Czech Republic vavra@utia.cas.cz

Frank J. Maile Schlenk Metallic Pigments GmbH Roth-Barnsdorf, Germany frank.maile@schlenk.de

ABSTRACT

Visually accurate capture of appearance of highly specular surfaces is of a great research interest of the coating industry, who strive to introduce highly reflective products while minimizing their production and quality assessment costs, and avoiding environmental issues related to the production process. An efficient measurement of such surfaces is challenging due to their narrow specular peak of an unknown shape and typically very high dynamic range. Such behavior puts higher requirements on capabilities of a measuring device and has impact on length of the measurement process. In this paper, we rely on a material probes with a predefined curved shape featuring slight local inhomogeneities. This defines a goniometric device as appropriate means of appearance capture. To shorten a typically long measurement time required when using these approaches, we introduce a method of material appearance acquisition by means of the isotropic BRDF using relatively sparse sampling adapted to each measured material individually.

CCS CONCEPTS

Computing methodologies → Reflectance modeling;

KEYWORDS

BRDF, gloss, material, specular, goniometer, adaptive, measurement, chrome-like appearance, high-reflective, mirror-like coatings

ACM Reference Format:

Jiří Filip, Radomír Vávra, and Frank J. Maile. 2017. BRDF Measurement of Highly-Specular Materials using a Goniometer. In SCCG '17: SCCG '17: Spring Conference on Computer Graphics 2017, May 15-17, 2017, Mikulov, Czech Republic. ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/ 3154353.3154370

1 INTRODUCTION

The understanding of principles defining the human perception of highly reflective mirror-like surfaces is one of the major research challenges of computer graphics. In particular, the visually accurate measurement and reproduction of such surfaces is of a vital research interest to coating industry striving to introduce highly reflective

SCCG '17, May 15-17, 2017, Mikulov, Czech Republic

© 2017 Association for Computing Machinery.

ACM ISBN 978-1-4503-5107-2/17/05...\$15.00

https://doi.org/10.1145/3154353.3154370

products that could substitute the appearance of more expensive natural materials while minimizing production and quality control costs. Also, there is no optical standard established which complicates color communication in this industry in general. Electroplated chrome surfaces are chosen as a reference, but their manufacturing is under pressure due to environmental reasons as the process uses harmful Cr⁶⁺ which causes cancer [Maile and Martins 2015]. For this reason, the complete industry is looking for chrome replacements in order to match as close as possible the appearance of this chrome-like look. Here, one possibility is the use of coatings incl. metallic pigments especially vacuum metallic pigments (VMP) [Maile et al. 2005].

Results shown in this paper are part of a wider research project analyzing human perception of highly specular or glossy surfaces. Our past experiments revealed that different shapes covered by the same specular material induce different perceptions of gloss (see Fig. 1). Therefore, an ultimate goal is the identification of links



Figure 1: Influence of 3D object shape on overall visual perception of highly-reflective coatings including VMPs [Maile et al. 2005]. Identical coatings sprayed on black (left) and white (right) panels and speedshapes.

between subjective visual perception and objective computational measures and their interaction with surface shape, unifying and simplifying the communication of the highly-specular material appearance at both academic and industrial levels.

For the sake of this project, a specific curved surface shape is selected as shown in Fig. 2, in order to be easily manipulated and evaluated by human subjects. As exactly the same samples should

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from permissions@acm.org.



Figure 2: Examples of physical samples used for subjective assessment and objective measurement of reflective materials. Samples courtesy of Lechler S.p.a. Como, Italy.

be used for surface appearance measurement and its further subjective evaluation, we cannot prepare proprietary flat, cylindrical, or spherical samples which are more suitable for image-based appearance capture systems. Although the selected shape is great for the subject, for the assessment of specular properties, it puts higher demands on the measurement process. Additionally, due to possible local spatial inhomogeneity of the curved sample, only a small area is selected for effective measurement. These requirements, together with the nature of specular materials, i.e., narrow specular peaks of a high dynamic range, resulted in an appearance measurement using a sequential goniometric sampling.

This paper focuses specifically on the measurement of material appearance by an isotropic Bidirectional Reflectance Distribution Function (BRDF). However, sequential measurement of the BRDF using goniometers is typically very slow, so the main contribution of this paper is an introduction of a data-driven measurement method that adapts the sampling steps particularly along specular highlights in accordance with reflective properties of measured materials. This allows for the relatively sparse measurement of the BRDF in a reasonable time-frame, even using a relatively slow measurement process. We also thoroughly discuss many practical issues related to the goniometric appearance measurement of highly specular materials.

Our paper is structured as follows. Section 2 introduces the related work. Section 3 describes the theoretical background of BRDF representation, while Section 4 describes the measurement device, material probes and other practical issues. Section 5 outlines the proposed adaptive method of BRDF measurement, whose results are visually compared with other similar public specular BRDF data in Section 6. Section 7 concludes the paper.

2 RELATED WORK

Our paper is related to BRDF parameterization methods and their respective measurement approaches.

Parameterization of BRDF data holds a key importance in development of efficient acquisition and rendering algorithms. Depending on the required priority, the data can be organized in a way more suitable to certain compression [Rusinkiewicz 1998] or importance sampling [Havran et al. 2010] methods. Different parameterizations suggested for several analytical BRDF models are studied in [Stark et al. 2005]. In this work, we focus ourselves on the half-difference BRDF parameterization [Rusinkiewicz 1998]. Although this parametrization is inherently anisotropic, it is typically used to represent isotropic materials only.

Anisotropic BRDF measurement methods can be split into two groups based on their ability to record material anisotropy or not. However, as a dense measurement of the anisotropic BRDF using gonioreflectometers [Filip et al. 2013; Holroyd et al. 2010; Höpe et al. 2012; Murray-Coleman and Smith 1990] is very time demanding, setups were developed that reduced the required number of mechanical degrees-of-freedom (DOF). Many setups use mirrors, e.g., spherical mirror [Ward 1992], kaleidoscopically arranged flat mirrors [Han and Perlin 2003], parabolic mirrors [Dana and Wang 2004], ellipsoidal mirrors [Mukaigawa et al. 2009], or a combination of concave parabolic and custom-built mirrors [Ghosh et al. 2010]. They allowed for the capture of many viewing directions simultaneously; however, a limited range of elevation angles resulted. Other methods used setups consisting of multiple light sources and sensors [Ben-Ezra et al. 2008; Schwartz et al. 2013], which shorten the measurement time significantly at the cost of a fixed measurement geometry. Another group of acquisition methods reduces the number of DOF by using a specimen of a known shape (e.g., spherical, cylindrical or flat). These setups capture either isotropic [Matusik et al. 2003] or anisotropic [Filip et al. 2014; Lu and Little 1995; Ngan et al. 2005] BRDF data. However, accuracy of these measurements is often compromised due to slight inhomogeneity of a specimen and its shape imperfections. A notable source of public isotropic BRDFs of several highly specular samples is the MERL BRDF database [Matusik et al. 2003].

In this paper, we focus on the measurement of the isotropic BRDF of highly specular materials using an image-based goniometer, i.e., using a camera to capture the reflected radiance intensity.

3 THEORETICAL BACKGROUND

Real-world appearance of spatially homogeneous materials can be represented by means of the BRDF as introduced by Nicodemus et al. [Nicodemus et al. 1977]. It is a four-dimensional vector-valued function $f_r(\theta_i, \theta_v, \varphi_i, \varphi_v)$ of the illumination direction $\omega_i = \{\theta_i, \varphi_i\}$ and the viewing direction $\omega_v = \{\theta_v, \varphi_v\}$ that defines how light is reflected at the surface of a material and where $\theta \in [0, \frac{\pi}{2}]$ is the elevation angle and $\varphi \in [0, 2\pi)$ is the azimuthal angle of a spherical coordinate system.

The general four-dimensional function can describe anisotropic materials, i.e., those that have variable reflectance when they are rotated along a surface normal. This property is common for many real-world materials that contain directional elements such as thread in fabric or grain in wood. A three-dimensional simplification of the BRDF is called the isotropic BRDF $f_r(\theta_i, \theta_v, \Delta \varphi = \varphi_v - \varphi_i)$ and it neglects anisotropic appearance.

The main limitation of the standard parameterization, which is shown in Fig. 3-a, is its inefficient representation of important features, such as specular highlights not aligned with axes of the coordinate system. Therefore, locations of the highlights depend on several variables and usage of standard parameterization for, e.g., compression of the BRDF, is limited.

These limitations are leveraged by the half-difference (HD) parameterization proposed by Rusinkiewicz [Rusinkiewicz 1998]. He changes variables from $f_r(\theta_i, \varphi_i, \theta_v, \varphi_v)$ to $f_r(\theta_h, \varphi_h, \theta_d, \varphi_d)$ as show in Fig. 3-b. The BRDF is represented by the half vector $\mathbf{H} = \{\theta_h, \varphi_h\}$ between the illumination and viewing directions, and by the difference vector $\mathbf{D} = \{\theta_d, \varphi_d\}$, which represents the illumination direction I with respect to the half vector **H**.

The HD parametrization is, due to its effective description of specular highlights, widely used in analytical BRDF models, e.g., [Ward 1992], [Cook and Torrance 1981]. The shape of specular highlights is represented by the elevation angle of the half vector θ_h , and the ideal mirror reflection is obtained for $\theta_h = 0^\circ$, i.e., when the half vector is aligned with the normal of the surface. A non-linear sampling along θ_h is often used to reproduce a highly specular material with a limited number of samples [Matusik et al. 2003]. Anisotropic behavior is controlled by the azimuthal angle of the half vector φ_h as represented by the rotation of a sample around its normal.

On the other hand, a value of the elevation angle of the difference vector θ_d is equal to one half of the angle between a camera and a light source. Therefore, at $\theta_d = 0^\circ$ are ideal retro-reflections. Reciprocity is introduced by symmetry of the azimuthal angle of the difference vector $\varphi_d = \varphi_d + c\pi$, where $c \in \mathbb{Z}$. Therefore, a range of the angles is $\theta_h, \theta_d \in [0, \frac{\pi}{2}], \varphi_h \in [0, 2\pi), \varphi_d \in [0, \pi)$. The isotropic BRDF can be described by its three-dimensional variant $f_r(\theta_h, \theta_d, \varphi_d)$ by omitting dependence on azimuth φ_h .



Figure 3: BRDF parameterizations: (a) spherical, (b) half-difference.

4 BRDF MEASUREMENT

In this section, we first introduce a BRDF acquisition device and material probes we use for experiments. Next, we discuss general practical issues we dealt with over the measurement process.

4.1 Acquisition Device

We use the UTIA gonioreflectometer [Filip et al. 2013] to capture appearance of the tested coatings (see Sec. 4.2). This state-of-the-art setup (see Fig. 4) consists of a rotary stage, holding a measured sample and two independently controlled arms with a camera (one axis) and a light source (two axes). It allows a flexible, adaptive measurement of a nearly-arbitrary combination of illumination and viewing directions. Although an occlusion of view of the camera by the arm with the light source may occur, it can be analytically detected and, in the most cases, an alternative positioning of the arms exists. Verified angular accuracy of positioning of the arms across all axes is 0.03 degree. The inner arm holds a LED light source 1.1 m far from a sample, which produces a narrow and uniform beam of light. The outer arm holds an industrial full-frame 16 Mpix



Figure 4: The UTIA gonioreflectometer.

RGB camera AVT Pike 1600C. The distance of the sensor from a sample is 2 m. When we use different optics, we can achieve an arbitrary spatial resolution up to 1071 DPI (i.e., 24 μ m/pixel). In our experiment, we used a resolution of 353 DPI (i.e., 70 μ m/pixel). We perform color calibration of the camera using the X-Rite Color Checker target.

4.2 Material Probes

We measure two highly-specular materials: a green paint with a thick layer of acrylic coating and casted silver 925 mechanically polished to maximal surface smoothness as shown in Fig. 5. As our work is related to other studies that analyze human visual perception of highly reflective materials, the samples feature rounded shapes. The samples were kindly provided by the Lechler S.p.a. Como, Italy refinishing-paint company. Since the rounded shape poses problems due to the repeated attachment of a sample to the measuring device and its precise geometrical alignment owing to the coordinate system of the device, we designed a proprietary holder mounted on an x-y-z linear positioning stage. As only a small area of 3×3 mm on the top of the sample is used for data collection, its normal should be aligned with the normal of the turntable. The alignment of a sample is adjusted and verified by iterative adjustment of its position, while we test stationarity of the specular highlight position for several rotations of the turntable.

4.3 Measurement Related Issues

Measurement of highly specular materials is tricky due to several visual artifacts related to high reflectivity and thus a high dynamic range of the measured material. Most of the artifacts are, due to its reflectivity, present only for the silver sample. Their overview is given in Fig. 6 and they are discussed in more detail in this section.



Figure 5: Two measured specular materials: (top) the green paint with acrylic coating and (bottom) the highly polished silver 925. Sample shape courtesy of Lechler S.p.a. Como, Italy

- anisotropy due to polishing
- light refraction on aperture
- lens flare artifact
- reflections of environment

Figure 6: Challenges encountered during measurement of the highly specular material.

4.4 Anisotropic artifacts

These artifacts originate from insufficient smoothness of the otherwise isotropic material. Such material often exhibits local microscopic scratches, which are visible when illumination and viewing directions are perpendicular to the direction of scratches (see Fig. 6). A correct appearance of scratches cannot be captured by the isotropic half-difference parameterization, and they result in anisotropic artifacts within the rendering. Examples of such artifacts for steel and chrome-steel materials from the MERL database [Matusik et al. 2003] are shown in Fig. 7-a,b, and in Fig. 7-c for our measurement of silver. These artifacts can be often avoided by selecting a proper value of the φ_h parameter, i.e., by an appropriate initial orientation of a sample before a measurement process. We use this solution to remove artifacts.

Lens flare 4.5

These artifacts occur in the presence of a strong light source in a scene. This phenomenon is caused by an internal reflection and scattering within the body of a lens, and is more pronounced for



(a) steel

(c) silver 925

Figure 7: Anisotropic artifacts in the captured isotropic BRDF: (a) steel, and (b) chrome-steel from the MERL database, and (c) silver from our measurement.

lenses with a large number of elements. For our fixed lens, it exhibits itself merely as a bright red spot (see Fig. 6). This artifact can be, to a certain extent, eliminated by using a sufficiently long cylindrical lens hood or by applying an appropriate photographic filter. The latter might, however, impact other aspects of measured appearance; therefore, we have carefully checked all captured images for the presence of local color changes so as to avoid contamination of measured data by this artifact.

4.6 Diffraction on an aperture

This star-like artifact occurs due to the wave nature of light. When distant bright light passes through a narrow slit, it causes that the light spreads perpendicularly to the slit. Usage of a small aperture creates a slit-like situation at the corners of the blades of the aperture. This effect is more pronounced for narrow apertures and bright point-like illumination. The resulting bright streaks in a starlike shape influence measured BRDF values in an unpredictable manner when the specular highlight approaches the sampled area. Therefore, as a counter measure, we replaced the original aperture in a lens by a circular one of a similar diameter. The results of this step are satisfactory as shown in Fig. 8. The diffraction effect is



Figure 8: Diffraction on the aperture of a lens (left), and its suppression by usage of the circular aperture (right).

more intensive the narrower the light source as shown in Fig. 9, which compares two light sources having different emitting areas.

4.7 Reflections from environment

Reflections of environment is naturally present when a specular material is measured. They can be suppressed by using diffuse black materials for all components surrounding the measured sample.

Filip, Vávra, and Maile

BRDF Measurement of Highly-Specular Materials using a Goniometer



Figure 9: Impact of the size of the area that emits light on diffraction level.

5 PROPOSED MEASUREMENT APPROACH

The proposed measurement process can sample even a highly specular isotropic material with a very limited number of samples. Specifically, we place samples along θ_d with a step of 3°, along φ_d with a step of 15° and we place 30 samples along θ_h non-linearly. It results into $|\theta_h| \times |\theta_d| \times |\varphi_d| = 30 \times 30 \times 7 = 6300$ samples which can be measured by the goniometer in reasonable time. The measurement process can be divided into two steps. The first one estimates the optimal parameter of a non-linear distribution of samples along a specular highlight (θ_h), while the second part realizes the sparse BRDF measurement using the parameter obtained in the previous step. The estimation of the optimal parameter is performed by a fine measurement of a single slice of variable θ_h for other parameters constant and by computation of its value enabling the best approximation of measured data.

Prior to any measurement of a new material, we performed analysis of already measured materials in the MERL database. The analysis serves for determining the optimal function of the nonlinear distribution of samples, whose parameter is then estimated for each new measured material. It also decides the optimal position of a slice, whose values are measured for further estimation of the parameter. An overview of the analysis and the entire measurement process is given in Fig. 10.

5.1 Analysis of the MERL database

Once we want to sample a highly specular material using the limited number of samples, one of the most challenging tasks is a proper non-linear sampling along θ_h , where the reflected intensity changes in orders of magnitude within a fraction of a degree. This is clearly shown in an example of the characteristic slice ($\theta_h \times \theta_d$) of *steel* from the MERL database [Matusik et al. 2003] in Fig. 11. On the left side, one can observe a very sharp transition between specular and off-specular values when the θ_h is sampled linearly. Therefore, non-linear sampling of θ_h using the square root is often applied (2) as shown on the right side.

However, application of the square root (2) is not always the best choice when we want to sample a material sparsely; therefore, our analysis is focused on identifying an appropriate non-linear function, whose parameter might be adapted to a measured material enabling the precise capturing of the dynamic shape of specular reflection along θ_h using the very limited number of samples.

SCCG '17, May 15-17, 2017, Mikulov, Czech Republic

To identify a proper sampling along θ_h , we have to select an appropriate fixed value of θ_d , i.e., choose a column of a characteristic slice as measured in the first step of the process. To this end, we use BRDFs from the MERL database as training data. To determine the non-linear sampling function that performs the best and the optimal value of θ_d , we tested three functions (see (3), (4), (4)) that distribute samples along θ_h non-linearly.

$$\hat{\theta}_h = \frac{\theta_h^2}{90^\circ} \tag{1}$$

$$\hat{\theta}_h = m \left(\frac{\theta_h}{m}\right)^k, \ k > 0$$
 (2)

$$\hat{\theta}_h = m \frac{\exp(k \cdot \frac{\theta_h}{m}) - 1}{\exp(k) - 1}, \quad k > 0$$
(3)

$$\hat{\theta}_h = m \frac{k \frac{\omega_h}{m} - 1}{k - 1}, \ k > 1$$
 (4)

Notice the square root mapping used in the MERL database (2) is the special case of (3) for k = 2. The parameter *m* is the maximal possible value of θ_h . A comparison of the square root mapping (red dashed) with the other tested functions for parameter k = 4 is given in Fig. 12.

We focus our analysis on a single characteristic slice for $\varphi_d = 90^{\circ}$ that holds the most descriptive information on the BRDF. Over all 100 BRDFs, we try to identify the function (3, 4, 4) and the value of θ_d , thus enabling on average, the best approximation of the characteristic slice based on a sparse non-linear measurement whose parameter *k* is estimated from the detailed measurement of the single column. Specifically, we compute a mean absolute error between the original characteristic slice and its reinterpolated variant. Finally, we identified that function (4) in combination with $\theta_d = 40^{\circ}$ works the best.

5.2 Material-Driven Sampling Pattern Adaptation

Once we have a fixed elevation $\theta_d = 40^\circ$ and a non-linear function (4), we can apply this information to an efficient measurement of an unknown specular material. First, we initially rotate the material to appropriate φ_h so as to avoid anisotropic artifacts. Then for $\varphi_d = 90^\circ$ and $\theta_d = 40^\circ$, we capture BRDF values by way of up to 90 samples distributed along θ_h using standard square root non-linear sampling. Next, we estimate parameter k of the function (4) to find its optimal value \hat{k} , that fits the measured data the best.

Finally, given the required number of samples, we prepare the sparse sampling pattern along θ_h , using the optimal parameter \hat{k} and the function (4) and perform the measurement. The estimated value of parameter \hat{k} for the paint is 5.64 and for the silver is 4.78.

A graph in Fig. 13 compares BRDF data for fixed $\varphi_h = 45^\circ$, $\theta_d = 40^\circ$, $\varphi_d = 90^\circ$ using the fine initial sampling along θ_h with up to 90 samples (shown as solid line), with the BRDF data obtained by the proposed adaptive sampling using up to 30 samples (shown as dashed line). One can observe a very close resemblance of values for both tested materials, especially near the specular highlight (see a detail in the bottom graph).

SCCG '17, May 15-17, 2017, Mikulov, Czech Republic



Figure 10: An overview of the analysis prior to the measurement, estimation of the parameter, and preparation of sparse sampling during the measurement of a new material.



Figure 11: The characteristic slice of the BRDF (dependency on θ_h , θ_d) of highly-specular material: (left) the linear sampling along θ_h , (right) the non-linear sampling along θ_h using square root (2).



Figure 12: A comparison of the functions tested for nonlinear mapping of θ_h .

5.3 Sparse BRDF measurement

The measurement process using a goniometric device is long due to sequential sampling of bidirectional pairs. To eliminate the number of taken samples, we suggest the following. We capture elevation angles by 30 samples each, while sampling along θ_d is linear with step 3°, sampling along θ_h is non-linear using the pattern derived by the method above. As the appearance of the characteristic slice is symmetrical around $\varphi_d = 90^\circ$, we capture φ_d only in interval $(0^\circ - 90^\circ)$ and replicate it to interval $(180^\circ - 90^\circ)$. Due to small differences between characteristic slices along φ_d , we capture only

seven of them with the linear sampling step of 15°. Azimuthal angle of the half direction is fixed at $\varphi_h = 45^\circ$ to avoid anisotropic artifacts. Therefore, the theoretical number of samples is $|\theta_h| \times |\theta_d| \times |\varphi_d| = 30 \times 30 \times 7 = 6300$ samples. However, due to limitations of the measuring device (i.e., $\theta_{\upsilon} \le 75^\circ$), the number of measured samples is 4073 in total. To capture these samples in a high dynamic range, multiple exposures and intensities of light are used, resulting in a measurement time of 15 hours.



Figure 13: A comparison of intensity captured for two tested materials by means of a standard squared root non-linear mapping using up to 90 samples along θ_h (solid line), compared to proposed adaptive non-linear mapping using up to 30 samples along θ_h (dashed line). The other parameters are fixed at $\varphi_h = 45^\circ$, $\theta_d = 40^\circ$, $\varphi_d = 90^\circ$. The second graph shows in more detail a surrounding of the specular highlight $\theta_h = 0 - 2^\circ$.

BRDF Measurement of Highly-Specular Materials using a Goniometer

Fig. 14 shows a captured BRDF with the contribution of anisotropic artifacts and a reddish hue due to the diffraction on the aperture of variable size (a) and (b), and the final BRDF with the artifacts compensated for (c).



Figure 14: Measured BRDF of the silver 925: (a) aperture f22, (b) aperture f11, (c) circular aperture ≈f11.

Finally, non-measured values shown as blue (due to a camera/light occlusion or low elevations) are extrapolated from measured values, and resulting data are linearly interpolated into the sampling format of the MERL database, i.e., in a resolution of $|\theta_h| \times |\theta_d| \times |\varphi_d| = 90 \times 90 \times 180 = 1458000$ samples. Such a dataset is eventually used for BRDF rendering in the following section.

6 **RESULTS**

All raw BRDF samples captured by the goniometer for both measured materials are illustrated in Fig. 15 as a consecutive sequence of characteristic slices.

Note, the wider width of specular highlight of the silver sample as compared to the paint sample. Similarly, the silver sample has, in order of magnitude higher dynamic range as shown in Fig. 13.

Ray-tracings in PBRT2 of the measured BRDFs compared to the most similar materials from the MERL BRDF database are shown in Fig. 16. Similar results on a speedshape object in a Mitsuba renderer are given in Fig. 17. In general, one can observe a higher intensity of reflection from silver when compared to *steel* and *chrome* materials. On the other hand, *steel* and *chrome* feature sharper reflections presumably due to the electrostatic plating surface finish as compared to mechanical polishing of the casted silver probe.

7 CONCLUSION

In this paper, we focused on the isotropic BRDF measurement of highly specular materials using a gonioreflectometer. We discussed challenges encountered during the measurement of such materials and proposed a novel approach to an efficient BRDF capturing of highly specular materials using a data-driven adaptive sampling of specular highlights. This approach allows us to considerably reduce the required measurement time while still maintaining a high accuracy of measured data. We tested our method by the capturing of a paint with an acrylic clear coat and a casted, polished silver sample. Finally, we compared our results with other state-of-the-art BRDF measurements of similar materials.

ACKNOWLEDGMENTS

This research has been supported by the Czech Science Foundation grant GA17-18407S.

REFERENCES

- M. Ben-Ezra, J. Wang, B. Wilburn, X. Li, and L. Ma. 2008. An LED-only BRDF measurement device. Computer Vision and Pattern Recognition, IEEE Computer Society Conference on 0 (2008), 1–8.
- R.L. Cook and K.E. Torrance. 1981. A reflectance model for computer graphics. ACM SIGGRAPH 1981, ACM Press 15, 3 (August 1981), 307–316.
- K.J Dana and J. Wang. 2004. Device for convenient measurement of spatially varying bidirectional reflectance. *Journal of Optical Society of America* 21, 1 (2004), 1–12.
- J. Filip, R. Vavra, M. Haindl, P. Zid, M. Krupicka, and V. Havran. 2013. BRDF Slices: Accurate Adaptive Anisotropic Appearance Acquisition. In CVPR. 4321–4326.
- J. Filip, R. Vávra, and M. Havlicek. 2014. Effective Acquisition of Dense Anisotropic BRDF. In Proceedings of the 22th International Conference on Pattern Recognition, ICPR 2014. 2047–2052.
- Abhijeet Ghosh, Wolfgang Heidrich, Shruthi Achutha, and Matthew Oï£iToole. 2010. A Basis Illumination Approach to BRDF Measurement. International Journal of Computer Vision 90, 2 (2010), 183–197.
- J.Y. Han and K. Perlin. 2003. Measuring Bidirectional Texture Reflectance with a Kaleidoscope. ACM SIGGRAPH 2003 22, 3 (2003), 741–748.
- V. Havran, J. Filip, and K. Myszkowski. 2010. Bidirectional Texture Function Compression based on the Multilevel Vector Quantization. *Computer Graphics Forum* 29, 1 (2010), 175–190.
- Michael Holroyd, Jason Lawrence, and Todd Zickler. 2010. A coaxial optical scanner for synchronous acquisition of 3D geometry and surface reflectance. ACM Trans. Graph. 29, Article 99 (2010), 12 pages. Issue 4.
- A. Höpe, T. Atamas, D. Hünerhoff, S. Teichert, and K.-O. Hauer. 2012. ARGon³: 3D appearance robot-based gonioreflectometer at PTB. *Review of Scientific Instr.* 83, 4 (2012), 8.
- Jiping Lu and J. Little. 1995. Reflectance function estimation and shape recovery from image sequence of a rotating object. In *Proceedings of the Fifth International Conference on Computer Vision (ICCV '95)*. IEEE Computer Society, Washington, DC, USA, 80–.
- Frank J. Maile and Andre C. Martins. 2015. Chrome-like effects without chromium. Pitture e Vernici 1 (2015), 16–22.
- Frank J Maile, Gerhard Pfaff, and Peter Reynders. 2005. Effect pigments: past, present and future. Progress in organic coatings 54, 3 (2005), 150–163.
- W. Matusik, H. Pfister, M. Brand, and L. McMillan. 2003. A data-driven reflectance model. ACM Transactions on Graphics 22, 3 (2003), 759–769.
- Yasuhiro Mukaigawa, Kohei Sumino, and Yasushi Yagi. 2009. Rapid BRDF Measurement using an Ellipsoidal Mirror and a Projector. IPSJ Trans. on Computer Vision and Appl. 1 (2009), 21–32.
- J.F. Murray-Coleman and A.M. Smith. 1990. The Automated Measurement of BRDFs and their Application to Luminaire Modeling. *Journal of the Illuminating Engineering Society* 19 (1990), 87–99.
- A. Ngan, F. Durand, and W. Matusik. 2005. Experimental Analysis of BRDF Models. Eurographics Symposium on Rendering 2005 2 (2005), 117–126.
- F.E. Nicodemus, J.C. Richmond, J.J. Hsia, I.W. Ginsburg, and T. Limperis. 1977. Geometrical considerations and nomenclature for reflectance. NBS Monograph 160 (1977), 1–52.
- S.M. Rusinkiewicz. 1998. A new change of variables for efficient BRDF representation. In Rendering techniques' 98. 11–22.
- Christopher Schwartz, Ralf Sarlette, Michael Weinmann, and Reinhard Klein. 2013. DOME II: A Parallelized BTF Acquisition System. In Eurographics Workshop on Material Appearance Modeling: Issues and Acquisition, Holly Rushmeier and Reinhard Klein (Eds.). Eurographics Association, 25–31.
- M.M. Stark, J. Arvo, and B. Smits. 2005. Barycentric parameterizations for isotropic BRDFs. IEEE TVCG 11, 2 (2005), 126 –138.
- G.J. Ward. 1992. Measuring and Modeling Anisotropic Reflection. Computer Graphics 26, 2 (July 1992), 265 – 272.

SCCG '17, May 15-17, 2017, Mikulov, Czech Republic

Filip, Vávra, and Maile



Figure 15: Visualization of captured raw samples used for BRDF reconstruction. The first row is paint, the second row is silver 925. Non-measured blue areas are further extrapolated.



Figure 16: A comparison of ray-tracing of captured BRDFs of paint and silver with similar materials from the MERL BRDF database using a PBRT2 renderer.

BRDF Measurement of Highly-Specular Materials using a Goniometer

SCCG '17, May 15-17, 2017, Mikulov, Czech Republic



Figure 17: A comparison of ray-tracing of the captured BRDFs of paint and silver with similar materials from the MERL BRDF database using a Mitsuba renderer.