USING REFLECTORS FOR ANALYSIS AND ACQUISITION OF ANISOTROPIC BRDF

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Abstract

BRDFs are commonly used for material appearance representation in applications ranging from gaming and the movie industry, to product design and specification. Most applications rely on isotropic BRDFs due to their better availability as a result of their easier acquisition process. On the other hand, anisotropic BRDF due to their structure-dependent anisotropic highlights, are more challenging to measure and process. This paper describes approaches to BRDF analysis and acquisition using ellipsoidal and parabolic reflectors commonly used for in illumination industry. First, we show how reflectors can be used for detection of anisotropic properties as anisotropic axes and highlight width. Second, we outline and approach for anisotropic BRDF capture using reflector that allows fast and convenient measurement without need of measured sample extraction.

Keywords: BRDF measurement, anisotropic, reflector, ellipsoidal, parabolic

1 Introduction

The most accurate representations of material appearance rely on view and illumination dependent reflectance. If we assume homogeneous and opaque materials we can focus on anisotropic $BRDF(\theta_i,\varphi_i,\theta_v,\varphi_v)$; a four-dimensional function for each spectral channel depending on variable illumination $\mathbf{I}(\theta_i,\varphi_i)$ and view $\mathbf{V}(\theta_v,\varphi_v)$ directions, where θ and ϕ are elevation and azimuthal angles (Nicodemus, 1977). One can simplify this representation to three-dimensional isotropic $BRDF(\theta_i, \theta_v, \varphi_i\text{-}\varphi_v)$ by relying only on a relative value between azimuthal angles of light and camera. We focus in our work on anisotropic BRDF, which enormously expands measurement state space due to one more dimension when compared to isotropic BRDF. Therefore, it is time demanding to sample this space uniformly using goniometers while still maintaining visual quality comparable to isotropic measurements.

In general, anisotropy is the property of being directionally dependent, as opposed to isotropy, which implies identical properties in all directions. In the context of our work, when a material's reflectance is not constant for mutually fixed view and illumination with respect to the rotation of the material around its normal, the material is considered anisotropic. Anisotropic materials are, due to their atypical attractive appearance, often used in achieving an eye-catching look of many man-made products (see Figure 1). Fabric, metals and plastics are probably the most typical examples. In this work we discuss using reflectors for rapid and affordable analysis and measurement of anisotropic BRDFs.

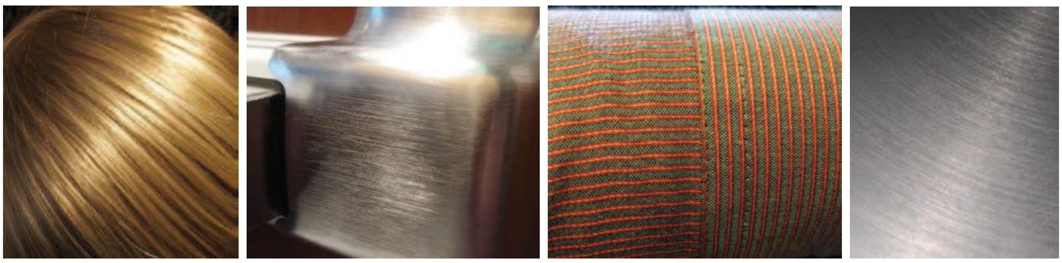


Figure 1 – Examples of anisotropic materials: hair, metal, fabric, plastic

2 Related work

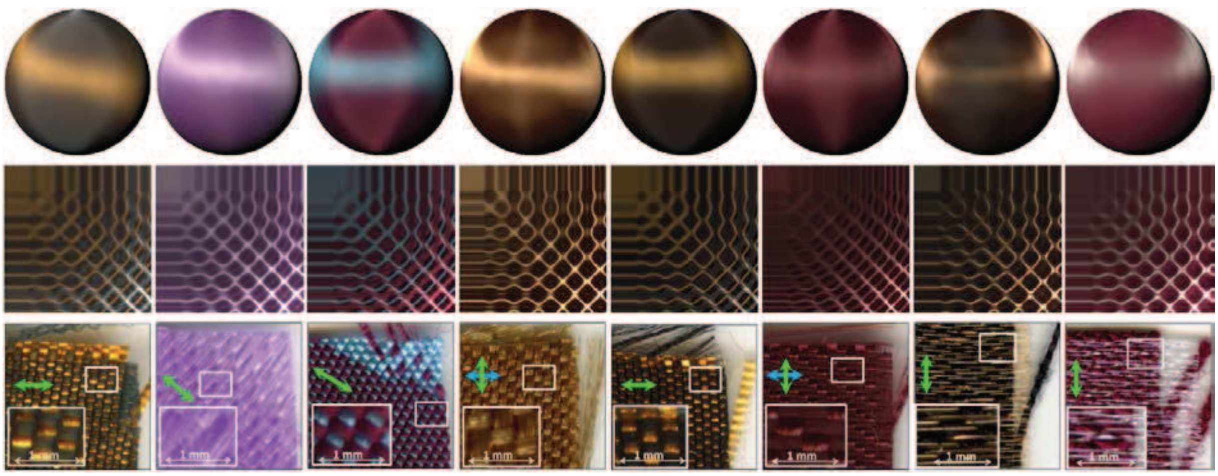
As our anisotropy detection and measurement setup is a mirror-based, we briefly survey previous work in this field. It can be divided depending on a type of mirror used. Previous anisotropic BRDF measurement approaches used kaleidoscopically arranged flat mirrors (Han, 2003), hemispherical mirrors (Ward, 1992), off-axis parabolic mirrors (Dana, 2001), ellipsoidal mirrors (Mukaigawa, 2007), (Mukaigawa, 2009), or a combination of concave parabolic and custom-built mirrors (Ghosh, 2010). Another approach called hemispherical confocal imaging uses collection of flat mirrors distributed over ellipsoid (Mukaigawa, 2011) and can be viewed as a set of virtual cameras and projectors positioned uniformly over the hemisphere.

All these setups place the measured material into a focal point of the mirror, share the optical and illumination axis using coaxial pair of camera and projector, and thus allow the recording of multiple illumination or view directions in a single image. The main advantages of such an arrangement are: (1) the elimination of any mechanical component in the measurement setup, and (2) capturing of retro-reflections which is impossible by goniometric acquisition techniques due to physical occlusion of light and sensor. Disadvantages are a limited range of recorded elevation angles, variable reflectance attenuation across the elevations, or a low dynamic range of the measurements due to using a projector as illumination.

Most of the setups place the material into a mirror‘s focal point in a way that the material is aligned with axis of the mirror (Dana, 2001), (Mukaigawa, 2009), (Mukaigawa, 2011) which is not ideal for fast anisotropy detection as it typically requires sample extraction and positioning inside the mirror. More appropriate are setups aligning mirror axis with surface normal (Ward, 1992), (Mukaigawa, 2009), therefore, this setup is adopted in our work. Our methods use standard consumer reflectors used for LED lighting, with an opening at the narrowest part attached to the measured material. This extremely simplifies the material handling process.

3 Test materials

We used eight fabric materials from the UTIA BRDF database (http://btf.utia.cas.cz) (Filip, 2014) for testing of the proposed methods. All of them consist of two interwoven threads and all materials exhibit strong specific anisotropic behaviour as shown in their rendering in the first row of Figure 2. The second row shows their acquired reference BRDFs. The third row of the figure shows the detailed materials' micro-structure and reveals the threads and weaving pattern structure that defines the materials' anisotropic behaviour. Primary and secondary (if applicable) anisotropy axes are shown by green and blue arrows respectively.



fabric002 fabric094 fabric106 fabric111 fabric112 fabric134 fabric135 fabric136

Figure 2 – The test materials rendered on sphere for point light illumination (the first row), their BRDFs (the second row). Detailed zoom into micro-structure of the tested materials with marked primary (green) and secondary (blue) anisotropy axes (the third row)

4 Material anisotropy analysis

For anisotropic behaviour analysis (Filip, 2015) we use ellipsoidal reflector (see Figure 5 left) and uncontrolled omni-azimuthal illumination using flash from the sourcing camera (Sony Cybershot H1). The reflector is photographed by the camera having an optical axis aligned with the reflector axis also representing normal of the measured surface. We do not use any special gantry and the image is taken from a distance 1.5 meters as shown in an inset in Figure 3.

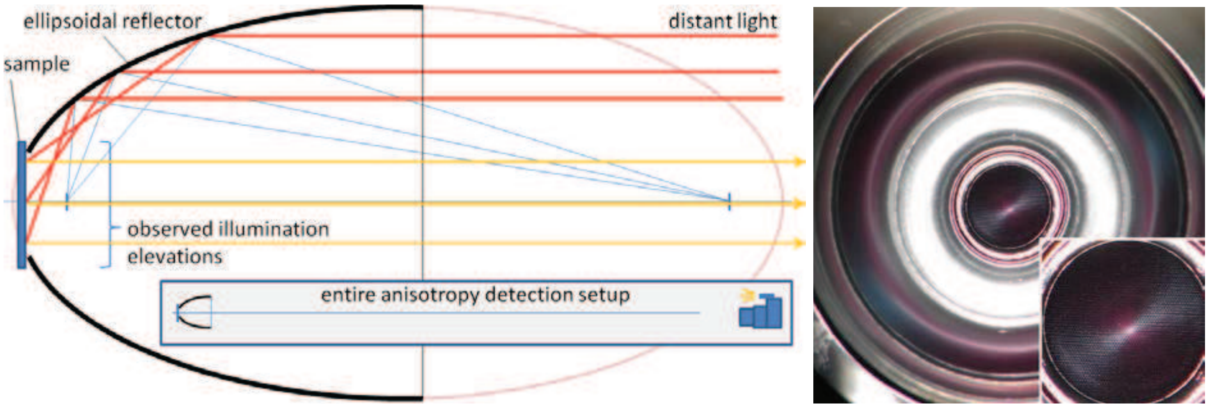


Figure 3 – Scheme of anisotropy detection using ellipsoidal reflector (left) and image captured by a camera for flashlight illumination (right)

This is done in order to capture the reflector (diameter 100 mm) approximately symmetrically. As the material sample is not positioned in the mirror's focal point, illumination elevations angles vary across its surface as shown in Figure 3 left. This allows for the capturing of anisotropic behaviour in the image of material at the mirror opening (25 mm wide) taken by the camera. Each surface location is illuminated from two elevations at azimuths 180 degrees apart. Contributions of these directions are averaged in the captured photo. Mean illumination elevation angle across entire material plane is 50 degrees. When an isotropic material is analysed, the captured image contains a circularly shaped peak in the centre. However, for an anisotropic material we additionally observe a couple of triangle shaped highlighted areas running symmetrically from the centre to the edges of the opening as shown in Figure 3 right. The highlights' azimuthal orientation coincides with the direction of the main anisotropy axes, while their width corresponds to width of the anisotropic highlight. The introduced method allows for a very convenient and fast detection of material's anisotropy strength, main anisotropy axes, and corresponding highlights shape in only several seconds.

This information is beneficial for variety of tasks, ranging from material appearance acquisition to its automatic classification or image-based material retrieval. We validated our detection method on eight test anisotropic fabric materials and compared their microstructure scans with the detected anisotropy direction recorded by our method as shown in Figure.4.

Two of the materials exhibited distinct anisotropy highlights corresponding to two anisotropy axes. When we plot reflectance from the edge to centre of the opening as a function of azimuthal illumination angle we can observe a different width and shape of anisotropic highlights. One can average these plots (the third row in Figure 4) along a vertical axis and obtain 1D profile of anisotropic highlights as shown in the fourth row. Given the predefined threshold, we can estimate the width of the highlights (red line). In validation of our method, we can observe a very close resemblance of the averaged values (red line) to the know reference BRDF values corresponding to viewing elevation $\theta_v=0^o$ and illumination elevation $\theta_i = 50^o$ (cyan line). Our method reliably detected anisotropy axis (azimuth of anisotropic highlights) as well as their typical profile at elevation 50 degrees.

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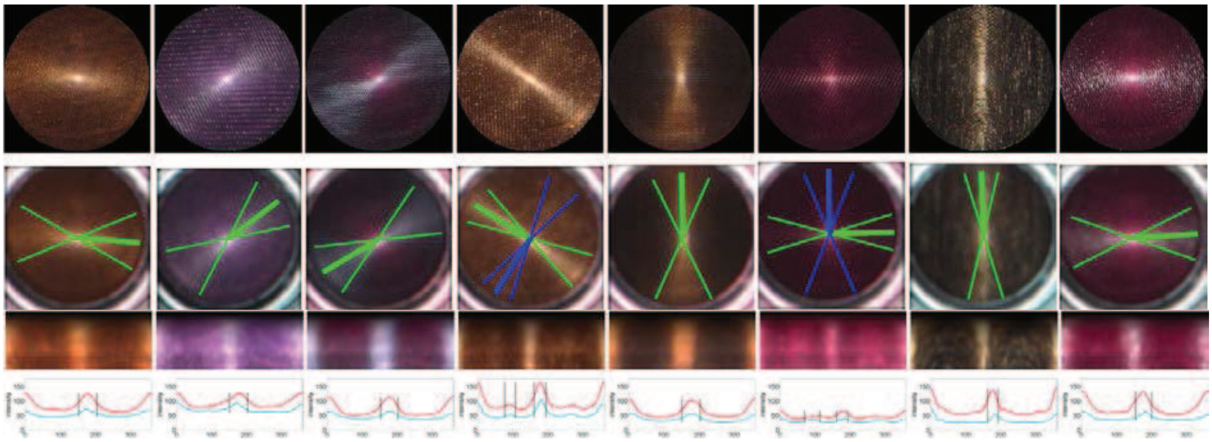


Figure 4 – Anisotropy highlight axis and width detection using ellipsoidal reflector: the first row – captured image of the reflector opening, the second row - its smoothed version with detected anisotropic highlights (green - primary anisotropy axis, blue - secondary anisotropy axis), the third row – radius/azimuth image with clear vertical anisotropic highlight (after isotropic behaviour compensation), the fourth row - 1D plot of anisotropic highlight profile (red line) with estimated width of anisotropic highlights. The reference BRDF values are shown in cyan.

4.1 Advantages and limitations

The main advantage of the proposed technique is fast measurement and processing, which takes 4.4 s using single core of Intel Core i7. Another advantage is the low setup acquisition cost as only an of-the-shelf ellipsoidal mirror (price $7) and a basic compact camera with sufficient zoom and resolution are needed. A final notable advantage is the fact that the setup does not require any calibration procedure apart from attaching the reflector to the measured nearly planar surface and taking its picture from a distance 1.5 m with a forced flash in lower ambient lighting conditions.

The proposed anisotropy detection approach is limited to nearly homogeneous and almost planar materials, i.e., without significant spatially varying appearance whose effects like texture or shadows would visually mask anisotropic highlights. Therefore, we have experimented with different smooth fabric materials that avoid this limitation while still providing a wide range of available types of anisotropic appearance. Similarly one can use this method for the analysis of any flat groove- or fiber-based types of anisotropy, e.g., present in wooden or in machined or polished surfaces. As the mirror detects anisotropy corresponding to elevation angle 50^{o} it cannot principally detect anisotropic highlights which are not apparent at such an elevation. This is the case in materials *fabric002*, *fabric106*, and *fabric112*, where a wide width of secondary anisotropic highlight makes its distinguishing from the background reflectance quite difficult.

5 Measurement of Anisotropic BRDF

In this section we extend usage of affordable mirror reflectors for an approximate BRDF measurement. We tested both ellipsoidal and parabolic reflectors.

5.1 Ellipsoidal reflector

The ellipsoidal reflector was identical to the one used in Section 4 and is shown in Figure 5-left. The reflector (type R-5216-WG) is moulded to approximately 1mm thick aluminium sheet.

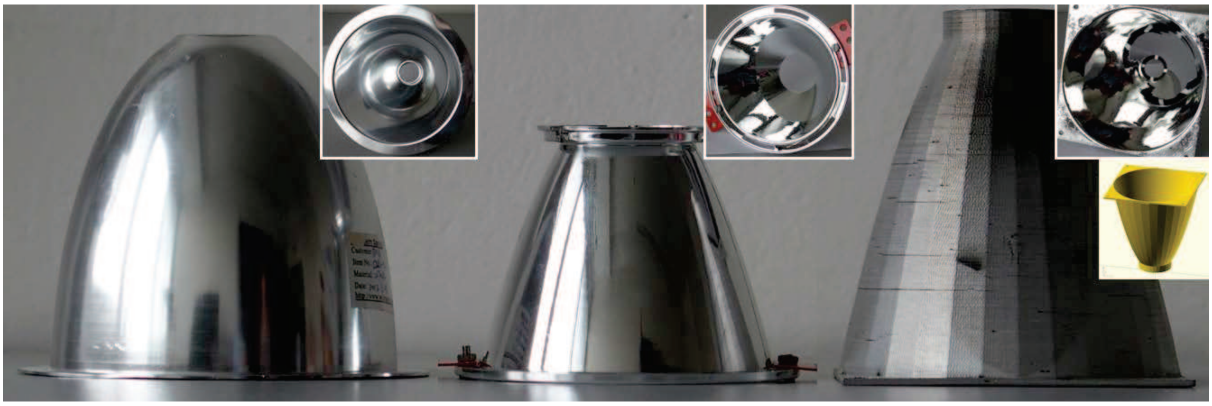
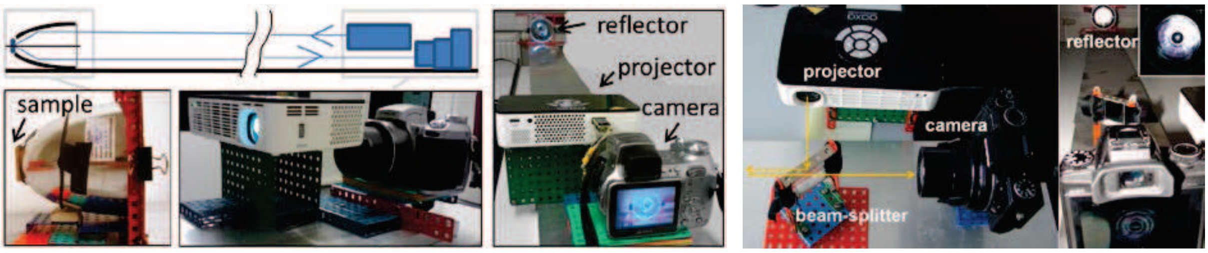


Figure 5 – Ellipsoidal (left) and parabolic off-the-shelf (middle), and parabolic 3D printed (right) reflectors tested

For BRDF capture we substituted flash illumination from the camera (Sony Cybershot H1), by a digital DSP projector AAXA P300 (intensity 300 lm) illuminating the reflector by a controlled ray of light. Outer diameter of the reflectors was approximately 10cm. The entire setup is shown in Figure 6-a.



(a) (b)

Figure 6 – Setups for anisotropic BRDF measurement: (a) approximate setup used with the ellipsoidal reflector, (b) a coaxial setup where light and camera share the same optical path

To guarantee camera, projector, and reflector alignment, we attached them to optical bench. The camera lens is positioned closely to projector emitting window to achieve almost identical optical paths. Distance of camera and projector from the reflector is 1.5 meters. The projector circularly sweeps interior of the reflector by ray of light at various elevations and azimuths (circles). The light reflects from the material in the reflector opening and from its inner body back in direction of illumination. For each azimuthal location of the ray a photo of reflector is captured, exhibiting appearance of the measured material for many azimuthal- and elevation-depending viewing directions. The capturing principle is shown schematically together with illustration of one captured frame in Figure 7.

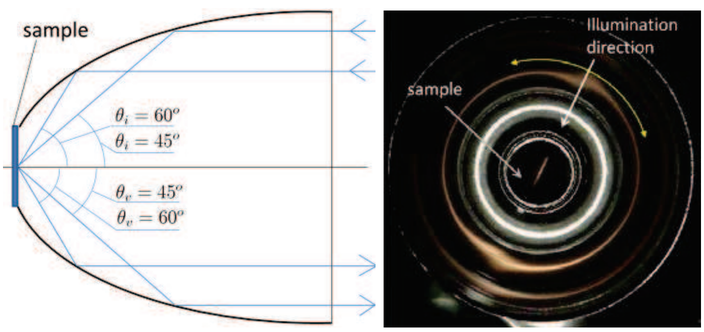


Figure 7 – A principle of BRDF measurement procedure

Main advantage of our technique is short BRDF acquisition time (12 seconds), which depends purely on camera frame-rate and the required azimuthal resolution. To compensate for slight illumination non-uniformity due to inaccurate reflector positioning and residual light from the projector, we record its image without a ray projected and subtract such images from all recorded frames.

Our capturing experiments using ellipsoidal reflector allowed BRDF acquisition of elevation angles near 50°. The experiment with ellipsoidal reflector achieved, due to its non-ideal properties, reasonable measurements only for two different combinations of illumination and viewing elevations as shown in Figure 8. However, even this approach captured main anisotropic features including retro-reflective highlights.

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θ_i = 50°/θ_v=50°

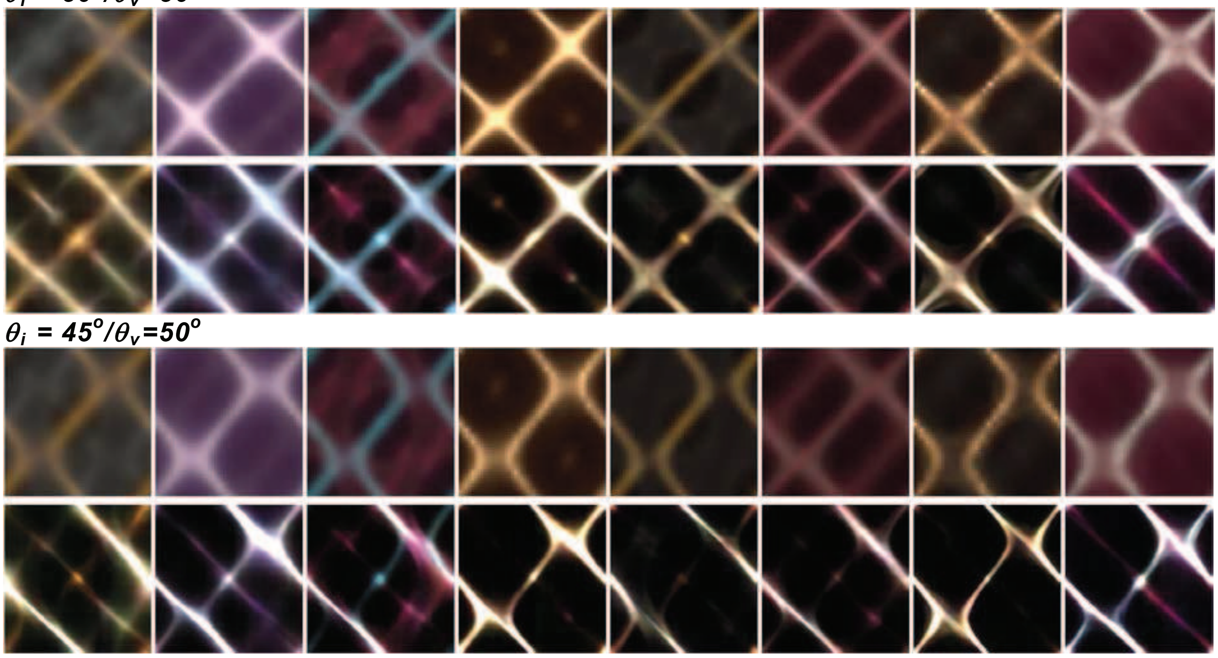
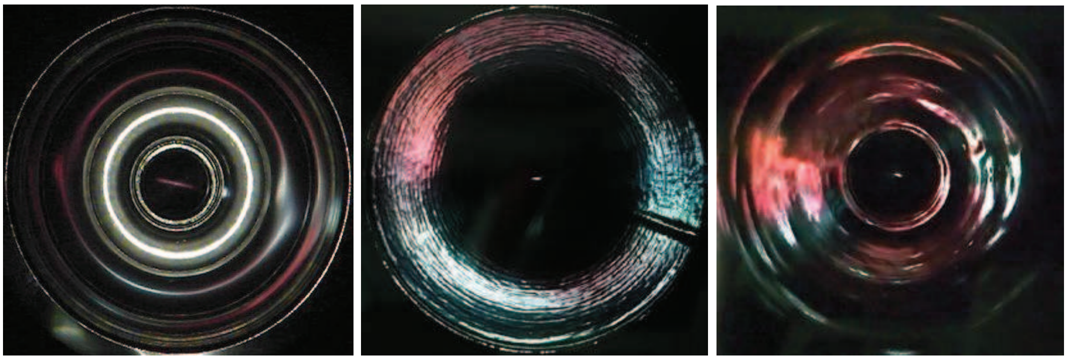


Figure 8 – Comparison of BRDF subspaces θ_i/θ_v=[50°/50°, 50°/45°] (odd rows) sparsely captured ground true, (even rows) ellipsoidal reflector measurements

5.2 Parabolic reflectors

As it is difficult to obtain affordable parabolic reflectors with smooth surface and with diameter around 10cm, we have used one consumer reflector and a custom 3D printed one as depicted in Figure 5-middle and left. The consumer reflector was a commercial plastic reflector LEDIL Lena-S-CL340 for area LED chip, while the second reflector was 3D printed based on a model created in OpenSCAD. The printed shape was first painted by filler, underwater sanded using very fine grain, sprayed by clear lacquer, and finally metallized by aluminium coating in dust-free environment. The reflectors range elevation angles 35-60° and 30-60°. In contrast to the ellipsoidal reflector, these expanded ranges are due to a focal point lying in measured sample plane for any viewing and illumination elevation angles. One can obtain even lower elevations, but the limiting factor is a physical size of the reflector.

The visual fidelity of captured BRDF is dependent on careful alignment of mirror axis with the projector and camera. Their slight displacement results in different optical axes, which causes deformation of some visual features in the acquired BRDF subspaces. Therefore, we resorted to coaxial setup sharing optical paths of light and camera as shown in Figure 6-b. We used a beam-splitter, DSP projector AAXA P300, and a camera Olympus Stylus1. A properly calibrated coaxial setup should feature less misalignment error at the cost of losing some illumination intensity. The calibration of the setup was achieved by projecting a target consisting of concentric circles onto the reflector and its surrounding mask. Its correctness was validated by all reflected light rays concentration to a single point on a measured material sample.



ellipsoidal parabolic parabolic 3D printed

Figure 9 – Example frame captured for individual tested reflectors (material *fabric106*)

Unfortunately, the measured results have revealed, that the approach is extremely sensitive to geometric precision of the reflector as well as its alignment owing to the lighting and sensing devices. Figure 9 showing one frame grabbed by the tested reflectors clearly demonstrates parabolic reflectors discontinuities caused by the manufacturing process. The results in Figure 10 reveal substantially lower accuracy of BRDF captured by the tested parabolic reflectors when compared to the results obtained by the ellipsoidal one (see the second row of Figure 8). Surprisingly the custom printed reflector (Figure 10 b) performed the worst; therefore, to avoid deviations introduced by surface finishing, a 3D printing technology with higher resolution should be used.

fabric094 *fabric106* *fabric111* *fabric112*

(a)

(b)

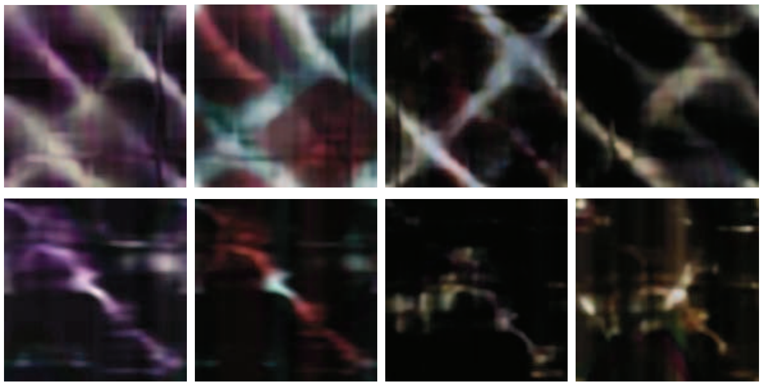


Figure 10 – Captured anisotropic BRDF subspace obtained by the tested parabolic reflectors for fixed elevation angles $\theta_i/\theta_v=50^o/50^o$: (a) consumer plastic reflector, (b) custom 3D printed reflector

5.3 Advantages and limitations

Main advantage is capturing of back scattering reflections which is impossible by most of the other acquisition techniques due to physical conflict of light and sensor. Another advantage is fast acquisition time, which depends purely on camera frame-rate and required resolution of azimuthal angles. For azimuthal step 1^o and acquisition frame-rate 30 fps, we finish measurement of single BRDF subspace in 12 seconds. High azimuthal resolution can be achieved and is limited only by the required measurement time.

A disadvantage is a low dynamic range due to limited intensity of the projector and its further restriction by mirror reflectance. Further, the lowest elevation angles are principally restricted to elevations around 30^o, however this drawback can be leveraged by a custom design of the reflector. An important factor is geometric accuracy of the reflector. To this end, we can comment that accuracy of the tested parabolic reflectors was insufficient probably due to manufacturing inaccuracies and combination of 3D printing and manual sanding deviations.

6 Conclusions

We discussed using of consumer ellipsoidal and parabolic mirror reflectors for affordable and fast BRDF anisotropy assessment and measurement of anisotropic BRDF. The mirror reflector is simply placed onto the measured surface, and thus our method requires neither separation of measured sample out of its original environment nor its difficult positioning inside the reflector. Additional advantage of the proposed method is capturing of retro-reflections that are often impossible to measure using goniometric approaches. We conclude that ellipsoidal mirror reflectors mirrors can be used for fast, convenient BRDF anisotropy analysis, while parabolic reflectors are better suited for an approximate BRDF measurement of real-world materials. We discussed advantages and limitations of such methods for use in practical applications. In our future work we would like to improve results of our BRDF measurement by testing parabolic reflectors of higher precision, either moulded or accurately milled.

7 Acknowledgements

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