A Literature Review of Reflectance Measurement and its Application in the Realistic Rendering of Surfaces

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Abstract

The progressive trend toward increased realism in Computer Graphics necessitates an increased accuracy in both the measuring of the reflective properties of surfaces and the subsequent rendering of the surfaces under arbitrary lighting and viewing conditions.

Various techniques and configurations are presented for measuring the reflectance of real-world surfaces in order to simulate their appearance. Each is essentially experimental and attempts to solve a particular problem relating to reflectance measurement. As yet, no configuration has been found to be ideal for all materials. Although the application of BRDFs to rendering algorithms is already fairly established, it is only in recent years that proposals have been made as to how to deal with the high-dimensionality of BTFs and BSSTFs.

This paper is composed of two sections. The first section aims to study a variety of approaches to reflectance measurement from an efficiency perspective. In particular it focuses on optimal configurations for surfaces exhibiting complex reflective properties. The second section discusses approaches in applying the acquired measurement functions to the realistic rendering of surfaces.

1 Introduction

Rendering realistic surfaces under arbitrary lighting and viewing directions requires well-defined information concerning light's interaction with a surface. The standard approach of acquiring this information is to study how incident light is reflected off a real-world surface by measuring both the incident and exitant intensities of light from a series of viewing and illumination directions. This data can be expressed as a Bidirectional Reflectance Distribution Function (BRDF) (NICODEMUS et al. 1977). However since the BRDF refers to light's interaction at a particular point on the surface, it is suitable only for homogeneous surfaces, that is surfaces that exhibit only negligible variation in their reflectance properties along the entire surface. Because this class of surface is very limited, it is far more useful to extend the BRDF so as to take spatial variance into account. These spatially-varying BRDFs are known as Bidirectional Texture Functions (BTF), as defined by (DANA et al. 1999b). BTFs can in turn be extended into Bidirectional Scattering Surface Texture Functions (BSSTF), which capture highly complex reflective properties such as subsurface scattering by additionally describing light that travels within the surface.

Recent years have seen greater flexibility and improved accuracy in measuring surface reflectance. The traditional technique of repositioning a light source and camera in all possible illumination and viewing directions above a sample (MURRAY-COLEMAN and SMITH 1990) is both impractical and time-inefficient. More recent techniques have seen the underlying principles extracted and applied to configurations that allow automated, less time-consuming and more economical measuring devices. Significant contributions to this particular field of research are discussed in section 2. Section 3 deals with methods to overcome the inherent problems of applying the high-dimensional data to rendering algorithms. Finally section 4 highlights the most efficient techniques of each of the preceding sections.

2 Measuring Reflectance of Surfaces

2.1 Basic reflectance measurement

The gonioreflectometer is the traditional device for measuring reflectance (MURRAY-COLEMAN and SMITH 1990). It is a highly complex device involving separate mechanical movement for each of its components (camera, light source and sample stage) and requires four degrees of mechanical freedom to measure the relatively simple 4-dimensional BRDF. The measuring process is highly-specialised and time-consuming and the device is incapable of measuring complex reflective properties.

The first significant improvement on the gonioreflectometer (MURRAY-COLEMAN and SMITH 1990) is the Lawrence Berkeley Laboratory (LBL) imaging gonioreflectometer (WARD 1992). It consists of a hemispherical mirror and fish-eye lens and allows the simultaneous measurement of light from all viewing directions without the need to change camera position. Although the presentation of this device marks a significant contribution to the reduction of complexity in reflectance measurement, the method has many problems associated with it. These include distortions caused by the fish-eye lens, and undesirable re-illumination of the sample. The required manual positioning of the light source means that measurements are not perfectly registered. Measurements are not good near grazing angles, and are unsuitable for highly specular or smooth surfaces.

(LU and LITTLE 1995) provide a technique for estimating the BRDF of a surface sample by capturing a sequence of images as the sample is rotated from 0° to 30°, 60° and 90° respectively on a turntable. The BRDF is estimated by calculating the average of the brightness values of the four acquired images. The technique requires that the sample be curved and uses a fixed, co-linear light source, meaning that the light source lies on the camera's optical axis. Although rather contrived and limited, the method is suitable for both matte and specular surfaces and represents a fundamentally new approach in thought by both significantly reducing the number of required images while still yielding satisfactory results, as well as simplifying the configuration of the light source.

Another significant contribution by means of the thinking it represents, is the work by (GORTLER et al. 1996) in which they devise a complete working system for capturing the entire appearance of a 3-dimensional object (of which reflectance is only a part). The complete system is described from its data acquisition to its representation and ultimately its rendering, being possible from any viewing position. Its central concept is the Lumigraph, which is a 4-dimensional function describing the flow of light at all positions in all directions. The main drawbacks are that it requires a lot of processing time, and does not provide the flexibility of varying the illumination of the rendered object. It also effectively treats the object as though it were monochromatic by not breaking up the light's data into different wavelengths.

An innovative method devised by (MATUSIK et al. 2003b), exploits the smoothness and slowly varying reflectance properties of BRDFs, to show how the number of sampling points can potentially be significantly reduced. The method is essentially recursive in that it uses known BRDFs to refine new BRDFs. The process involves first acquiring a densely sampled BRDF, and then determining the local signal variation at each point. Wavelet analysis is then used to derive an optimal set of basis functions from which optimal BRDF sampling procedures can be derived. The method has only been shown to dramatically shorten the acquisition time for isotropic BRDFs. It is limited both by its use of only spherical specimens and its assumption that BRDFs are similar. It also excludes exitant illumination, and therefore cannot measure specular reflectance, and is neither robust nor extensible.

An acquisition optimisation method technique for reflectance measurement (LANG et al. 2003) selects advantageous viewing and illumination directions for greater efficiency. Although specifically concerned with BRDF measurement, its principles are potentially far-reaching. The paper describes an acquisition planning algorithm based on minimizing uncertainty, by using previously acquired views to compute the next best view of the camera and light source. Its results are impressive in that they show an improvement on human experts by sampling the surfaces more evenly.

2.2 More complex reflectance measurement

(DANA et al. 1999b) overcome the problem of having to vary the viewing and light source directions over the entire hemisphere of possible directions, by using a robot to rotate the sample in front of a fixed light source for the range of viewing/illumination directions. This work results in the first publicly available BTF database of real-world surfaces (DANA et al. 1999a) with over 60 samples from more than 200 viewing/illumination direction pairs. Unfortunately this technique requires that the sample be affixed to the device, and is very time-consuming, while also involving calibration. For anisotropic surfaces, the entire process needs to be repeated with the object tilted. The limited viewing angles are also restrictive, and the device cannot be used to measure complex reflectance properties such as self-occlusion and self-shadowing. Simplicity is favoured over accuracy.

A more recent approach (DANA 2001) uses a concave parabolic mirror and illumination aperture, each on a translation stage. Planar translations scan the surface of the sample, as opposed to hemispherical positioning of the camera and light source relative to the sample. The aperture provides convenient automated control of illumination. The result is a compact and more convenient device, described by Dana as ideal for measuring the reflectance of human skin in a clinical setting. Multiple views of the same surface point can be captured simultaneously, allowing more rapid data acquisition. In this work Dana provides a useful summary of what would constitute an optimal BTF measuring device:

1. The device should facilitate rapid and convenient data acquisition.
2. It should have as few parts as possible.
3. It should have a minimal number of moving parts.
4. Moving parts should follow simple paths.
5. The device should be portable.
6. The device should be structured so that the sample is not re-illuminated by reflections off its components.

(DANA and WANG 2004) is a related, yet more detailed, account of the above technique. It mentions an inherent problem of the parabolic mirror in that it has a maximum limit, becoming infinitely large as its range is increased. They provide a reference to (FOO and TORRANCE 1995) as giving a trusted overview of various equipment issues concerning reflectance measurement.

An alternative technique for BTF measurement proposed by (FURUKAWA et al. 2002) involves a fairly complex arrangement in which a set of cameras and a set of lights are each affixed to two large motorized arcs, surrounding the object on a turntable. The technique is extremely flexible in that it has no limitations on any of its four viewing/illumination parameters. Any combination of lamp(s), camera, turntable angle or rotation angle of the lamp arc are possible. This flexibility allows it ultimately to render highly complex reflective effects such as inter-reflection and self-shadowing, but at the cost of a relatively coarse sampling.

(MALZBENDER et al. 2001) have devised a simple yet effective method that varies only the illumination, while both the viewpoint direction and the sample remain fixed, thereby not requiring any calibration. The acquisition procedure is both rapid and automated, and the device portable. The device consists of a rigid dome of inward-directed lights creating a hemisphere above the sample. For simplicity, the exitant direction is kept constant; specularity can therefore not be measured, which is a rather limiting feature. In much the same vein as (GORTLER et al. 1996), this paper presents a complete working system that essentially concerns a specialised form of texture-mapping, as opposed to reflectance measurement and simulation.

(HAN and PERLIN 2003) have devised an innovative technique for BTF measurement that requires no moving parts. A tapered kaleidoscope is used to acquire multiple simultaneous views of a sample, from a single viewpoint and with a single structured light source. The method has many advantages for BTF measurement: it is inexpensive and potentially portable; all measurements are perfectly registered to each other which contributes towards accuracy; sampling is potentially dense; calibration is deemed trivial; acquisition is rapid. The device meets all of the requirements advised by Dana (DANA 2001), being an optimal device for BTF measurement. The co-linear illumination bears relation to the configuration used in (DANA 2001). Han and Perlin discuss the extensibility of the method to measuring the highly complex BSSTFs. They also mention a minor inherent shortcoming of the technique in that both resolution and brightness fade at extreme angles. However some questions are left unanswered. Nothing is mentioned of ambient light, for example, as to whether the surface need be flush against the sample.

An interesting alternative approach to measuring reflectance that is both time- and cost-efficient is proposed by (GARDNER et al. 2003). Instead of measuring the light at each point on a surface, the technique estimates the entire BTF by a single pass of a linear light over the surface, captured from a fixed camera viewpoint. This has the effect of illuminating the sample from every possible incident direction and provides a reliable estimation of the diffuse and specular properties of each point on the surface. The resulting BTF models are sufficiently realistic even for translucent objects.

2.3 Highly complex reflectance measurement

The Light Stage devised by (DEBEVEC et al. 2000) marks a significant contribution to reflectance measurement research. It consists of a two-axis rotation system in which a small set of viewpoints (two fixed video cameras) are combined with a dense sampling of incident illumination. Polarizers on the lights and cameras separate specular and subsurface reflection components, making it an ideal method for diffuse and specular reflection, self-shadowing, translucency, mutual illumination and subsurface scattering. Although essentially measuring the BSSTF (of a human face), it reduces the function from 8 to 6 dimensions by implementing only *distant* illumination, effectively speeding up and simplifying the data acquisition. Sampling is dense: the results in the paper recorded as many as 2048 images per camera. The paper also includes an example of how the technique can be used in combination with environment matting, producing good results even with objects exhibiting highly complex reflective properties such as refraction or transmission.

A variation on the Light Stage involves a two meter sphere of computer-controlled inward-pointing lights surrounding a controlled live-action stage (DEBEVEC et al. 2002). Similarly the viewpoints are fixed and illumination variable, yet in this case the illumination replicates a real-world lighting environment in which the actor is to be composited. In this way the technique bears relation to the Lumigraph (GORTLER et al. 1996) approach, in that the lighting ultimately rendered is predefined at acquisition time. It is therefore not an ideal method for acquiring a useful reflectance measurement database.

(HAWKINS et al. 2001) extend the original Light Stage (DEBEVEC et al. 2000) in order to capture even more complex reflective properties. The paper is specifically related to the digital viewing of artifacts for documentation under any illumination conditions, and ultimately from any viewing angle. However the latter is not yet implemented, but only discussed. The acquisition involves a series of hundreds of strobe lights attached to a rotating arm - potentially covering an entire hemisphere of incident illumination - captured from a fixed viewpoint. This variation on the Light Stage allows more precise, rapid and thorough acquisition, but at a higher financial cost. The Future Work section is interesting in its discussion of the possibility of further evolving the Light Stage so that *both* arcs rotate, much like the arrangement devised by (FURUKAWA et al. 2002). This however would undesirably increase the complexity and financial expense of the device.

Another significant contribution to the field of reflectance measurement is by (MATUSIK et al. 2002) in the form of a complex system of turntables, cameras, lights and background monitors, capturing the BSSTF of transparent, translucent and highly-specular objects. Although the technique actually belongs to the class of Environment Mapping and additionally involves capturing an approximation of the geometric shape of the object, its acquisition method is potentially relevant for further exploration in reflectance measurement.

3 Rendering Reflectance of Surfaces

Hardware limitations make it infeasible to simulate the physics of the reflection of light at each point on a surface due to the high-dimensionality of reflectance data. The alternative simplified techniques of bump- and texture-mapping are only sufficiently realistic for very simple materials. Methods are therefore being developed to effectively manage reflectance functions, by essentially compressing the data and then interpolating the results. However interpolation does not always yield perfect results since it assumes an even field of illumination - as mentioned by (HAWKINS et al. 2001). A promising alternative technique has therefore been developed which involves synthesizing a continuous BTF.

3.1 Advanced bump- and texture-mapping

The TensorTextures algorithm proposed by (VASILESCU and TERZOPOULOS 2003) is essentially a texture-mapping technique that samples a sparse set of images acquired under different viewpoints and illumination directions in order to learn the interaction between the viewpoint, illumination and geometry. The technique can be used to estimate a complete BTF, including both illumination and viewpoint directions. Interpolation can be used on the data to rapidly synthesize textures for both arbitrary viewpoints and illumination.

(MALZBENDER et al. 2001) propose a variation on texture-mapping that can be applied under varied illumination conditions, without losing the textured appearance. The technique fits polynomial curves to sampled images taken from a fixed viewpoint and under different known illumination directions, and involves no modeling of complex geometry. Renderable effects include self-shadowing, subsurface scattering and inter-reflections, making it a superior technique to bump-mapping. The technique is however restricted by its preceding acquisition technique in which the viewpoint is fixed, and so does not allow reconstruction of the sample from arbitrary viewpoints. The potential illumination variations however are very flexible, effectively rendering enhancements in contrast (for example specular enhancement or diffuse gain), arbitrary positioning of the light source, and change in depth of focus.

3.2 Compression of reflectance functions

(FURUKAWA et al. 2002) have devised a method firstly to compress a BTF database into tensors[1], and then to approximate the BTFs using tensor product expansion before interpolation. The com-

[1] a generalized form of vector involving an arbitrary number of indices

plexity of their acquisition phase enables the rendering to include even deformation. However an inherent shortcoming to the technique is that tensors cannot accurately render specular reflection or occlusions.

(LENSCH et al. 2003) apply a clustering technique, exploiting the coherence in reflectance properties of surface points belonging to the same material. Parameters extracted from these clusters are then projected onto the La Fortune model per RGB colour channel. The La Fortune model takes four parameters (incident and exitant viewing directions and diffuse and specular components) and is chosen because it is physically plausible. The paper shows how even a very small sample (as few as 15 to 25 images from different camera and light source positions, but including at least one highlight) is sufficient. It results in a compact representation well suited for rendering reasonable results in real-time, although often the textures can appear artificial. Essentially it provides accurate *shading* from new viewpoints and arbitrary lighting conditions.

(MESETH et al. 2004) have devised a BTF approximation technique that reduces the high-dimensionality of data to produce a real-time, high-quality rendering of BTFs, including substantial variation in surface depth. The method combines the high quality (yet memory inefficiency) of linear interpolation with the low quality (yet efficient) strategy of model-fitting, as in the technique used by (LENSCH et al. 2003). Unresolved problems include the occasional exclusion of pixels and a high memory requirement.

3.3 Interpolation of reflectance data

(DANA et al. 1999b) suggest the potential of using BTF databases in developing 3-dimensional texturing algorithms as an alternative to bump-mapping in providing realistic texture, but do not suggest how the interpolation can be achieved.

Although not directly related to the application of reflectance functions, (GORTLER et al. 1996) describe the rapid reconstruction of images from any viewpoint and the paper is therefore worthy of mention. Particularly significant is their reference to the smooth image interpolation technique of (WERNER et al. 1995).

(DEBEVEC et al. 2000) show how the additive nature of light allows an object to be rendered from an arbitrary viewpoint by simply computing a linear combination of recorded images from a database, for each colour channel. The technique is shown to be a far better alternative to texture-mapping and includes diffuse and specular effects.

The data-driven reflectance model developed by (MATUSIK et al. 2003a) uses newly created BRDFs that were created by interpolating acquired isotropic BRDFs. The technique is not thoroughly tested and can produce physically implausible BRDFs, but represents a possible method of dimensionality reduction. So far it has had success in producing effects such as rust, dust and oxidation.

Instead of employing a complex geometric model, (HAWKINS et al. 2001) compute linear combinations of densely sampled BTFs to synthetically illuminate an object under arbitrary forms of complex incident illumination including specular reflection, subsurface scattering, translucency, self-shadowing and mutual illumination. Since the acquired images are from a fixed viewpoint, they discuss (but do not implement) how the method could be adapted so as to allow the object to be viewed from an arbitrary viewpoint, essentially by applying a texture map to an acquired geometric model of the artifact.

3.4 Synthesizing continuous BTFs

Since any database of acquired BTF images would be too sparse for all graphical rendering purposes, the approach of (LIU et al. 2001) is to synthesize a continuous BTF. They describe a technique for generating BTFs from a sparse set of images under different viewing/illumination settings. Essentially the approximate geometrical structure is recovered on an intricate mesoscopic scale (as opposed to the microscopic scale of a BRDF). BTFs are then generated by statistical analysis. Details derived from the mesostructure include effects such as mutual shadowing, inter-reflection, occlusion and the direction of the surface normals. Although time-consuming, the results are very good in rendering under different combinations of lighting and viewing directions.

(TONG et al. 2002) explain how it is not feasible to apply a BTF as a 2-dimensional texture-map because of the extremely lengthy computation time required. They present an alternative technique to (LIU et al. 2001) for synthesizing BTFs on arbitrary surfaces. The method involves deriving surface textons and is based on a technique proposed by (LEUNG and MALIK 2001), but made significantly more efficient by employing a coherency-based search strategy. Surface textons, which are described as a compact data structure containing essential information extracted from the BTF sample, are synthesized to form a surface texton map which can be applied directly in the rendering. They demonstrate the effectiveness of their algorithm by testing it on the CUReT database (DANA et al. 1999a). The results are impressive, being realistic for all samples under any arbitrary viewing and illumination settings, and with consistent mesostructures.

4 Conclusions

The reflectance measurement technique devised by Han and Perlin (HAN and PERLIN 2003) involving a tapered kaleidoscope is advantageous for many reasons, most notably its economy, simplicity and efficiency. Its potential use in measuring the highly complex BSSTF is promising and could make it an optimal reflectance measuring device, even for highly complex reflectance.

Regarding the application of reflectance data, the method developed by (TONG et al. 2002) produces impressive results which far exceed those of other techniques, making it a preferred technique for simulating the reflectance of real-world surfaces.

References

DANA, KRISTIN J. (2001). BRDF/BTF measurement device. In *Eighth IEEE International Conference on Computer Vision (ICCV), Volume 2* (Vancouver, British Columbia, July 2001), Vancouver, British Columbia, IEEE Computer Society, pp. 450–456.

DANA, KRISTIN J., B. VAN GINNEKEN, S. K. NAYAR and J. J. KOENDERINK (1999a). CUReT: Columbia-utrecht reflectance and texture database. `http://www1.cs.columbia.edu/CAVE/CUReT/`, 1999.

DANA, KRISTIN J., B. VAN GINNEKEN, S. K. NAYAR and J. J. KOENDERINK (1999b). Reflectance and texture of real-world surfaces. *ACM Transactions on Graphics 18*, 1 (1999), pp. 1–34.

DANA, KRISTIN J. and J. WANG (2004). Device for convenient measurement of spatially varying bidirectional reflectance. *Journal of the Optical Society of America 21*, 1 (January 2004), pp. 1–12.

DEBEVEC, PAUL, T. HAWKINS, C. TCHOU, H.-P. DUIKER, W. SAROKIN and M. SAGAR (2000). Acquiring the reflectance field of a human face. In *Proceedings of the 27th Annual Conference on Computer Graphics and Interactive Techniques* (2000), ACM Press/Addison-Wesley Publishing Co., pp. 145–156.

DEBEVEC, PAUL, A. WENGER, C. TCHOU, A. GARDNER, J. WAESE and T. HAWKINS (2002). A lighting reproduction approach to live-action compositing. In *Proceedings of the 29th annual conference on Computer graphics and interactive techniques* (2002), ACM Press, pp. 547–556.

FOO, S. C. and K. E. TORRANCE (1995). Equipment acquisition for the light measurement laboratory of the cornell program of computer graphics. Tech. Rep. PCG 95-5, Program of Computer Graphics, Cornell University, Ithaca, New York, 1995.

FURUKAWA, R., H. KAWASAKI, K. IKEUCHI and M. SAKAUCHI (2002). Appearance based object modeling using texture database: acquisition, compression and rendering. In *Proceedings of the 13th Eurographics workshop on Rendering* (2002), Eurographics Association, pp. 257–266.

GARDNER, ANDREW, C. TCHOU, T. HAWKINS and P. DEBEVEC (2003). Linear light source reflectometry. *ACM Transactions on Graphics 22*, 3 (2003), pp. 749–758.

GORTLER, STEVEN J., R. GRZESZCZUK, R. SZELISKI and M. F. COHEN (1996). The lumigraph. In *Proceedings of the 23rd annual conference on Computer graphics and interactive techniques* (1996), ACM Press, pp. 43–54.

HAN, JEFFERSON Y. and K. PERLIN (2003). Measuring bidirectional texture reflectance with a kaleidoscope. *ACM Transactions on Graphics 22*, 3 (2003), pp. 741–748.

HAWKINS, TIM, J. COHEN and P. DEBEVEC (2001). A photometric approach to digitizing cultural artifacts. In *Proceedings of the 2001 conference on Virtual reality, archeology, and cultural heritage* (2001), ACM Press, pp. 333–342.

LANG, JOCHEN, H.-P. SEIDEL and H. P. A. LENSCH (2003). View planning for BRDF acquisition. In *Proceedings of the SIGGRAPH 2003 conference on Sketches & applications* (2003), ACM Press, pp. 1–1.

LENSCH, HENDRIK P. A., J. KAUTZ, M. GOESELE, W. HEIDRICH and H.-P. SEIDEL (2003). Image-based reconstruction of spatial appearance and geometric detail. *ACM Transactions on Graphics 22*, 2 (2003), pp. 234–257.

LEUNG, THOMAS and J. MALIK (2001). Representing and recognizing the visual appearance of materials using 3D textons. *International Journal of Computer Vision 43*, 1 (June 2001), pp. 29–44.

LIU, XINGUO, Y. YU and H.-Y. SHUM (2001). Synthesizing bidirectional texture functions for real-world surfaces. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques* (2001), ACM Press, pp. 97–106.

LU, JIPING 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* (Massachusetts Institute of Technology, Cambridge, Massachusetts, June 1995), Massachusetts Institute of Technology, Cambridge, Massachusetts, IEEE Computer Society, p. 80.

MALZBENDER, TOM, D. GELB and H. WOLTERS (2001). Polynomial texture maps. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques* (2001), ACM Press, pp. 519–528.

MATUSIK, WOJCIECH, H. PFISTER, M. BRAND and L. MCMILLAN (2003a). A data-driven reflectance model. *ACM Transactions on Graphics 22*, 3 (2003), pp. 759–769.

MATUSIK, WOJCIECH, H. PFISTER, M. BRAND and L. MCMILLAN (2003b). Efficient isotropic BRDF measurement. In *Proceedings of the 14th Eurographics workshop on Rendering* (2003), Eurographics Association, pp. 241–247.

MATUSIK, WOJCIECH, H. PFISTER, R. ZIEGLER, A. NGAN and L. MCMILLAN (2002). Acquisition and rendering of transparent and refractive objects. In *Proceedings of the 13th Eurographics workshop on Rendering* (2002), Eurographics Association, pp. 267–278.

MESETH, JAN, G. MULLER and R. KLEIN (2004). Reflectance field based real-time, high-quality rendering of bidirectional texture functions. *Computers & Graphics 28*, 1 (February 2004), pp. 105–112.

MURRAY-COLEMAN, J. F. and A. M. SMITH (1990). The automated measurement of BRDFs and their application to luminaire modeling. *Journal of the Illuminating Engineering Society* (Winter 1990), pp. 87–99.

NICODEMUS, F. E., J. C. RICHMOND, J. J. HSIA, I. W. GINSBERG and T. LIMPERIS (1977). Geometrical considerations and nomenclature for reflectance. Tech. Rep. NBS MN-160, National Bureau of Standards, Washington, October 1977.

TONG, XIN, J. ZHANG, L. LIU, X. WANG, B. GUO and H.-Y. SHUM (2002). Synthesis of bidirectional texture functions on arbitrary surfaces. In *Proceedings of the 29th annual conference on Computer graphics and interactive techniques* (2002), ACM Press, pp. 665–672.

VASILESCU, M. ALEX O. and D. TERZOPOULOS (2003). Tensortextures. In *Proceedings of the SIGGRAPH 2003 conference on Sketches & applications* (2003), ACM Press, pp. 1–1.

WARD, GREGORY J. (1992). Measuring and modeling anisotropic reflection. In *Proceedings of the 19th annual conference on Computer graphics and interactive techniques* (1992), ACM Press, pp. 265–272.

WERNER, T., R. D. HERSCH and V. HLAVAC (1995). Rendering real-world objects using view interpolation. In *Fifth IEEE International Conference on Computer Vision (ICCV'95)* (1995), IEEE Computer Society, pp. 957–962.