Obtaining the Bidirectional Texture Reflectance of Real-World Surfaces by means of a Kaleidoscope

Judith Radloff

Abstract

The aim of this research is to enable the rendering of more realistic surfaces for use within virtual environments. This paper investigates the use of a kaleidoscope in measuring the reflectance properties of real-world surfaces, in particular to obtain the Bidirectional Texture Reflectance (BTF) of the surfaces. The technique is discussed in practical terms, highlighting pertinent issues as well as potential optimisations. Various configurations are explored through simulation and confirmed through physical implementation. The results show that the technique has significant merit in its efficiency and accuracy at a fraction of the overhead required for current alternative techniques. Hardware optimisations proposed in the paper could lead to improvements on the technique.

1 Introduction

Rendering realistic surfaces under arbitrary lighting and viewing directions requires detailed 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). However since it refers to light's interaction at a particular point on the surface, the BRDF 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. 1999).

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 less time-consuming and more economical measuring devices.

(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 in theory which would contribute towards accuracy; sampling is potentially dense; calibration is comparatively trivial; acquisition is rapid. The device is economical, efficient and easy to use, making it a potentially optimal device for BTF measurement.

While Han and Perlin mention the minor inherent shortcoming of both resolution and brightness fading at extreme angles, few issues concerning the implementation or the potential of alternative configurations are discussed. This paper is a detailed investigation into the technique proposed by Han and Perlin, with particular focus on its practical implementation, its improvements on alternative techniques and its limitations.

The paper is structured as follows: Section 2 highlights related work within the field of real-world surface reflectance measurement. Section 3 is a discussion of the principles behind the technique, while Section 4 details the implementation. Section 5 is a brief examination of the results to date, comparing simulated and real results.

2 Related Work

The first publicly available BTF database of real-world surfaces was presented by (DANA et al. 1999). It comprises over 60 samples and more than 200 view/illumination direction pairs. The technique used in acquiring the samples involves rotating a sample of the surface in front of a fixed light source over a hemisphere of viewing/illumination directions. The device has inherent limitations: it is very time-consuming and involves much calibration, which sacrifices accuracy.

A recent enhancement to the above technique (DANA and WANG 2004) involves a more compact device requiring only planar, as opposed to *hemispherical*, translations and using reflections off a concave parabolic mirror.

Prior to the innovative work by (HAN and PERLIN 2003), there has been no significant scientific study of the properties of kaleidoscopes nor their potential uses. (BANGAY and RADLOFF 2004) examine, through simulation, the merits of symmetrical kaleidoscope configurations and describe a systematic process for calculating the structural parameters involved in the implementation of the kaleidoscope technique for a particular camera/projector configuration. This work by Bangay and Radloff (BANGAY and RADLOFF 2004) forms the basis for this paper, which is in many ways a continuation of that research.

3 Technique

The kaleidoscope technique for reflectance measurement utilises the reflective properties of a kaleidoscope to build up a BTF database comprising a series of view/illumination direction pairs. As illustrated by Figure 1, a sample of the surface is placed at one end of the kaleidoscope; a camera placed at the opposite end of the kaleidoscope then has the view of a series of reflected images of the sample. Each reflected image represents a different viewing direction of the sample. In the case of a non-tapered configuration, the reflected images are effectively tiled (see Figure 3a,b); in a tapered configuration, by contrast, these reflections appear to be mapped onto a virtual sphere (see Figure 3c,d).

Light projected down the kaleidoscope, and occupying the same optical path as the camera, is structured so as to isolate a single reflected image of the sample at a time. The angle of the light relative to the reflected image corresponds to the incident direction of light that is in turn reflected onto the original sample. Each reflected image of the sample therefore represents

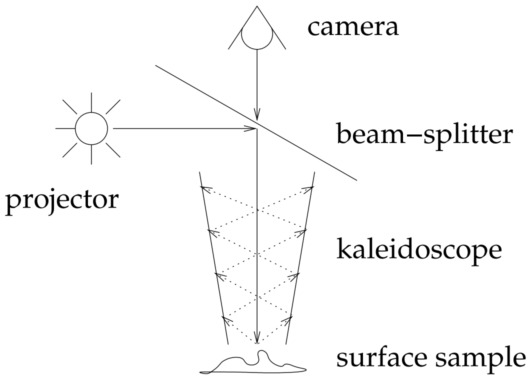

Figure 1: Components of the Kaleidoscope System

a unique view/illumination pair. These reflected images are captured digitally and stored in a database representing BTF information.

The acquired BTF database can then be used directly in the rendering of realistic surfaces under arbitrary lighting and viewing conditions. This can be achieved, as shown by (DEBEVEC et al. 2000), by calculating a linear combination of the images. This research however is confined to acquiring BTF information and not to the application of this data.

4 Implementation

The investigation of the kaleidoscope technique has been undertaken in two distinct phases. The first, a simulated implementation, has served to derive possible parameters for the physical implementation, including optimal kaleidoscope configurations. The subsequent physical implementation has revealed practical issues relating to the hardware that will ultimately affect the efficiency and merit of the technique.

4.1 Simulation

In the simulation phase, various kaleidoscope configurations have been built using ray-tracing. The view taken is that of the optical path of the camera/projector, directed down the kaleidoscope toward the sample. Rays were traced from this virtual camera/projector position through the kaleidoscope onto the sample, being a two-dimensional image. In this way the reflective properties of various kaleidoscope configurations have been investigated by altering parameters such as the angle of taper (referring to the slant of the mirrors) and the number of sides of the kaleidoscope (which would determine the shape outlining the sample).

It was found that there is a direct relationship between the angle of taper and the number of levels of reflection produced. Optimising the number of levels of reflection involves a trade-off: increasing the depth of reflection allows for more incident directions to be sampled yet decreases the size of each sample; decreasing the depth however allows for larger samples, but fewer incident directions.

Figure 2: Physical Implementation of the Kaleidoscopes: Two Views

While both asymmetrical and symmetrical configurations have been investigated, it has been discovered that symmetrical configurations are most suitable for reflectance measurement as these have the unique property of allowing sampling at regular parametric intervals. Within symmetrical configurations, in the case of non-tapered kaleidoscopes (in which the sample is effectively tiled), the optimal number of sides of a kaleidoscope corresponds to a degree of polygon that could result in regular tessellations on a flat plane, namely an equilateral triangle, square or hexagon. For non-tapered configurations, symmetrical kaleidoscopes of either three, four or six sides would therefore allow most effective utilisation of the technique without wasted unusable regions.

A significant advantage of the simulation phase has been that it has enabled the exploration of novel configurations not discussed by (HAN and PERLIN 2003). Of particular potential value are cylindrical and reflective base kaleidoscopes. Cylindrical kaleidoscopes are seen to give rise to continuous rings of reflection - one ring for each level of reflection, comprising a rich merge of incident angles (see Figure 3e,f). Each point in the sample occurs twice in each reflected ring, which would potentially allow sampling of the incident directions of illumination at regular polar coordinate intervals.

Reflective base kaleidoscopes are constructed by extending the sides of the kaleidoscope beyond the sample, and then sealing off the base of the kaleidoscope with an additional reflective surface. Reflective base kaleidoscopes have the benefit of including incident directions from the far end of the sample, and would be particularly useful in measuring the reflectance properties of surfaces that exhibit a degree of translucency.

Besides revealing optimal configurations for BTF measurement, the simulation phase has also contributed to the devising of a step-by-step strategy for calculating optimal parameters for the physical implementation, based on kaleidoscope optics. Full details of this devised strategy can be found in the (BANGAY and RADLOFF 2004) paper.

4.2 Physical Implementation

Each of the kaleidoscopes built in the physical implementation (see Figure 2) has been constructed according to dimensions calculated from the (BANGAY and RADLOFF 2004) paper. The configurations are as follows:

- non-tapered three-sided

- tapered four-sided
- tapered four-sided as above, extended with reflective base
- non-tapered cylindrical
- tapered cylindrical

As mentioned earlier, the reflective base and cylindrical kaleidoscopes represent novel configurations in reflectance measurement.

The cylindrical kaleidoscopes posed a problem regarding their construction. Unlike the other three kaleidoscopes which could be built conventionally using back-surface mirrors, the problem of the cylindrical kaleidoscopes was solved by constructing them from glass. Once blown, the glass cylinders were cut in half so as to be coated with a reflective chemical, before being later rejoined. This alternative means of construction, from glass, has proved to be of significant potential value. Chemically-coated glass kaleidoscopes effectively give rise to front-surface reflection, which exhibits a marked reduction in loss of resolution in successive levels of reflection, as compared to kaleidoscopes built from back-surface mirrors. Another potential advantage for using chemically-coated glass as opposed to back-surface mirrors is that glass can be made thinner than mirrors, which would allow panes to be glued together more seamlessly.

This issue of gluing mirrors together is by no means negligible, although not discussed by (HAN and PERLIN 2003). It is a consequence of the fact that it is not possible to build perfect kaleidoscopes in practice. Slight imprecision in the cutting of the mirrors, though unavoidable, could result in kaleidoscopes that are not perfectly symmetrical and thereby detract from the accuracy of the measurements, in addition to allowing light to leak between mirrors. The situation could be improved by first creating a model of the interior of the kaleidoscope from a block of wood, and then using the model both to measure the mirrors, and to act as a support in gluing the mirrors together. In this way the mirrors would be correctly aligned to each other, thereby improving symmetry.

The setup for the physical implementation used in this research is derived from (HAN and PERLIN 2003), though is currently in a preliminary stage. A digital camera is used to capture the BTF data while a projector provides the structured illumination. The camera and projector occupy the same optical path by means of a pane of glass acting as a beam-splitter, angled at 45 degrees relative to each of the camera and projector. It has been found that the original technique, as described by (HAN and PERLIN 2003), can be simplified by using a horizontal, as opposed to vertical, implementation. This negates the need for a clamp to suspend the kaleidoscope above the sample. Only the camera is positioned on a tripod, which is for stability - aiding in registering the images to each other and thereby reducing the need for calibration.

Following is a description of the experimental procedure to be used in capturing and storing the BTF information:

1. The illumination will be structured by means of a simple program run on a desktop computer connected to the projector. The program will allow the manual selection of vertices that define a single reflected image of the sample. The resulting image will then be captured and the process repeated for each reflected image.
2. Both the viewing and illumination angles will be calibrated for each acquired image.
3. The acquired BTF data will then be stored in a two-dimensional database of view/ illumination direction pairs.

5 Results

The results obtained in the simulation phase have been confirmed in the preliminary physical implementation, including the novel configurations of the reflective base and cylinder.

A close investigation of the kaleidoscope technique has shown that hardware factors play a more significant role than anticipated. A comparison of real versus simulated images (Figure 3) reveals a fairly substantial loss in resolution in the real images, compounded with other factors such as camera focus features, leaking light and dust. The slight asymmetry of the kaleidoscopes in practice also means that the samples are not perfectly registered to each other. These negative effects are largely due to construction issues and could be considerably minimised.

6 Conclusions

The use of kaleidoscopes in obtaining BTF samples of real-world surfaces have been investigated through both simulation and preliminary practical implementation.

The simulation phase has revealed optimal configurations for reflectance measurement, including the novel cylindrical and reflective base kaleidoscope configurations which could lead to even richer BTF data than other configurations.

Although the technique is confirmed to be of merit, hardware is the limiting factor. Alternative implementations, in particular using chemically-coated glass, would improve the accuracy of the technique.

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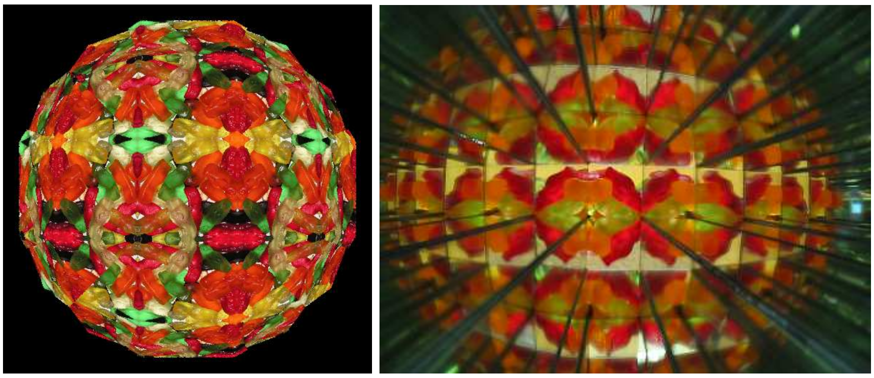
(a) Non-tapered Simulated (b) Non-tapered Real



(c) Tapered Simulated (d) Tapered Real

(e) Cylindrical Simulated (f) Cylindrical Real

Figure 3: Views through the Kaleidoscopes: Simulated Versus Real