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

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Abstract

This thesis investigates the use of a kaleidoscope in measuring the reflectance properties of real-world surfaces, in particular to obtain the Bidirectional Texture Function (BTF) of the surfaces.

The kaleidoscope technique for reflectance measurement represents an innovative economical and simple approach to obtaining reflectance functions of real-world surfaces. While theoretically the technique has been shown to be of merit, there has been no prior research conducted to investigate practical issues arising from its implementation; neither have optimal kaleidoscope or other design configurations been derived.

This research is an investigation of the kaleidoscope technique as an economical and simple means of obtaining BTF information of surfaces. The investigation is conducted in two phases. The first phase involves a simulation of kaleidoscope architectures in order to study the effects of the structural parameters of kaleidoscopes, using this study to derive optimal kaleidoscope configurations for use in surface reflectance measurement. The second phase investigates the technique from a practical perspective through a complete working physical implementation of the system, highlighting pertinent practical issues as well as potential optimisations.

The investigation reveals design features that would yield optimal kaleidoscope configurations for reflectance measurement. These features have been used to design five kaleidoscope configurations, the first of which has successfully been used to obtain an extensive BTF database consisting of 585 view/illumination direction pairs. This makes it one of the largest recorded BTF databases to date. 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. Optimisations are proposed in the thesis which could lead to the acquisition of even richer BTF information.

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Chapter 1

Introduction

1.1 Problem Statement

This research investigates the use of kaleidoscopes in obtaining the Bidirectional Texture Function (BTF) of real-world surfaces. The fundamental objective of the research is to gain an in-depth practical understanding of the technique that would potentially lead to improvements in the acquisition of BTF information of surfaces. A simulation phase will be conducted to derive structural parameters that would yield optimal kaleidoscope configurations for reflectance measurement. A full physical implementation of the system, aimed at yielding a rich database of BTF information, will investigate the merit of the technique while revealing potential pitfalls and optimisations.

1.2 Background

Rendering realistic surfaces from 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 over a series of viewing and illumination directions. This information can be expressed in the form of surface reflectance functions that vary in complexity according to the properties of the particular surface.

1.2.1 Surface Reflectance Functions

The Bidirectional Reflectance Distribution Function (BRDF) [Nicodemus et al. 1977] describes light's interaction at a particular point on the surface. The BRDF assumes that light's interaction remains constant across the surface, making it a function 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 the spatial variance into account. A spatially-varying BRDF is known as a Bidirectional Texture Function (BTF), as defined by [Dana et al. 1999b], and is the focus of this research. A BTF can in turn be extended into the Bidirectional Scattering Surface Texture Function (BSSTF), which captures highly complex reflective properties such as subsurface scattering by additionally describing light that travels within the surface.

1.2.2 Representation of Reflectance Data

These surface reflectance functions can be represented by parameters that describe light's interaction with a surface by virtue of the incident and exitant directions of light. These incident and exitant directions of light correspond respectively to the illumination and viewing directions relative to the surface.

A BRDF is typically represented as the four dimensional function BRDF($\theta_i, \phi_i, \theta_e, \phi_e$), where θ_i and $\phi_i$represent the incident direction of light, being the illumination, and $\theta_e$and ϕ_e represent the exitant direction of light, being the viewing direction relative to the surface.

Likewise, a BTF is typically represented as the six dimensional function BTF($\upsilon, \nu, \theta_i, \phi_i, \theta_e, \phi_e$), where the additional parameters υ and ν allow the reflectance to vary along the surface by attributing the interaction to a single isolated point on the sample.

A BSSTF is extended by a further two dimensions to form the eight dimensional function BSSTF($\upsilon_i, \nu_i, \upsilon_e, \nu_e, \theta_i, \phi_i, \theta_e, \phi_e$), which accounts additionally for light traveling within the surface, such that the light is emitted at a point (υ_e, ν_e) that differs from its incident point (υ_i, ν_i).

1.2.3 Measuring Surface Reflectance

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 simpler, less time-consuming and more economical measuring devices.

1.2.3.1 Kaleidoscope Technique

[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 multiple illumination conditions with a single structured light source. These views can provide BTF information of a surface sample under a variety of viewing and illumination conditions. Theoretically, the method has many advantages for BTF measurement: it is inexpensive and potentially portable; for each illumination condition, all measurements are perfectly registered to each other which would contribute towards accuracy; sampling is potentially dense; calibration is comparatively trivial; acquisition is rapid. The device can be constructed economically and is efficient and easy to use, making it a potentially optimal device for BTF measurement.

While Han and Perlin briefly discuss the extensibility of the method to measuring the highly complex BSSTFs and mention a 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 thesis is a detailed investigation into the technique proposed by [Han and Perlin 2003], with particular focus on its practical implementation, its limitations and potential optimisations.

1.3 Research Focus

The specific issues to be investigated in this research are:

- the merit of the kaleidoscope technique for obtaining accurate BTF information of real-world surfaces, with regards it accuracy and efficiency
- improving the technique by:
  - deriving optimal kaleidoscope configurations
  - optimising the measurement process

1.4 Document Structure

The thesis is structured as follows: Chapter 2 highlights related work within the field of real-world surface reflectance measurement. Chapter 3 is a discussion of the principles behind the kaleidoscope technique for reflectance measurement and includes a simulation phase in which structural parameters that would yield optimal kaleidoscope configurations are investigated. Chapter 4 details the actual physical implementation of the technique and highlights various practical issues. Chapter 5 describes the results, comparing simulated and real results and discusses issues arising from the implementation as well as potential optimisations.

Chapter 2

Related Work

Obtaining information of the reflective properties of real-world surfaces requires that at least one of viewing and illumination incident direction relative to the surface be altered - under known conditions. The techniques used vary in their complexity and efficiency, usually sacrificing ease of use and economy in favour of acquiring richer reflectance measurements. Ideally each possible incident direction in the hemisphere above a sample of the surface should be captured from every possible illumination incident direction.

The degree of realism of the subsequent rendering of the surfaces is limited by the flexibility of the measurement phase. Measuring systems with varying view directions yet with only fixed illumination would allow the surface to be simulated only from arbitrary viewing directions and not from arbitrary illumination conditions.

BTF measurement differs from BRDF by requiring an additional two degrees of freedom. Not only must the sample be viewed and illuminated from a variety of positions in the hemisphere above the sample, but the sample itself must be incrementally repositioned in its own hemisphere relative to these incident directions, typically by tilting and rotation. In this way the reflectance properties of the surface can be allowed to vary spatially across the sample.

2.1 Basic Reflectance Measurement (BRDF)

2.1.1 Gonioreflectometer

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 any complex reflective properties.

2.1.2 [Murray-Coleman and Smith 1990] LBL Imaging Gonioreflectometer

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 this device marks a significant contribution to the reduction of complexity in reflectance measurement, the method has many problems associated to it. These include distortions caused by the fish-eye lens, and undesired re-illumination of the sample. The required repeated manual positioning of the light source means that neither are the measurements perfectly registered. Measurements are not good near grazing angles, and the technique is shown to be unsuitable for highly specular or smooth surfaces.

2.1.3 [Lu and Little 1995]

[Lu and Little 1995] provide a technique for estimating the BRDF of a surface sample by capturing a sequence of images of the sample as it is rotated from 0 degrees to 30, 60 and 90 degrees 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.

2.1.4 [Gortler et al. 1996] Lumigraph

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.

2.1.5 [Matusik et al. 2003]

An innovative method devised by [Matusik et al. 2003], 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 derive 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.

2.1.6 [Lang et al. 2003]

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 (BTF)

2.2.1 [Dana et al. 1999a, Dana et al. 1999b] CUReT Database

The first publicly available BTF database of real-world surfaces, CUReT [Dana et al. 1999a], was presented by [Dana et al. 1999b]. It comprises 61 samples each comprising 205 view/illumination direction pairs. The technique used in acquiring the samples involves incrementally rotating and tilting a sample of the surface in front of a fixed light source over a hemisphere of viewing/illumination directions. Though the device represents a significant breakthrough in being the first device to obtain BTF data, it has inherent limitations, being very time-consuming and involving much calibration, which sacrifices efficiency and accuracy.

2.2.2 [Dana and Wang 2004, Dana 2001]

A recent enhancement on the above technique [Dana and Wang 2004, Dana 2001] involves a more compact device requiring only planar, as opposed to *hemispherical*, translations and using reflections off a concave parabolic mirror. The technique requires that the surface sample be affixed to a translation stage which is its single-most potential limiting factor.

2.2.3 [Furukawa et al. 2002]

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.

2.2.4 [Malzbender et al. 2001] Polynomial Texture Maps

[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. [Malzbender et al. 2001] present a complete working system that essentially concerns a specialised form of texture-mapping, as opposed to reflectance measurement and simulation.

2.2.5 [Gardner et al. 2003] Linear Light Source Reflectometry

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.

2.2.6 [Bangay and Radloff 2004] Kaleidoscope Configurations

The technique for BTF measurement proposed by [Han and Perlin 2003] represents an innovative approach to reflectance measurement requiring no moving parts, by use of a kaleidoscope. Prior to their work, 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 the implementation section of this thesis, which is in many ways a continuation of that research.

2.3 Highly Complex Reflectance Measurement (BSSTF)

BSSTF measurement requires a different approach to techniques for capturing less complex surface reflectance. It is not sufficient to alter simply the relative positions of the camera(s), light-source(s) and sample. The light-source must be structured differently.

2.3.1 [Debevec et al. 2000] Light Stage

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. The focus of their research was on obtaining reflectance information of human skin, in particular the human face. Human skin represents the most complex class of surface in which light not only reflects off the surface, but is also transmitted through it. Although essentially measuring the BSSTF (of a human face), their approach reduces the function from 8 to 6 dimensions by considering 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.

2.3.2 [Debevec et al. 2002] Variation on Light Stage

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.

2.3.3 [Hawkins et al. 2001]

[Hawkins et al. 2001] extend the original Light Stage [Debevec et al. 2000] to capture even more complex reflective properties. The paper is specifically related to the digital viewing of artifacts for documentation under arbitrary illumination conditions, and ultimately from arbitrary viewing angles. However the latter is only discussed and not yet implemented. The acquisition involves a series of hundreds of strobe lights attached to a rotating arm - potentially covering the 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 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 cost of the device.

2.3.4 [Matusik et al. 2002]

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.

2.4 Summary

All the technique for reflectance measurement described in this chapter share the same principal of requiring that multiple images the surface sample be captured from multiple known illumination and viewing direction pairs. The technique proposed by [Han and Perlin 2003] is unique in its not requiring any mechanical movement or repositioning of any of the sample, light-source or camera, and offers a potentially simple and economical alternative to reflectance measurement.

The BTF data yielded by [Han and Perlin 2003] is sufficiently comparable in dimension and accuracy only to that obtained by [Dana et al. 1999b] and [Debevec et al. 2000]. The next chapter discusses the kaleidoscope technique in more detail, and its potential for being an optimal device for measuring surface reflectance.

Chapter 3

Technique

This chapter details the principles behind the kaleidoscope technique for obtaining BTF information of surfaces, and includes a discussion of design considerations for a subsequent physical implementation of the technique.

Parameters defining kaleidoscope configurations are outlined in Section 3.2. This serves as preparation for the focus of the chapter (Section 3.3) which comprises a description of an extensive simulation phase investigating the structural parameters of kaleidoscopes and the resulting configurations. Finally, the extensibility of the technique for obtaining BSSTF information is briefly discussed in Section 3.4.

3.1 Fundamental Principles

3.1.1 Obtaining BTF Data

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 3.1, 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, seen from a single physical position.

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. By illuminating each reflected image in turn, a series of illumination conditions are created. The effective incident angle of illumination on the surface sample for each of these illumination conditions can be

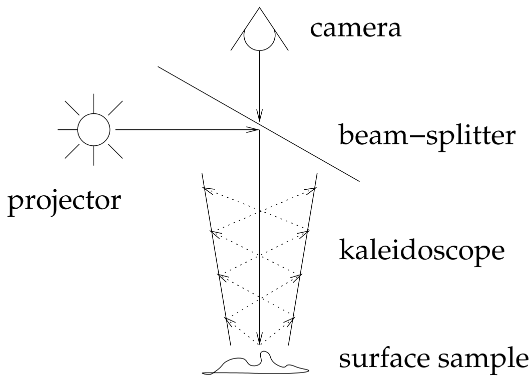


Figure 3.1: Components of the Kaleidoscope System

calculated geometrically. This utilises a useful property of kaleidoscope reflectance of the angle of light relative to the reflected image inherently corresponding to the incident direction of light that is in turn reflected onto the original sample [Herman 1900], as shown by Figure 3.2. Each reflected image of the sample therefore represents not only a different viewing direction of the sample, but also a unique view/illumination direction pair - precisely what is needed to obtain BTF information.

These reflected images are captured by taking successive digital images of the view through the kaleidoscope from a single physical position, while altering the illumination configuration.

3.1.2 Storing Acquired BTF Data

The acquired data is stored in a database representing BTF information by pairing view and illumination directions. The resulting database can 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 according to the lighting and viewing conditions of the scene to be rendered. It follows that the denser the sampling of the images, the richer the BTF data and therefore the more accurate the rendered surface, due to it being more sensitive to subtle changes in it reflective properties.

This research concerns first verifying and then optimising the kaleidoscope technique to acquire as rich a BTF database as possible by most efficient means, and is not concerned with the application of this data.

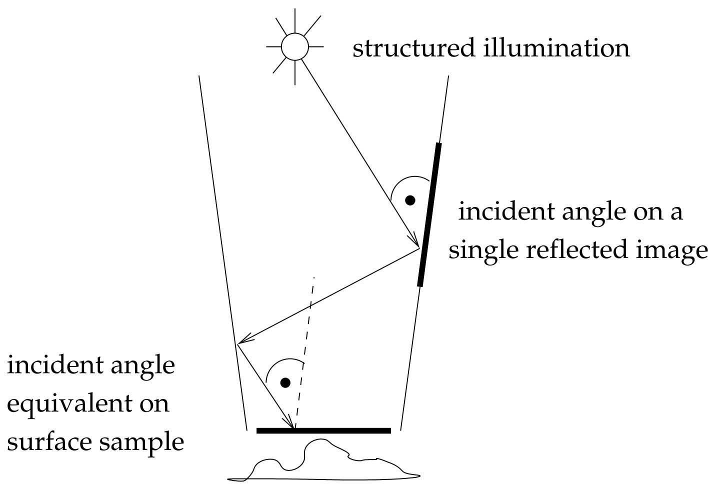


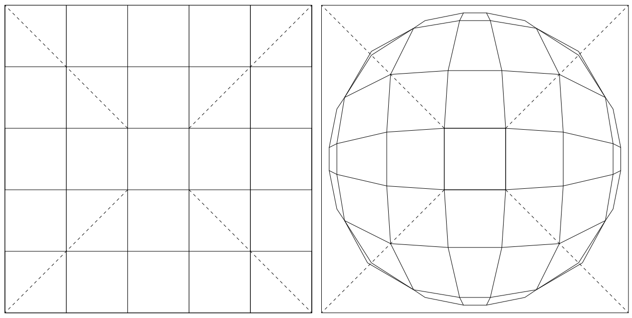
Figure 3.2: Incident angle of structured illumination

3.2 Kaleidoscope Design Considerations

Kaleidoscope configurations can be characterised by the following structural parameters:

- the number of sides of the kaleidoscope
- the arrangement of the sides of the kaleidoscope
- the angle of taper, referring to the slant of the sides of the kaleidoscope - typically where the near end is larger than the far end (relative to the viewer)
- the height and scale of the kaleidoscope

The architectural design of a kaleidoscope affects both the shape of the images produced within, as well as the pattern of the reflections. This can be clearly illustrated by considering the cases of a configuration with no angle of taper as compared to a configuration with an angle of taper. In the case of a non-tapered kaleidoscope configuration, the reflected images are effectively tiled (refer to Figure 3.3a); in a tapered configuration, by contrast, in which the end of the kaleidoscope closest to the sample is smaller than the opposite end, these reflections appear to be mapped onto a virtual sphere (refer to Figure 3.3b). This effect is due to each successive layer of reflection re-orienting the surface sample incrementally further away from the perpendicular, and results in the reflected images disappearing over a horizon.



(a) Non-tapered (b) Tapered

Figure 3.3: Effect of Non-Tapered versus Tapered Configurations

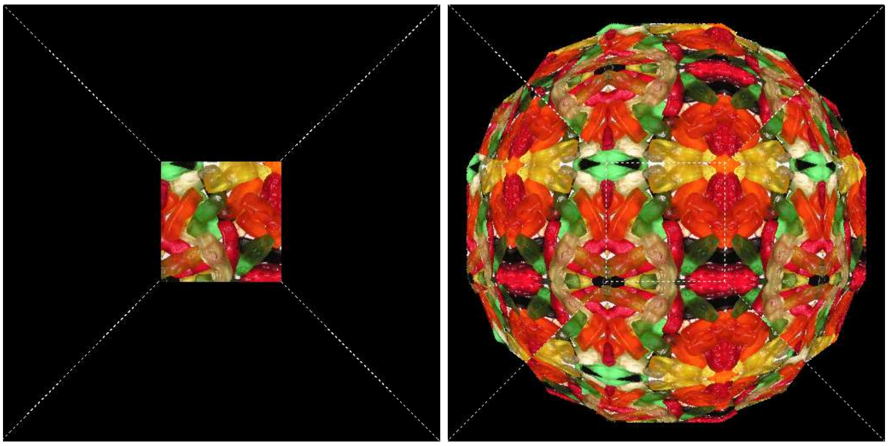
Dotted lines show the positioning of the mirrors.

To investigate more extensively the effects of altering the various structural parameters of the kaleidoscope, a simulation phase has been conducted, which serves to ultimately derive optimal kaleidoscope configurations for surface reflectance measurement.

3.3 Simulation

A wide variety of kaleidoscopes have been simulated to model light's behaviour within a kaleidoscope. This has been achieved by means of ray-tracing. The view taken is that of the optical path of the camera/projector, directed down the kaleidoscope toward the sample, being a two-dimensional image. Rays are traced from this virtual camera/projector position through the kaleidoscope onto the image, representative of the real-world surface. In this way it is possible to investigate the reflective properties of any kaleidoscope configuration by altering the various kaleidoscope structural parameters. (For a description of these structural parameters, refer to Section 3.2.)

Figure 3.4 illustrates the effect of the ray-tracing technique by showing two identical views through a simulated four-sided kaleidoscope. Figure 3.4a is a view through the kaleidoscope before ray-tracing is applied; Figure 3.4b is a view after ray-tracing has been applied. The configuration is similar to that of Figure 3.3b. The sample is a digital image of jellybabies.



(a) Kaleidoscope Setup Without Ray-Tracing

(b) Same View With Ray-tracing Applied

Figure 3.4: Simulating Kaleidoscopes by means of Ray-tracing

Dotted lines illustrate the positioning of the mirrors.

3.3.1 Simulation versus Physical Implementation

A simulated implementation of the kaleidoscope technique differs critically from a physical implementation in two ways. Firstly, since the sample is a two-dimensional digital image, it has no geometrical structure. The images produced within the kaleidoscope therefore do not vary in their reflective properties; neither do they represent different viewing angles of the sample. Secondly, the illumination is not structured, but simply provides an even distribution of light throughout the interior of the kaleidoscope. The consequence of these differences is that no BTF information can be obtained by simulation. Simulation does however provide accurate information of the behavioural effects of the kaleidoscope configurations with regard reflections of the sample.

3.3.2 Optimising Parameters for Reflectance Measurement

In the context of the kaleidoscope technique, reflectance measurement is optimised by kaleidoscope configurations that yield the greatest possible number of the images of highest resolution, therefore of greatest dimension.

However, since these two results are inversely related to each other, the design must be carefully considered for a balance to be found. The simulation phase has enabled detailed observation of the relationships between the various structural parameters.

For example it has been found that there is a direct relationship between the angle of taper and the number of levels of reflection produced: as the taper angle increases, so does the number of levels of reflections produced. Finding an optimal number for these 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.

3.3.2.1 Symmetry

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,

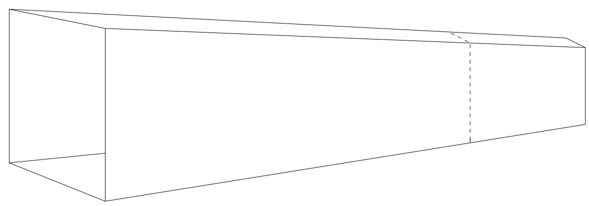


Figure 3.5: Reflective Base Kaleidoscope

A side-view showing how the original tapered kaleidoscope is extended, represented by the section to the right of the dotted line.

four or six sides would therefore allow most efficient utilisation of the technique without wasted unusable regions.

3.3.3 Novel Configurations for Reflectance Measurement

A significant advantage of this simulation phase has been how it has enabled the exploration of novel configurations not discussed by [Han and Perlin 2003]. Of particular potential value are reflective base and cylindrical kaleidoscope configurations.

3.3.3.1 Reflective Base Kaleidoscope

A reflective base kaleidoscope (refer to Figure 3.5) is 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. In this simulation phase, the properties of reflective base kaleidoscopes have been explored by mapping the two-dimensional image of jellybabies onto a three-dimensional sphere. This sphere is then placed in an elevated position above the reflective base, effectively its original position had the kaleidoscope not been extended. In this way the part of the sample not visible to the viewer, is reflected off the underneath mirrors.

It has been found through this investigation that reflective base kaleidoscopes have the benefit of including incident directions from the far end of the sample. This means that they could be particularly useful in measuring the reflectance properties of surfaces that exhibit some degree of translucency.

3.3.3.2 Cylindrical Kaleidoscopes

Prior to this research there has been no evidence found of the existence of cylindrical kaleidoscopes. Cylindrical kaleidoscopes are seen to give rise to continuous rings of reflection - one ring for each level of reflection (refer to Figure 5.1e,f). Each ring comprises a rich merge of incident angles, with each point in the sample occurring twice in each reflected ring. This novel configuration could potentially allow sampling of the incident directions of illumination at regular polar coordinate intervals, making it a particularly advantageous configuration in the context of this research.

3.4 Extensibility for BSSTF Measurement

Since the kaleidoscope technique for reflectance measurement involves no mechanical movement, it can easily be extended into measuring the BSSTF of surfaces. This would be useful for surfaces that exhibit highly complex reflective properties. This can be achieved, as mentioned by [Han and Perlin 2003], by incrementally moving a single small spot of illumination over the surface sample and measuring the light that emerges around the spot.

3.5 Summary

In preparation for the physical implementation of the kaleidoscope system for reflectance measurement, a simulation phase has been conducted, revealing the effects of the various structural parameters of kaleidoscope architectures. An understanding of these parameters could be used to design optimal kaleidoscope configurations that could potentially yield rich BTF information.

In addition, the simulation phase has contributed to the devising of a step-by-step strategy for calculating optimal parameters for the physical implementation, based on kaleidoscope optics. This strategy will form the basis of the design phase in the next chapter. Full details of this devised strategy can be found in the [Bangay and Radloff 2004] paper.

Chapter 4

Implementation

This chapter details the physical investigation of the kaleidoscope system for measuring surface reflectance, by means of a complete working physical implementation. It draws on observations derived in the preceding simulation phase of the effects of the various structural parameters of kaleidoscope. These led to the derivation of optimal design features for the technique that have been adopted in the physical implementation. Significantly, this chapter reveals practical issues relating to hardware, which have a noticeable effect on the efficiency and subsequent merit of the technique.

4.1 Kaleidoscope Construction

Each of the kaleidoscopes built in the physical implementation (pictured in Figure 4.1) has been constructed according to dimensions calculated from the [Bangay and Radloff 2004] paper.

4.1.1 Parameter Derivation

The step-by-step strategy derived in the [Bangay and Radloff 2004] paper calculates optimal structural parameters for kaleidoscopes for use in reflectance measurement. It requires the input of the following parameters:

- the required number of levels of reflection
- the number of sides of the kaleidoscope
- the radius of the sample

Figure 4.1: Physical Implementation of the Kaleidoscopes: Two Views

- the field of view of the camera/projector

The strategy yields:

- an optimal taper angle
- the minimum height of the kaleidoscope
- an optimal distance between the sample and the camera/projector that would result in the most complete view of the image produced by the kaleidoscope

4.1.2 Design Considerations

The decisions leading to the selection of the parameters to be used in the derivation of the dimensions for the physical kaleidoscopes are described below.

4.1.2.1 Configurations

The kaleidoscope configurations have been chosen to span a cross-section of tapered and non-tapered kaleidoscopes as well as a varied number of sides. Five kaleidoscopes are constructed in total. These 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.

4.1.2.2 Experimental Design

The kaleidoscopes are designed to each yield three complete levels of reflection. This number has been chosen to allow for rich BTF data acquisition. In the case of a four-sided kaleidoscope, for example, three levels of reflection potentially yields 2401 view/illumination pairs, which is a particularly rich BTF dataset.

The tessellating effect of a non-tapered configuration is to be confirmed by the construction of the three-sided non-tapered kaleidoscope. This particular configuration, consisting of only three sides, has been selected for its simplicity of design and construction.

The decision to create kaleidoscopes of four sides is due to their potential for yielding rich BTF data. Han and Perlin's implementation [Han and Perlin 2003] of a three-sided kaleidoscope could yield only 484 view/illumination pairs for three complete levels of reflection. The square images that result from a four-sided configuration are also desirable as this will reduce the complexity of the data acquisition phase, lead to images that are easy to use, as well as reduce the storage cost of the resulting image database.

4.1.2.3 Hardware Constraints

The field of view is a hardware constraint, and is effectively the smaller field of view of either the camera or projector. The camera and projector used in this research each have a field of view of 21 degrees.

The dimensions of each cylindrical kaleidoscope has been constrained to a maximum length of 20 centimetres, due to a limited availability of aluminium. To allow for simpler comparison between the various kaleidoscope configurations, all kaleidoscopes have been constructed to be of similar dimensions.

4.2 Construction Issues

The construction of the kaleidoscopes has highlighted practical issues that were not previously encountered during the simulated design phase.

4.2.1 Material

While the three- and four-sided kaleidoscopes can be built conventionally using regular back-surface mirrors, the cylindrical kaleidoscopes have posed a problem regarding their construction. This problem of creating kaleidoscopes with a smooth and highly reflective interior surface has been solved by constructing them from glass, coated with a highly reflective chemical. The process of construction of these cylindrical glass kaleidoscopes is as follows:

Once blown, the glass cylinders are cut in half so as to be coated with aluminium (being a highly reflective chemical). Once coated, these two glass halves are rejoined. This alternative construction material has proved to be of significant value. Aluminium-coated glass kaleidoscopes effectively give rise to front-surface reflection. This front-surface reflection has shown to exhibit an improvement in clarity of reflection as well as a marked reduction in loss of resolution in successive levels of reflection as compared to reflection off back-surface mirrors. This is due to the rays of light being directly reflected off the front-surface of the glass and not having to first penetrate (and then exit) the layer of glass before being reflected.

Another advantage for using aluminium-coated glass as opposed to back-surface mirrors is that glass can be made thinner than mirrors. This could allow panes to be glued together more seamlessly.

4.2.2 Alignment

The issue of gluing mirrors together is by no means negligible, although not discussed by [Han and Perlin 2003]. It is extremely difficult to align the mirrors so that there is no substantial seam between the mirrors. This difficulty can be compounded should the mirrors not be cut perfectly and the edges not angled so as to fit perfectly together. Slight imprecision in the cutting of the mirrors used in this research has resulted in kaleidoscopes that are not perfectly symmetrical. This has detracted from the accuracy of the measurements by causing increasing distortions in the reflected images for each successive layer of reflection.

Another complication resulting from imprecision in gluing the mirrors together is that light may leak between the mirrors. This requires that the kaleidoscopes be sealed to prevent leaking light from affecting the accuracy of the measurements. In this research, black insulation tape has been sufficient in eliminating any light from leaking in through the sides of the kaleidoscopes.

A construction approach that could assist in creating symmetrical kaleidoscopes would be to first cut an accurate model of the interior of the kaleidoscope from a block of wood. This model could then used both to assist in cutting the mirrors more accurately, and to act as a support when gluing the mirrors together. In this way the mirrors could be more easily correctly aligned to each other and the construction of symmetrical kaleidoscopes thereby assisted.

4.2.3 System Design

The setup for the physical implementation used in this research is derived from [Han and Perlin 2003], though with minor alterations. As with Han and Perlin, a digital camera is used to capture the BTF data and a digital projector used to provide the 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.

A slight alteration to the original technique, as described by [Han and Perlin 2003], is a horizontal, as opposed to a vertical, implementation. This allows a simplification of the setup of the technique as this configuration negates the need for any clamps - neither to suspend the kaleidoscope above the sample nor to angle the beam-splitter. The kaleidoscope and camera are raised by simply positioning each on separate platforms. The beam-splitter is stabilised in an upright position by affixing a small weighted box to one end. This horizontal configuration is simple and ideal for cohesive surfaces that have a structure that is relatively insensitive to gravity. It is not suitable however for surfaces consisting of loose particles since this horizontal configuration requires that the sample be positioned vertically as opposed to lying flat relative to the ground.

4.3 Experimental Procedure

This section details the experimental procedure used in capturing and storing BTF information of real-world surfaces. It outlines the components of the system and defines the role of a simple computer program written to enable the structuring of the illumination. This is followed by a full step-by-step description of the experimental procedure: from the setup through to the capturing and storing of the BTF data.

4.3.1 Components of the System

In addition to the particular kaleidoscope chosen, the key components of the system are a desktop computer, a digital projector, a pane of glass to act as a beam-splitter, a matte black sheet, and a simple program written to structure the illumination, to be described in Section 4.3.2. Elevation stages will be required for both the kaleidoscope and camera, and a weight would assist in stabilising the beam-splitter in the case of a horizontal implementation. A vertical implementation will additionally require a tripod for the camera and a clamp for each of the kaleidoscope and beam-splitter. Finally, an image manipulation software tool is required in order to extract the individual view/illumination pairs from the captured digital images.

The structuring of the illumination by means of the illumination program requires that the entire system be set up on a flat surface, positioned next to a blank wall. The wall plays no role other than in the initial setting up of the system; it would therefore be possible to allow the system to be made portable once the setup is complete.

4.3.2 Program to Structure Illumination

The illumination is structured by means of a simple program run on a desktop computer connected to the projector. The program allows the manual selection of vertices that define a single reflected image of the sample. This selection process forms part of a pre-acquisition phase and significantly reduces the data acquisition time.

4.3.3 Setup of Kaleidoscope System

Following is a description of the setup of the key components of the kaleidoscope system, and how these components relate to each other. While the setup is described according to a horizontal configuration, as is implemented in this research, the relationships between the components would be the same for a vertical configuration.

1. The projector is set up to ensure that it projects a rectangular field of illumination. This is to ensure that the relative dimensions of the projected image align with those of the original image on the computer and are not distorted.

2. The projector is positioned parallel to the blank wall, at a distance away from the wall of at least the combined length of the particular kaleidoscope and surface sample used. The beam-splitter is set horizontally at an angle of 45 degrees relative to the blank wall and the projector, with this orientation allowed to be adjusted slightly by a couple of degrees

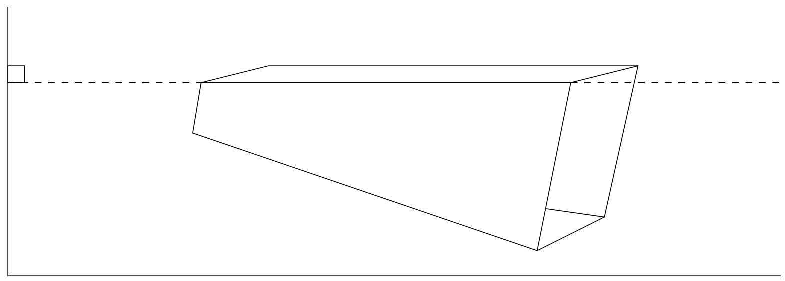


Figure 4.2: Optimal setup for tapered kaleidoscope

Roof of kaleidoscope is parallel to the floor plane.

if necessary to ensure that the deflected light from the projector remains rectangular and is not skewed.

3. The kaleidoscope is positioned perpendicular to the projector, between the beam-splitter and the blank wall (refer to Figure 4.3). This position is adjusted both horizontally and vertically until the greatest number of polygons illuminate the back wall behind the kaleidoscope by light directed through the kaleidoscope via the beam-splitter. Each of these generated polygons represents a different illumination angle, corresponding to the reflections available within the particular kaleidoscope configuration. Care must be taken to minimise both the overlap of these generated polygons and the space between them, while maximising the number of visible levels of reflection.
   It has been found that in the case of tapered kaleidoscopes, the optimal kaleidoscope setup (that is with the maximum number of levels of reflection with minimum amount of overlap or space between the polygons) occurs when the roof of the kaleidoscope is parallel to the floor plane, as shown in Figure 4.2.
   The kaleidoscope must be placed behind the path of the projector to prevent extra illumination from entering the kaleidoscope.

4. Finally, the camera is positioned behind the beam-splitter, and directed through the kaleidoscope. The positioning of the camera is critical. In order for the camera to have as complete a view as possible of the image produced by the kaleidoscope, it must be positioned as close to the beam-splitter as possible. However an inevitable problem is that the slanted angle of the beam-splitter restricts the positioning of the camera. As a result the

view captured by the camera is compromised.

4.3.4 Capturing BTF data

1. The illumination program (described in Section 4.3.2) is fed as input into the projector. The matte black sheet is placed behind the beam-splitter on the wall facing the projector, to absorb as much of the remaining light transmitted through the beam-splitter as possible. Light is projected through the projector and redirected via the beam-splitter through the empty kaleidoscope so that it illuminates the wall behind the kaleidoscope.
   The vertices of each available illumination angle are manually selected with a mouse by studying the polygons of light illuminated on the wall behind the kaleidoscope. Each selected polygon is stored in an array within the program for later retrieval.

2. The sample is positioned behind the kaleidoscope and the room is blackened. As the recorded array of polygons is traversed one at a time, images through the kaleidoscope are captured by the stationary digital camera. Each polygon traversed defines a different illumination condition.

4.3.5 Building up a BTF Database

1. For each digital image captured through the kaleidoscope, the individual reflected images (being unique view/illumination pair) are cut up and oriented by means of a image manipulation software tool so as to align with the sample. This reorientation is required so that the view/illumination pairs that build up the BTF database correspond to each other. By example, Figure 4.4 shows how each image must be oriented in the case of a four-sided kaleidoscope for the first two levels of reflection. The reorientation pattern required for a particular kaleidoscope configuration can be easily derived for any configuration by examining the reflections within the kaleidoscope.

2. The correctly oriented BTF data is then stored in a two-dimensional database of view/illumination direction pairs. The polar coordinate view and illumination angles for each pair can be calibrated by a simple geometric calculation due to the taper angle being known. Since these angles will cover a range for each view/illumination pair, it is a useful simplification to calculate the angles at the midpoint of each image, as is the approach taken in this research. (Refer to Figure 5.3.)

Figure 4.3: Setup for the Implementation of the Kaleidoscope System

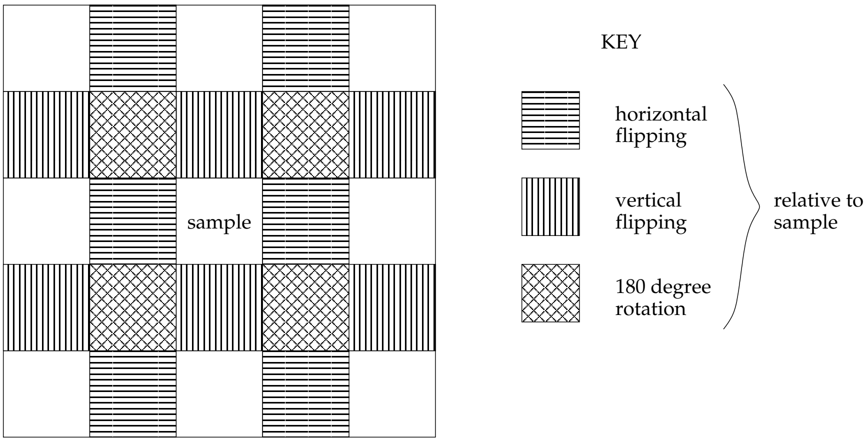


Figure 4.4: Diagram of the mirroring effect of a four-sided kaleidoscope configuration for the first two levels of reflection.

4.4 Future Optimisations

The experimental procedure described earlier (Section 4.3) could be optimised in the future in two ways. The first optimisation involves simplifying the setup of the system. The second optimisation involves reducing the time taken to process the acquired data.

4.4.1 Field of View

The beam-splitter is a relatively weak design feature within the system. It complicates the system, and can potentially detract from the system's efficiency and accuracy. It would be beneficial to design a way for both the camera and projector to occupy the same field of view without requiring the projector to be offset to one side and the illumination deflected into the kaleidoscope. If a camera and projector pair could be used whose lenses lie on the opposite extremes relative to one other, the pair could be positioned side-by-side, requiring only a simple calibration to calculate the effective incident angles of each.

4.4.2 Automation of Extraction Process

The process of manually selecting and reorienting each individual captured image of the sample before storing them in a database is extremely time-consuming and involved. It would be a significant optimisation to automate as much of the process as possible. A program could be written that requires only the selection of vertices of the polygons from only a single captured image through the kaleidoscope, under a single illumination condition. Since the position of the camera remains constant while the illumination condition changes, the relative positioning of each reflected polygon remains the same for each captured digital image captured. This coherence of relative position can be utilised to automate the process of extracting each reflected image of the sample.

The program could be extended to then automatically perform the required transformations on the images requiring reorientation. The particular transformation to be performed could be decided by analysis of the relative positioning of the polygon in the extracted array of images. The program could then be designed to automate the storing of these correctly oriented images in the database format.

4.5 Summary

This chapter has described the second and final phase in the investigation of the kaleidoscope technique for reflectance measurement, by detailing the physical implementation from the initial derivation of parameters through to the storing of the obtained BTF data. It has highlighted various practical issues and suggested future optimisations to the technique.

The results yielded from both these simulation and implementation phases are presented in the next chapter.

Chapter 5

Results

Each of the simulation and physical implementation phases have yielded results that provide deeper insight into the reflective properties of kaleidoscopes and the extent to which they can be used in obtaining accurate reflectance measurements of surfaces. This chapter presents these results and examines what they mean in terms of revealing areas for optimisation of the technique and potential pitfalls to be avoided.

5.1 Simulated versus Real Kaleidoscope Configurations

The results obtained in the simulation phase regarding the effects of various kaleidoscope configurations have been conclusively confirmed in the physical construction of the kaleidoscopes.

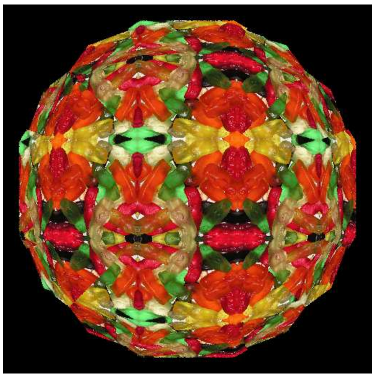
Figure 5.1 shows a comparison of views through simulated versus real kaleidoscopes. The figure clearly illustrates the tiling effect of a non-tapered configuration (Figure 5.1a,b), the appearance of a virtual sphere in a tapered configuration (Figure 5.1c,d), and the rings of reflection produced in a cylindrical configuration (Figure 5.1e,f). These direct correspondences between the images confirm the reliability of the simulated kaleidoscopes and thereby confirm too the observations made concerning the effects of the various kaleidoscope parameters.

5.1.1 Novel Configurations

The design of the novel configurations of the reflective base and cylinder are of particular significance regards optimising and enhancing the kaleidoscope technique for reflectance measurement. Each of these have been shown through simulation to result in a more dense supply of incident angles to the sample.

(a) Non-tapered Simulated

(b) Non-tapered Real



(c) Tapered Simulated

(d) Tapered Real

(e) Cylindrical Simulated

(f) Cylindrical Real

Figure 5.1: Views through the Kaleidoscopes: Simulated Versus Real

5.2 Kaleidoscope Implementation

The strategy derived by [Bangay and Radloff 2004] that is based on observations made by the simulation of various kaleidoscope configurations, has been successfully implemented to design the structural parameters of five kaleidoscopes. Each of these have been optimised to enable rich BTF data acquisition. The physical implementation of these kaleidoscopes has included an alternative approach to the implementation of the kaleidoscope technique, by constructing two of the kaleidoscopes from glass coated with aluminium. This alternative means of construction is advantageous in its giving rise to front-surface reflection. The front-surface reflection results in reflected images that are of high visual clarity and have less significant attenuation in resolution with each successive layer of reflection (refer to Figure 5.1f).

5.3 Full Implementation of the Kaleidoscope System

A full implementation of the kaleidoscope system has facilitated a close investigation into practical aspects of the technique. The investigation has revealed the significant role played by hardware factors, and how hardware can significantly detract from the quality of the BTF information obtained. An awareness and understanding of these factors can allow these negative effects to be considerably minimised, leading to an improvement in the measuring of surface reflectance.

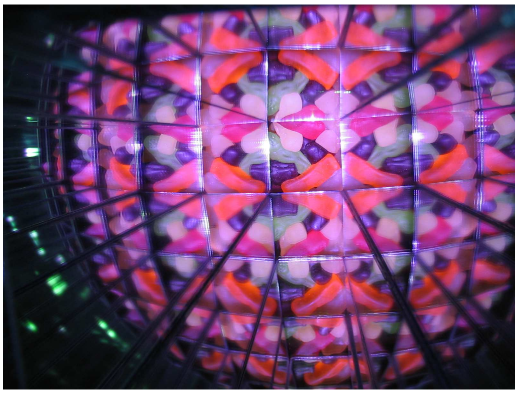
5.3.1 Acquired BTF Database

The system has been fully implemented for the four-sided tapered kaleidoscope configuration, measuring the reflectance of a surface sample of jellybabies. The results are impressive. A BTF database comprising 585 view/illumination pairs has been obtained, consisting of 23 illumination and 25 viewing angles (refer to Figure 5.3).

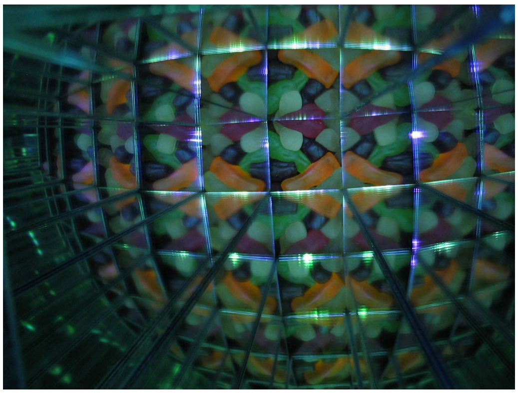
The four-sided configuration has allowed for a rich dataset of view/illumination pairs, exceeding that obtained by [Han and Perlin 2003] who implemented a three-sided kaleidoscope configuration.

5.4 Issues regarding Physical Implementation

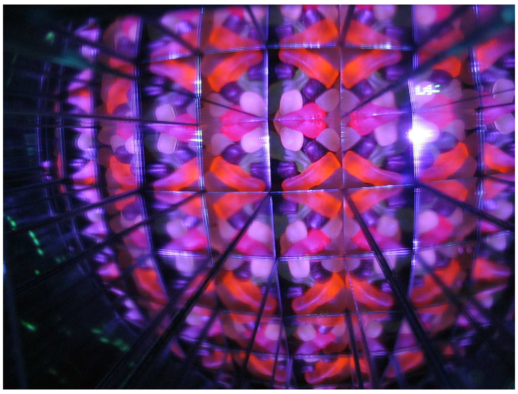
The comparison of real versus simulated images (Figure 5.1) reveals a loss in resolution in the real images that is by no means negligible. This can be attributed to a number of factors, each



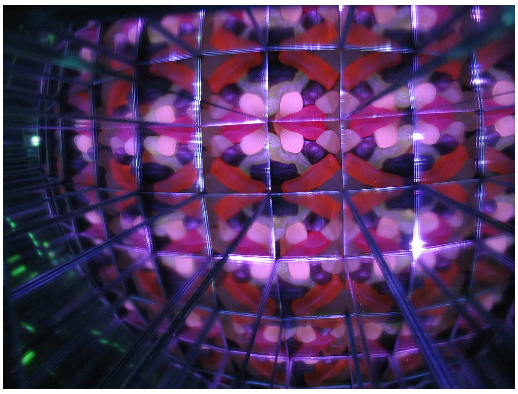
(a) 0, 0



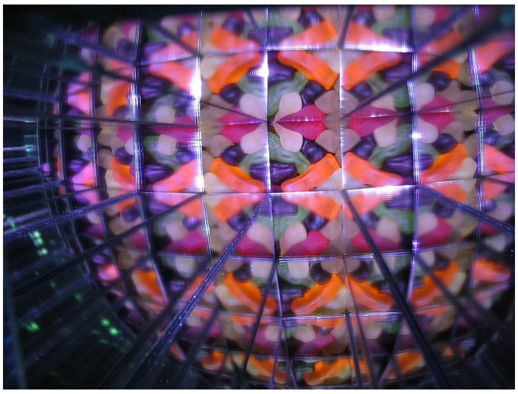
(b) 51, -45



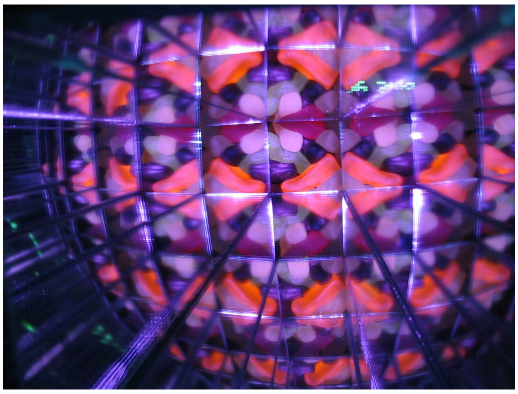
(c) 36, 90



(d) 41, -157.5



(e) 52, 45



(f) 52, -135

Figure 5.2: View through the tapered four-sided kaleidoscope under six different illumination conditions (elevation, azimuth angles)

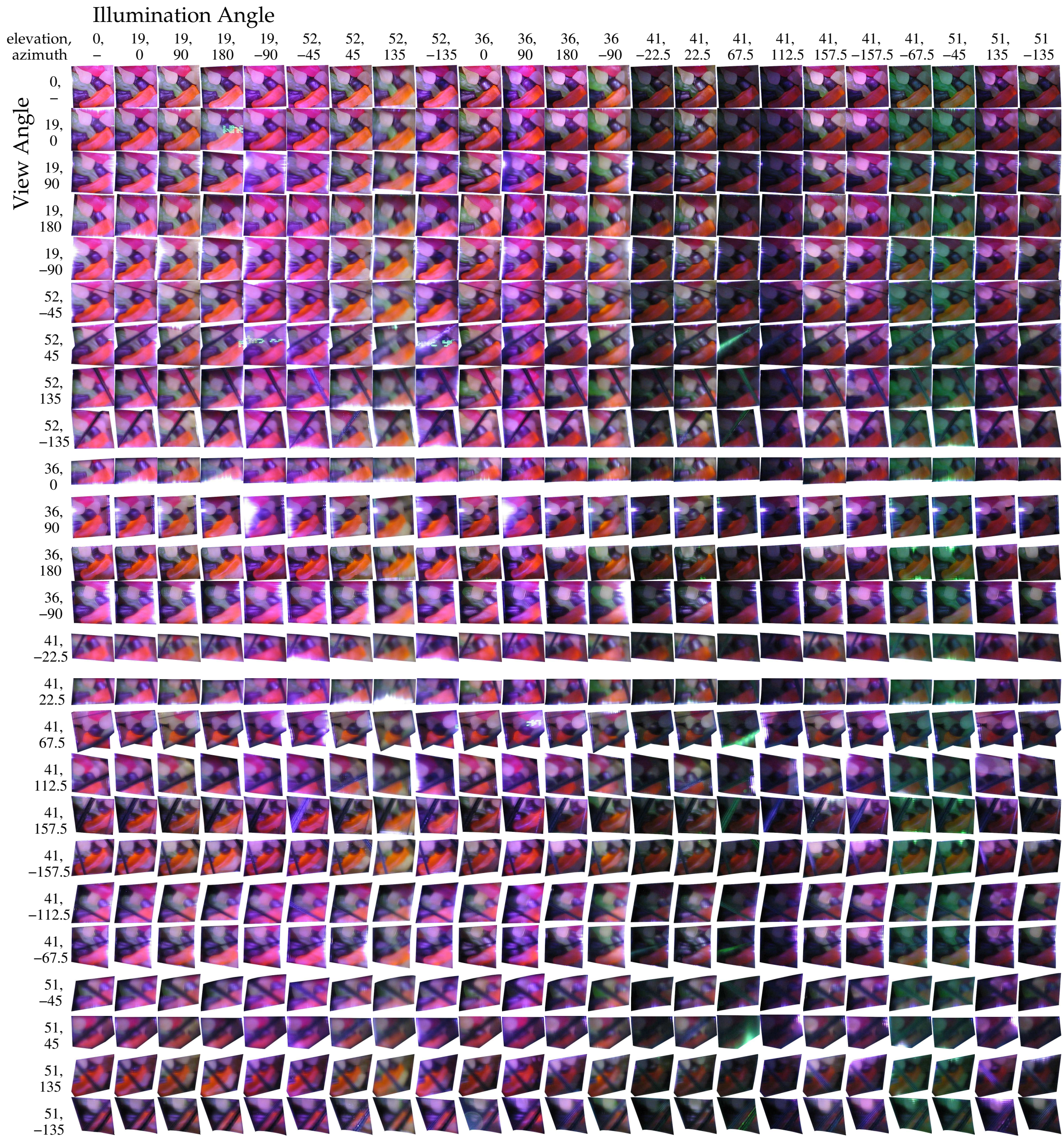


Figure 5.3: BTF Database of Real-World Surface Sample of Jellybabies

directly related to hardware. These include imprecision in the construction of the kaleidoscopes, automatic camera focus features, leaking light and dust.

The slight asymmetry of the kaleidoscopes due to the imprecision in the cutting of the mirrors has meant that the reflected images produced by the kaleidoscopes in this research are not perfectly registered to each other. This has had a negative effect on the images produced within the kaleidoscopes that increases with each successive layer of reflection. This accounts for the distortion of the reflected images BTF database (shown in Figure 5.3) that correspond to the second layer of reflection.

It is suspected that the colour-cast seen on many of the images in the database (Figure 5.3) is due to the light being directed through the kaleidoscope via the beam-splitter. This gives further justification to the redesigning of the system as discussed in Section 4.4.1.

5.5 Summary

The simulation phase has been shown to have produced reliable results. The subsequent full implementation of the kaleidoscope technique has been successful, not only in yielding a rich BTF database, but also in highlighting practical issues pertaining to the technique that could be used to improve the measurement process in the future.

Chapter 6

Conclusion

6.1 Conclusions

The use of kaleidoscopes in obtaining BTF samples of real-world surfaces has been investigated through both simulation and physical 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.

The technique has been confirmed to be of merit, particularly through the obtaining of a rich BTF database of a real-world surface, by very economical means.

Hardware is the inherent limiting factor. Awareness of the particular limiting factors can be used to improve the accuracy of the technique. In particular, aluminium-coated kaleidoscopes have been shown to produce clearer reflected images than the kaleidoscopes built using back-surface mirrors. A horizontal configuration can also be used to simplify the design of the system in the case of cohesive surface samples.

6.2 Contributions

This thesis is a detailed investigation into the real-world surface BTF measurement technique proposed by Han and Perlin, with particular focus on its practical implementation, its advantages over alternative techniques and its limitations. The research has yielded a rich BTF database of a surface sample of jellybabies. The database comprises 585 images of the sample, making it one of the largest recorded BTF databases to date.

6.3 Future Work

- The technique could be implemented for the reflective base and cylindrical kaleidoscope configurations.
- The extensibility of technique for measuring BSSTF (as discussed in Section 3.4) could also be investigated by means of a practical implementation.

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