A SURVEY OF IMAGE-BASED RELIGHTING TECHNIQUES

First author name
Organization name
Organization address
Email: someone@some.place

Second author name
Organization name
Organization address
Email: someoneelse@some.place

Keywords: Image based Techniques, Relighting, Survey

Abstract: Image-based Relighting (IBRL) has recently attracted a lot of research interest for its ability to relight real objects or scenes, for novel illuminations that were captured in natural/synthetic environments. Complex lighting effects such as subsurface scattering, interreflection, shadowing, mesostructural self-occlusion, refraction and other relevant phenomena can be generated using IBRL. The main advantage of Image-based Graphics is that the rendering time is independent of scene complexity as the rendering is actually a process of maipulating image pixels, instead of simulating light transport. The goal of this paper is to provide a complete and systematic overview of the research in Image-based Relighting. We observe that essentially all IBRL techniques can be broadly classified into three categories, based on how the scene information is captured: Reflectance function based, Basis function based, and Plenoptic function based. We discuss the charecteristics of each of these categories and their representative methods. We also discuss about sampling density and light source type, relevant issues of IBRL.

1 INTRODUCTION

Image-based Modeling and Rendering(IBMR) synthesizes realistic images from pre-recorded images without a complex and long rendering process as in traditional geometry-based Computer Graphics. The major drawback of IBMR is rigidity. Once the scene is captured as images, these images are no longer modifiable. Most previous techniques in IBMR assumes that the lighting condition is fixed and the surface is Lambertian. Obviously, these assumptions cannot fully satisfy the computer graphics needs since illumination modification is a key operation in Computer Graphics. The ability to control illumination of the modeled scene, enhances the three-dimensional illusion, which in turn improves viewers' understanding of the environment. If the illumination can be modified by relighting the images, instead of rendering the geometric models, the time for image synthesis will also be independent of the scene complexity. By relighting, we mean generating desired images with novel illumination conditions from pre-rendered images. This saves the artist/designer enormous amount of time in fine tuning the illumination conditions to achieve realistic atmospheres. The motive of Image-based Relighting(IBRL) (Fig. 1) is to modify the illumination in an interactive fashion while preserving the correct visual appearance. Applications range from global illumination and lighting design to augmented and mixed reality, where real and virtual objects are combined with consistent illumination. Two major motivations for IBRL are :

- Variability allows the user to illuminate only interesting portions of the scene improving recognition and satisfaction.
- It brings us a step closer to realizing the use of image-based entities as the basic rendering primitives/entities.

For didactic purposes, we classify the various image-based relighting techniques into three categories, namely: Reflectance-based Relighting, Basis Function-based Relighting, Plenoptic Function-based Relighting. These categories should be actually viewed as a continuum rather absolute discrete ones, since there are techniques that defy these strict categorizations.

Reflectance Function-based Relighting techniques explicitly estimate the reflectance field at each visible point of the object or scene. This is also known as the Bidirectional Reflectance Distribution

(a) (b) (c)

Figure 1: Image based Relighting

Function(BRDF) (Kajiya, 1985). It is defined as the ratio of the incoming to the outgoing radiance. Reflectance estimation can be achieved by calibrated light sources, where the setup of lights provide full control of the direction of incident illumination. For uncontrolled illumination, one iteratively fits a reflectance model to the measured data, followed by optimizing for each point of the scene independently. Some techniques recover the illumination information using images of light probes in the scene. These techniques then apply novel illumination conditions to the scene and use the reflectance function calculated, for generating synthetic novel illumination effects.

Basis Function-based Relighting techniques take advantage of the linearity of the rendering operator, with respect to illumination, for a fixed scene. These techniques address the problem of efficient dynamic re-rendering of a scene under scene changes. Rerendering is accomplished via linear combination of a set of pre-rendered "Basis" images. These techniques, for the purpose of computing a solution determine a time-independent basis - a small number of global solutions - that suffice to simulate all the effects. Techniques which enumerate all the viewing directions and permutes with all possible illumination conditions tend to go out of hand quickly, as far as the data size is concerned. So, one generates a "generative" structure of the set of image under varying illumination and viewpoint.

Plenoptic Function-based Relighting techniques basically deal with the computational model that many image-based techniques are based on, the "Plenoptic Function"(Adelson and Bergen, 1991). The original plenoptic function is very general. All the illumination and the scene changing factors are aggregated in a single "time" parameter. So most research concentrates on view interpolation and leaves the time parameter untouched. The time parameter (scene and illumination) is usually assumed constant for simplicity. Therefore techniques that are based on the plenoptic function frequently assume that the illumination and the scene are unchanged. The techniques which adopt a plenoptic function-based relighting extract out the illumination component from the aggregate time parameter, and facilitates relighting of scenes.

The remainder of the paper is organized as follows: Section 2, Section 3 and Section 4 discusses, in detail, each of the three relighting categories, as mentioned above, along with their representative methods. In Section 5, we discuss some of the other relevant issues of relighting like, Light Sources, Sampling density. We then provide some directions of future research in Section 6. Finally, we provide our concluding remarks in Section 7.

2 REFLECTANCE FUNCTION

A reflectance field is the measurement of how materials reflect light, or more specifically, how they transform incident illumination into radiant illumination.

The *bidirectional reflectance distribution function* (BRDF) (Kajiya, 1985) is the most general form of representing surface reflectivity. A better representation of the reflectance properties is the *bidirectional subsurface scattering reflectance distribution function* (BSSRDF) (Nicodemus et al., 1977). As introduced by (Debevec et al., 2000), the reflectance function R is an 8D function. It determines the light transfer between light entering a bounding volume at a direction and position $\psi_{incident}$ and leaving at $\psi_{exitant}$:

$$\mathbf{R} = \mathbf{R}(\psi_{incident}, \psi_{exitant})$$

The calculated reflectance functions can be used to compute relit images of the objects, lit with all-frequency illumination. The computation for each relit pixel is reduced to multiplying corresponding coefficients of the reflectance function and the incident illumination.

$$\mathbf{L}_{exitant}(\omega) = \int_{\Omega} \mathbf{R}\mathbf{L}_{incident}(\omega)d\omega$$

where, Ω is the space of all light directions over a hemisphere centered around the object to be illuminated ($\omega \in \Omega$).

The reflectance functions are sampled from real objects by illuminating the object from a set of directions while recording photographs from different viewpoints. Each pixel in a photograph is a sample of the reflectance function. Thus, for every viewing direction, each pixel in an image stores its appearance under all illumination directions.

We classify the estimation of reflectance functions into four different categories:

1. **Forward**
2. **Inverse**
3. **Hybrid**
4. **Pre-computed radiance transport**

In the following section, we describe each of these categories, along with their corresponding representative techniques.

2.1 FORWARD

The forward methods of estimating reflectance functions sample these functions exhaustively and tabulate the results. For each incident illumination, they store the reflectance function weights for a fixed observed direction.

The forward method of estimating reflectance functions can further be divided into two categories, on the basis of illumination information provided:

1. **Known Illumination**
2. **Unknown Illumination**

In the following section, we describe each of the two above mentioned categories and discuss their representative techniques.

2.1.1 KNOWN ILLUMINATION

These techniques incorporates illumination information in the setup. The user is provided full control over the direction, position and type of incident illumination. This information is directly used for finding the reflectance properties of the scene.

(Debevec et al., 2000) use the highest resolution incident illumination with roughly 2000 directions and construct a reflectance function for each observed image pixel from its values over the space of illumination directions (Fig. 2). (Masselus et al., 2004) sample the reflectance functions from real objects by illuminating the object from a set of directions while recording the photographs. They reconstruct a smooth and continuous reflectance function, from the sampled reflectance functions, using the multilevel B-spline technique. The reflectance functions and

(Masselus et al., 2003) measure six-dimensional slices of the eight-dimensional reflectance field by varying both the position and the direction of the incident illumination for a fixed viewpoint. They exploit the richness in the angular and spatial variation of the incident illumination. On the other hand, [(Wong et al., 1997), (Wong et al., 2001)] propose a concept of *apparent-BRDF* to represent the outgoing radiance distribution passing through the pixel window on the image plane. By treating each image as an ordinary surface element, the radiance distribution of the pixel under various illumination conditions is recorded in a table. (Wong et al., 2001) incorporate this table in the panoramic data structure for interactive relighting of pan aromas.

(Malzbender et al., 2001) store the coefficients of a biquadratic polynomial for each texel, thereby improving upon the compactness of the representation, and uses it to reconstruct the surface color under varied illumination conditions.

Some more interesting forward techniques of reflectance functions estimation are provided in [(Li et al., 2002), (Koudelka et al., 2001), (Boivin and Gagalowicz, 2001)].

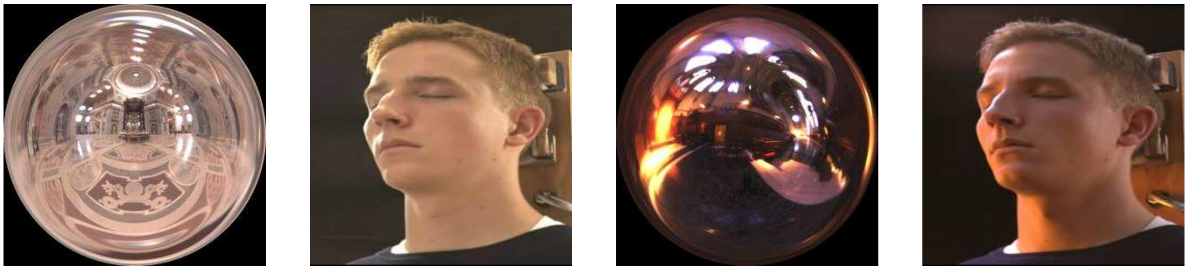
2.1.2 UNKNOWN ILLUMINATION

The incident illumination information is not specified as an input to the reflectance function estimation. These techniques indirectly compute the incident illumination information (direction and position of light sources) by using light probes such as metallic spheres, mirrored balls, black snooker balls and eyes of a human subject in scene. This information is then used for reflectance estimation of the scene.

(Nishino and Nayar, 2004) use eyes for relighting. They compute a large field of view of the illumination distribution (in the form of an environment map) of the environment surrounding a person, using the characteristics of the imaging system formed by the cornea of an eye and a camera viewing it. Their assumption of a human subject in the scene, at all times, may not be practical though. (Lensch et al., 2003) used six steel spheres to recover the light source positions. They fit an average BRDF function to the different materials of the objects in the scene.

(Shim and Chen, 2005) propose a statistical approach for estimating the surface reflectance function (SRF). Their algorithm has two stages: in the first stage they collect the true SRF statistics from synthetic images and apply PCA on them. PCA results show that the most efficient lighting patterns are the eigen vectors of the covariance matrix of the SRFs. In the second stage, they use these lighting patterns to acquire basis images for relighitng.

(Debevec, 2001) and (Debevec, 2002) use specific lighting devices for acquiring the lighting information and then sampling the reflectance functions of the scene under different illumination conditions from a



(a) Illumination used for Fig 2(b) | (b) Relit Image 1 | (c) Illumination used for Fig. 2(d) | (d) Relit Image 2

Figure 2: Metallic spheres (light probe) used for determining Illumination information (Debevec et al., 2000)

fixed viewpoint.

2.2 INVERSE

The inverse problem can be then be stated as follows:

Given an observation, what are the weights and parameters of the basis functions that best explain the observation?

Inverse methods observe an output and compute the probability that it came from a particular region in the incident illumination domain. The incident illumination is typically represented by a bounded region, such as an environment map, which is modeled as a sum of basis functions [rectangular (Zongker et al., 1999) or Gaussian kernels (Chuang et al., 2000)]. They capture an *environment matte*, which in addition to capturing the foreground object and its traditional matte, also describes how the object refracts and reflects light. This can then be placed in a new environment, where it will refract and reflect light from that scene. Techniques [(Matusik et al., 2004), (Peers and Dutre, 2003)] have been proposed which progressively refine the approximation of the reflectance function with an increasing number of samples.

2.3 HYBRID

For a more accurate reflectance estimation, (Matusik et al., 2002) combine a forward method (Debevec et al., 2000) for the low-frequency surface reflectance function and an inverse method, environment matting (Chuang et al., 2000), for the high-frequency surface reflectance function. This is used for capturing all the complex lighting effects, like high-frequency reflections and refractions. Finally both the high and low reflectance fields are used for producing accurate relighting and compositing.

2.4 PRE-COMPUTED RADIANCE TRANSPORT

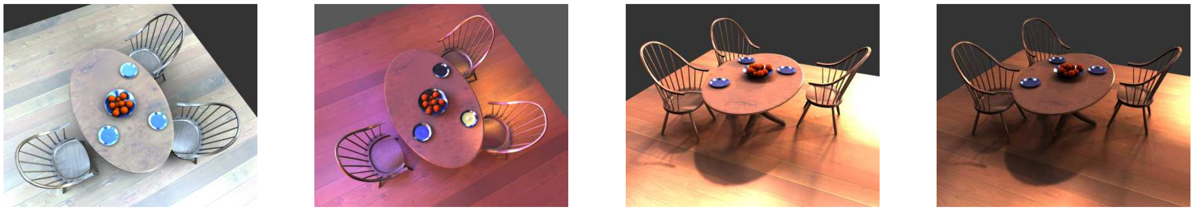
A global transport simulator creates functions over the object's surface, representing transfer of arbitrary incident lighting, into transferred radiance which includes global effects like shadows and interreflections from the object onto itself. It also enables captures occlusion and scattering effects of light. When the actual lighting condition is substituted at run-time, the resulting model provides global illumination effects like soft shadows, interreflections and caustics.

The radiance transport is pre-computed using a detailed model of the scene (Sloan et al., 2002). To improve upon the rendering performance, the incident illumination can be represented using spherical harmonics [(Kautz et al., 2002), (Ramamoorthi and Hanrahan, 2001), (Sloan et al., 2002)] or wavelets (Ng et al., 2003). The reflectance field, stored per vertex as a transfer matrix, can be compressed using PCA [(Sloan et al., 2003)] or wavelets (Ng et al., 2003).

(Ng et al., 2004) focuses on relighting based on pre-computed radiance transport for changing illumination and viewpoint, while including all-frequency shadows, reflections and lighting (Fig. 3). They propose a novel technique of factorizing the visibility and the material properties, followed by relighting using triple product integrals at each vertex, involving the lighting, viewpoint and BRDF.

3 BASIS FUNCTION

In this section, we describe the representative techniques for relighting using basis functions. In these methods, the luminous intensity distributions are decomposed into a series of basis functions, and illuminances are obtained by simply summing each luminance from light sources whose luminous intensity distribution obey each basis function.



(a) (b) (c) (d)

Figure 3: Image based Relighting: Pre-computed Radiance Transport (Ng et al., 2004)

Assuming multiple light sources, luminance at a certain point is obtained by calculating the luminance from each light source and summing them. In general, luminance calculation obeys the two following rules of superposition:

1. The image resulting from an additive combination of two illuminants is just the sum of the images resulting from each of the illuminations independently.
2. Multiplying the intensity of the illumination sources by a factor of α results in a rendered image that is multiplied by the same factor.

These techniques calculate luminance in the case of alterations in the luminous distributions and the direction of light sources. The luminous intensity distribution of a point light source is expressed as the sum of a series of basis distributions. Luminance due to light source whose luminance intensity distribution corresponds to one of the basis distributions is calculated in advance, and stored as basis luminance. Using the aforementioned property 1, the luminance due to the light source with luminous intensity distribution is calculated by summing the pre-calculated basis luminances corresponding to each individual basis distribution. Using property 2, the luminance due to a light source, whose luminous intensity distribution can be expressed as the weighted sum of the basis distributions, is obtained by multiplying each basis luminance with corresponding weights and summing them. Thus, once the basis luminance is calculated in the pre-process, the resulting luminance can be obtained quickly by calculating the weighted sum of the basis luminances.

3.1 ILLUMINANT BASIS

An appropriate basis set of Illumination functions is required for all these techniques. Some of the desirable properties for this set of functions are:

1. The basis functions should be general enough to for any light source one desires.
2. The number of basis functions should be small, since this corresponds to the number of basis images we must actually store and render.

3.2 REPRESENTATIVE BASIS FUNCTIONS

In this section, we classify the type of basis functions (used in Relighting) into five categories and also provide their corresponding representative methods.

1. Steerable Functions(Nimeroff et al., 1994).
2. Spherical Harmonics Function (Dobashi et al., 1995).
3. Singular Value Decomposition (Principal Component Analysis) [(Fuchs et al., 2005), (Georghiades et al., 2001), (Osadchy and Keren, 2001), (Hawkins et al., 2004)].
4. N-mode SVD: Multilinear Algebra of higher-order Tensors [(Vasilescu and Terzopoulos, 2003), (Furukawa et al., 2002), (Suykens et al., 2003), (Tong et al., 2002)].
5. Sampling Illumination Space [(Masselus et al., 2002), (Wenger et al., 2005), (Georghiades, 2003)].

4 PLENOPTIC FUNCTION

The appearance of the world can be thought of as the dense array of light rays filling the space, which can be observed by posing eyes or cameras in space. These light rays can be represented through the *plenoptic function* (from *plenus*, complete or full; and *optic*), proposed by Adelson and Bergen (Adelson and Bergen, 1991).

All basic visual measurements can be considered to characterize local change along one or more dimensions of a single function that describes the structure of the information in the light impinging on an observer. The plenoptic function represents the intensity of the light rays passing through the camera center at every location, at every possible viewing angle. The plenoptic function is a $7D$ function that models a $3D$ dynamic environment by recording the light rays at every space location (V_x, V_y, V_z), towards every possible direction (θ, ϕ), over any range of wavelengths (λ) and at any time (t), i.e.,

$$P = P^{(7)}(V_x, V_y, V_z, \theta, \phi, \lambda, t)$$

An image of a scene with a pinhole camera records the light rays passing through the camera's center-of-projection. They can also be considered as samples of the plenoptic function. Basically, the function tells us how the environment looks when our eye is positioned at $V{=}(V_x, V_y, V_z)$. The time parameter t actually models all the other unmentioned factors such as the change of illumination and the change of the scene. When t is constant, the scene is static and the illumination is fixed. Theoretically, the plenoptic function is continuous over the range of all parameters.

Plenoptic Function-based relighting techniques propose new formulations of the plenoptic function, which explicitly specify the illumination component. Using these formulations, one can generate complex lighting effects. One can simulate various lighting configurations such as multiple light sources, light sources with different colors and also arbitrary types of light sources (Section 5.1).

4.1 REPRESENTATIVE TECHNIQUES

(Wong and Heng, 2004) discusses a new formulation of the plenoptic function, *Plenoptic Illumination Function*, which explicitly specifies the illumination component. To relight images with various illumination configurations, they propose a local illumination model, which utilizes the rules of superposition.

(Lin et al., 2002) propose a representation of the plenoptic function, the *reflected irradiance field* for IBRL. The reflected irradiance field stores the reflection of surface irradiance as an illuminating point light source moves on a plane. With the reflected irradiance field, the relit object/scene can be synthesized simply by interpolating and superimposing appropriate sample reflections.

5 DISCUSSION

In this section, we discuss some of the relevant issues involving IBRL.

5.1 LIGHT SOURCE TYPE

Illumination is a complex and high-dimensional function of computer graphics. To reduce the dimensionality and to analyze their complexity and practicality, it is necessary to assume a specific type of light source. Two types of light sources most commonly used for purposes of Relighting:

1. **Directional Light Source (DLS)**: A direction light source emits parallel rays which do not diverge or become dimmer with distance. It is parametrized using only two variables (θ, ϕ), which denotes the direction of the light vector. The light vector of a DLS is constant throughout the space. The computations required for directional lights are considerably less than other types of light source because the angle at which any ray is approaching an object is always the same. For most surfaces lighted by a DLS, the degree of shading will be the same right across the surface. Using a DLS is more meaningful, because the captured pixel value in an image tells us what the surface elements behind the pixel window look like when all surface elements are illuminated by parallel rays in the direction of the viewing point. DLS serves well with synthetic object/scene where it is used to approximate the light coming from an extremely distant (infinite) light source. But it poses practical difficulties for capturing real and large object/scene. They can approximated with strong spotlights at a distance which greatly exceeds the size of the object/scene.
2. **Point Light Source (PLS)**: A Point light source shines uniformly in all directions, like an unshaded halogen bulb. A PLS emits light is all directions and the light's intensity decreases with the distance to the light source. A PLS is parametrized using three variables (P_x, P_y, P_z), which denote the 3D position of the PLS in space. As a result, the angle between the light source and the normals of the various affected surfaces can change dramatically from one surface to the next. In practical terms, this means that having more than one local light source in a scene incurs many more calculations since each vertex must have lighting calculations performed upon it for each local light in the scene. So for a point light source, one has to determine the depth map of the images using computer vision algorithms, which only provide approximations. Point light source are local light sources; i.e., they are usually close to the observer (as opposed to a directional light which is assumed to be infinitely far away) and so more practical for real and large objects/scenes.

5.2 SAMPLING

Sampling is one of the key issues of image-based graphics. It is a non-trivial problem because it involves the complex relationship among three elements: the depth and texture of the scene, the number of sample images, and the rendering solution. One needs to determine the *minimum sampling rate* for anti-aliased image-based rendering technique. Comparatively, very little research [(Chai et al., 2000), (Shum and Kang, 2000), (Zhang and Chen, 2004), (Zhang and Chen, 2001), (Zhang and Chen, 2003)] has gone into trying to tackle this problem.

In the context of IBRL, sampling deals with the illumination component for efficient and realistic relighting (Wong and Heng, 2004). (Lin et al., 2002) prove that there exists a *geometry-independent* bound of the sampling interval, which is analytically bound to the BRDF of the scene. It ensures that the intensity error in the relit image is smaller than a user-specified tolerance. This eliminates noticeable artifacts in the relit images.

6 FUTURE DIRECTIONS

In IBRL, a lot of research is yet to be done. In this section, we mention some of the directions of future work.

1. **Efficient Representation**: A lot of research has gone into finding more accurate and efficient representations of a scene, which capture all the complex phenomenas of lighting and reflectance functions. BRDF function-based IBRL techniques require huge number of samples to accurately estimate a reflectance function. Most techniques, for practical purposes, consider low-frequency components, which compromises with the visual quality of the rendered image. Almost all Basis function-based techniques also require a number of basis images for relighting. Variability in terms of viewpoint and illumination leads to huge data sets, which further incurs huge computational costs. One of the other areas, which deserve considerable investigation, is IBRL for real and large environments.
2. **Sampling**: Most techniques do not deal with the *minimum* sampling density required for anti-aliased IBRL. (Lin et al., 2002) discusses about a geometry-independent sampling density based on *radiometric* tolerance. Though this serves our purpose of efficient sampling of certain scenes, what we need is a *photometric tolerance*, which takes into account the response function of human vision. (Dumont et al., 2005) discusses about the psychophysical quality scale for realistic IBRL of glossy surfaces.
3. **Compression**: No matter how much the storage and memory increase in the future, compression is always useful to keep the IBRL data at a manageable size. A high compression ratio in IBRL relies heavily on how good the images can be predicted. The sampled images for IBL, usually have a strong inter-pixel and intra-pixel correlation, which needs to be harnessed for efficient compression. Currently, techniques such as spherical harmonics, vector quantization, direct cosine transform and spherical wavelets are used for compressing the datasets of IBRL, but all of these have their own inherent disadvantages.
4. **Dynamics**: Most IBRL techniques deal with static environments, in terms of change in geometry of the scene/object. With the development of high-end graphics processors, it is conceivable that IBRL can be applied to dynamic environments.

7 FINAL REMARKS

We have surveyed the field of Image=based Relighting. In particular, we observe that IBRL techniques can be classified into three categories based on how they capture the scene information: reflectance function-based, basis function-based and plenoptic function-based. We have presented each of the categories in detail, along with their corresponding representative methods. Relevant issues of IBRL like type of light source and sampling have also been discussed.

It is interesting to note the trade-off between geometry and images, needed for anti-aliased image-based rendering. Efficient representation, realistic rendering, limitations of computer vision algorithms and computational costs will motivate researchers to invent efficient Image-based relighting techniques in future.

REFERENCES

Adelson, E. H. and Bergen, J. R. (1991). The plenoptic function and the elements of early vision. *Computational Models of Visual Processing*.

Boivin, S. and Gagalowicz, A. (2001). Image-based rendering of diffuse, specular and glossy surfaces from a single image. In *SIGGRAPH '01: Proceedings of the 28th annual conference on Computer graphics and interactive techniques*, pages 107–116, New York, NY, USA. ACM Press.

Chai, J.-X., Chan, S.-C., Shum, H.-Y., and Tong, X. (2000). Plenoptic sampling. In *SIGGRAPH '00: Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, pages 307–318, New York, NY, USA. ACM Press/Addison-Wesley Publishing Co.

Chuang, Y.-Y., Zongker, D. E., Hindorff, J., Curless, B., Salesin, D. H., and Szeliski, R. (2000). Environment matting extensions: towards higher accuracy and real-time capture. In *SIGGRAPH '00: Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, pages 121–130, New York, NY, USA. ACM Press/Addison-Wesley Publishing Co.

Debevec, P. (2002). Image-based lighting. *IEEE Comput. Graph. Appl.*, 22(2):26–34.

Debevec, P., Hawkins, T., Tchou, C., Duiker, H.-P., Sarokin, W., and Sagar, M. (2000). Acquiring the reflectance field of a human face. In *SIGGRAPH '00: Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, pages 145–156, New York, NY, USA. ACM Press/Addison-Wesley Publishing Co.

Debevec, P. E. (2001). Pursuing reality with image-based modeling, rendering, and lighting. In *SMILE '00: Revised Papers from Second European Workshop on 3D Structure from Multiple Images of Large-Scale Environments*, pages 1–16, London, UK. Springer-Verlag.

Dobashi, Y., Kaneda, K., Nakatani, H., and Yamashita, H. (1995). A quick rendering method using basis functions for interactive lighting design. *Computer Graphics Forum*, 14(3):229–240.

Dumont, O., Masselus, V., Zaenen, P., Wagemans, J., and Dutre, P. (2005). A perceptual quality scale for image-based relighting of glossy surfaces. In *Tech. Rep. CW417, Katholieke Universiteit Leuven, June 2005*.

Fuchs, M., Blanz, V., and Seidel, H.-P. (2005). Bayesian relighting. In *Rendering Techniques*, pages 157–164.

Furukawa, R., Kawasaki, H., Ikeuchi, K., and Sakauchi, M. (2002). Appearance based object modeling using texture database: acquisition, compression and rendering. In *EGRW '02: Proceedings of the 13th Eurographics workshop on Rendering*, pages 257–266, Aire-la-Ville, Switzerland, Switzerland. Eurographics Association.

Georghiades, A. S. (2003). Recovering 3-d shape and reflectance from a small number of photographs. In *EGRW '03: Proceedings of the 14th Eurographics workshop on Rendering*, pages 230–240, Aire-la-Ville, Switzerland, Switzerland. Eurographics Association.

Georghiades, A. S., Belhumeur, P. N., and Kriegman, D. J. (2001). From few to many: Illumination cone models for face recognition under variable lighting and pose. *IEEE Trans. Pattern Anal. Mach. Intell.*, 23(6):643–660.

Hawkins, T., Wenger, A., Tchou, C., Gardner, A., Göransson, F., and Debevec, P. E. (2004). Animatable facial reflectance fields. In *Rendering Techniques*, pages 309–321.

Kajiya, J. T. (1985). Anisotropic reflection models. In *SIGGRAPH '85: Proceedings of the 12th annual conference on Computer graphics and interactive techniques*, pages 15–21, New York, NY, USA. ACM Press.

Kautz, J., Sloan, P.-P., and Snyder, J. (2002). Fast, arbitrary brdf shading for low-frequency lighting using spherical harmonics. In *EGRW '02: Proceedings of the 13th Eurographics workshop on Rendering*, pages 291–296, Aire-la-Ville, Switzerland, Switzerland. Eurographics Association.

Koudelka, M. L., Belhumeur, P. N., Magda, S., and Kriegman, D. J. (2001). Image-based modeling and rendering of surfaces with arbitrary brdfs. In *CVPR (1)*, pages 568–575.

Lensch, H. P. A., Kautz, J., Goesele, M., Heidrich, W., and Seidel, H.-P. (2003). Image-based reconstruction of spatial appearance and geometric detail. *ACM Trans. Graph.*, 22(2):234–257.

Li, Y., Lin, S., Kang, S. B., Lu, H., and Shum, H.-Y. (2002). Single-image reflectance estimation for relighting by iterative soft grouping. In *Pacific Conference on Computer Graphics and Applications*, page 483.

Lin, Z., Wong, T.-T., and Shum, H.-Y. (2002). Relighting with the reflected irradiance field: Representation, sampling and reconstruction. *Int. J. Comput. Vision*, 49(2-3):229–246.

Malzbender, T., Gelb, D., and Wolters, H. (2001). Polynomial texture maps. In *SIGGRAPH '01: Proceedings of the 28th annual conference on Computer graphics and interactive techniques*, pages 519–528, New York, NY, USA. ACM Press.

Masselus, V., Dutre;, P., and Anrys, F. (2002). The free-form light stage. In *EGRW '02: Proceedings of the 13th Eurographics workshop on Rendering*, pages 247–256, Aire-la-Ville, Switzerland, Switzerland. Eurographics Association.

Masselus, V., Peers, P., Dutre;, P., and Willems, Y. D. (2003). Relighting with 4d incident light fields. *ACM Trans. Graph.*, 22(3):613–620.

Masselus, V., Peers, P., Dutre, P., and Willems, Y. D. (2004). Smooth reconstruction and compact representation of reflectance functions for image-based relighting. In *Rendering Techniques*, pages 287–298.

Matusik, W., Loper, M., and Pfister, H. (2004). Progressively-refined reflectance functions from natural illumination. In *Rendering Techniques*, pages 299–308.

Matusik, W., Pfister, H., Ziegler, R., Ngan, A., and McMillan, L. (2002). Acquisition and rendering of transparent and refractive objects. In *EGRW '02: Proceedings of the 13th Eurographics workshop on Rendering*, pages 267–278, Aire-la-Ville, Switzerland, Switzerland. Eurographics Association.

Ng, R., Ramamoorthi, R., and Hanrahan, P. (2003). All-frequency shadows using non-linear wavelet lighting approximation. *ACM Trans. Graph.*, 22(3):376–381.

Ng, R., Ramamoorthi, R., and Hanrahan, P. (2004). Triple product wavelet integrals for all-frequency relighting. *ACM Trans. Graph.*, 23(3):477–487.

Nicodemus, F., Richmond, J., Hsia, J. J., Ginsberg, I. W., and Limperis, T. (1977). Geometric considerations and nomenclature for reflectance. In *NBS Monograph 160, National Bureau of Standards (US)*.

Nimeroff, J. S., Simoncelli, E., and Dorsey, J. (1994). Efficient Re-rendering of Naturally Illuminated Environments. In *Fifth Eurographics Workshop on Rendering*, pages 359–373, Darmstadt, Germany. Springer-Verlag.

Nishino, K. and Nayar, S. K. (2004). Eyes for relighting. *ACM Trans. Graph.*, 23(3):704–711.

Osadchy, M. and Keren, D. (2001). Image detection under varying illumination and pose. In *ICCV*, pages 668–673.

Peers, P. and Dutre, P. (2003). Wavelet environment matting. In *EGRW '03: Proceedings of the 14th Eurographics workshop on Rendering*, pages 157–166, Aire-la-Ville, Switzerland, Switzerland. Eurographics Association.

Ramamoorthi, R. and Hanrahan, P. (2001). An efficient representation for irradiance environment maps. In *SIGGRAPH '01: Proceedings of the 28th annual conference on Computer graphics and interactive techniques*, pages 497–500, New York, NY, USA. ACM Press.

Shim, H. and Chen, T. (2005). A statistical framework for image-based relighting. In *ICASSP*.

Shum, H.-Y. and Kang, S. B. (2000). A review of image-based rendering techniques. In *IEEE/SPIE Visual Communications and Image Processing (VCIP)*, pages 2–13.

Sloan, P.-P., Hall, J., Hart, J., and Snyder, J. (2003). Clustered principal components for precomputed radiance transfer. *ACM Trans. Graph.*, 22(3):382–391.

Sloan, P.-P., Kautz, J., and Snyder, J. (2002). Precomputed radiance transfer for real-time rendering in dynamic, low-frequency lighting environments. In *SIGGRAPH '02: Proceedings of the 29th annual conference on Computer graphics and interactive techniques*, pages 527–536, New York, NY, USA. ACM Press.

Suykens, F., Vom, K., Lagae, A., and Dutre, P. (2003). Interactive rendering with bidirectional texture functions. *Computer Graphics Forum*, 22(3).

Tong, X., Zhang, J., Liu, L., Wang, X., Guo, B., and Shum, H.-Y. (2002). Synthesis of bidirectional texture functions on arbitrary surfaces. In *SIGGRAPH '02: Proceedings of the 29th annual conference on Computer graphics and interactive techniques*, pages 665–672, New York, NY, USA. ACM Press.

Vasilescu, M. A. O. and Terzopoulos, D. (2003). Tensortextures. In *GRAPH '03: Proceedings of the SIGGRAPH 2003 conference on Sketches & applications*, pages 1–1, New York, NY, USA. ACM Press.

Wenger, A., Gardner, A., Tchou, C., Unger, J., Hawkins, T., and Debevec, P. (2005). Performance relighting and reflectance transformation with time-multiplexed illumination. *ACM Trans. Graph.*, 24(3):756–764.

Wong, T.-T. and Heng, P.-A. (2004). Image-based relighting: representation and compression. *Integrated image and graphics technologies*, pages 161–180.

Wong, T.-T., Heng, P.-A., and Fu, C.-W. (2001). Interactive relighting of panoramas. *IEEE Comput. Graph. Appl.*, 21(2):32–41.

Wong, T.-T., Heng, P.-A., Or, S.-H., and Ng, W.-Y. (1997). Image-based rendering with controllable illumination. In *Proceedings of the Eurographics Workshop on Rendering Techniques '97*, pages 13–22, London, UK. Springer-Verlag.

Zhang, C. and Chen, T. (2001). Generalized plenoptic sampling. In *Tech. Rep. AMP01-06, Carnegie Mellon Technical Report, 2001.*

Zhang, C. and Chen, T. (2003). Spectral analysis for sampling image-based rendering data. In *IEEE Transaction on Circuit, System on Video Technology 13, 11 (2003), 1038– 1050. 1.*

Zhang, C. and Chen, T. (2004). A survey on image-based rendering: Representation, sampling and compression. *SPIC 2004*, 19(1):1–28.

Zongker, D. E., Werner, D. M., Curless, B., and Salesin, D. H. (1999). Environment matting and compositing. In *SIGGRAPH '99: Proceedings of the 26th annual conference on Computer graphics and interactive techniques*, pages 205–214, New York, NY, USA. ACM Press/Addison-Wesley Publishing Co.