A SURVEY OF IMAGE-BASED RELIGHTING TECHNIQUES

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Abstract: Image-based Relighting (IBRL) has recently attracted a lot of research interest for its ability to relight real objects or scenes, from novel illuminations 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 manipulating 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/illumination information is captured: Reflectance function based, Basis function based, and Plenoptic function based. We discuss the characteristics of each of these categories and their representative methods. We also discuss about sampling density and types of light source, 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 its inherent rigidity. Most IBMR techniques assume that the static illumination condition. 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 (Fig. 1). If the illumination can be modified by relighting the images, instead of rendering the geometric models, the time for image synthesis will be independent of the scene complexity. This also saves the artist/designer enormous amount of time in fine tuning the illumination conditions to achieve realistic atmospheres. 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 :

- Allows the user to vary illuminance of the whole (or only interesting portions of the) scene improving recognition and satisfaction.
- Brings us a step closer to realizing the use of image-based entities as the basic rendering primitives/entities.

For didactic purposes, we classify image-based relighting techniques into three categories, namely: Reflectance-based, Basis Function-based, Plenoptic Function-based. 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 function at each visible point of the object or scene. This is also known as the Anisotropic Reflection Model (Kajiya, 1985) or the Bidirectional Surface Scattering Reflectance Distribution Function (BSSRDF) (Jensen et al., 2001). It is defined as the ratio of the outgoing to the incoming radiance. Reflectance estimation can be achieved with calibrated light setup, which provide full control of the incident illumination. A reflectance function is modeled with the data of the scene, cap-

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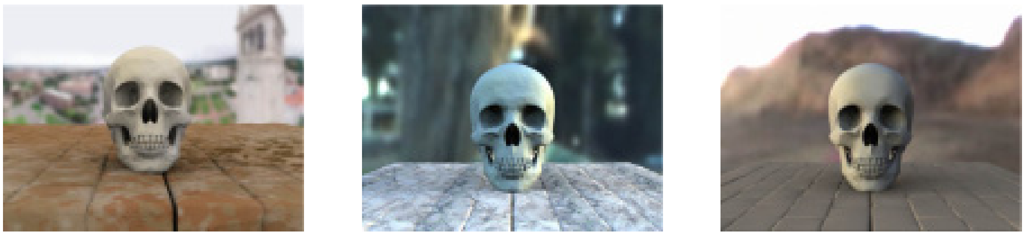


(a) (b) (c)

Figure 1: IBRL: The skull is relighted with the illumination of different environments. Notice that the lighted and dark parts of the skull correctly corresponds to the lighting in the scene.

tured under varying illumination and view direction. Techniques then apply novel illumination and use the reflectance function calculated, for generating novel illumination effects in the scene.

Basis Function-based Relighting techniques take advantage of the linearity of the rendering operator with respect to illumination, for a fixed scene. Re-rendering 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 "generative" global solutions - that suffice to simulate the set of images under varying illumination and viewpoint.

Plenoptic Function-based Relighting techniques are based on the computational model, the Plenoptic Function (Adelson and Bergen, 1991). The original plenoptic function aggregates all the illumination and the scene changing factors in a single "time" parameter. So most research concentrates on view interpolation and leaves the time parameter untouched (illumination and scene static). The plenoptic function-based relighting techniques extract out the illumination component from the aggregate time parameter, and facilitate relighting of scenes.

The remainder of the paper is organized as follows: Section 2, Section 3 and Section 4 discuss each of the three relighting categories, along with their representative methods. In Section 5, we discuss some of the other relevant issues of relighting. 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 function 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) (Nicodemus et al., 1977) is a general form of representing surface reflectivity. A better representation is the *Bidirectional Surface Scattering Reflectance Distribution Function* (BSSRDF) (Jensen et al., 2001), which model effects such as color bleeding, translucency and diffusion of light across shadow boundaries, otherwise impossible with a BRDF model. As introduced by (Debevec et al., 2000), the reflectance function R, an 8D function, determines the light transfer between light entering a bounding volume at a direction and position $\psi_{incident}$ and leaving at $\psi_{exitant}$:

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

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

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

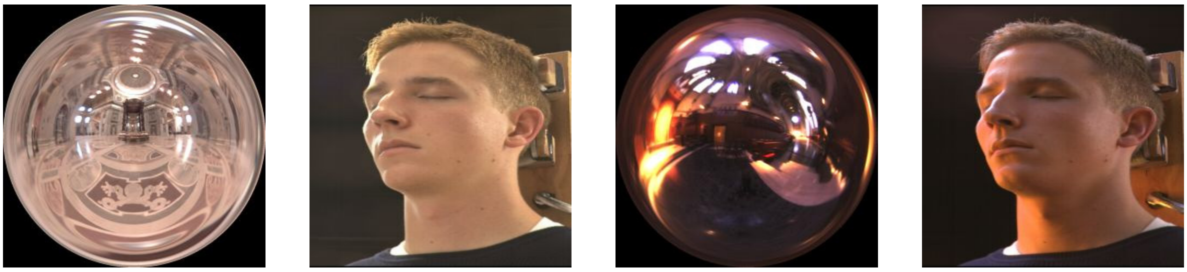
where, Ω is the space of all light directions over a hemisphere centered around the object to be illuminated ($\omega \in \Omega$). For every viewing direction, each pixel in an image stores its appearance under all illumination directions. Thus each pixel in an image is a sample of the reflectance function.

We classify the estimation of reflectance functions into three different categories: **Forward**, **Inverse** and **Pre-computed radiance transport**.

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, **Known** and **Unknown**.

The techniques with **known** illumination incorporate the information in their setup. The user is provided full control over the direction, position and



(a) Illumination 1 (b) Relit face using Illumination 1 of Fig 2(a) (c) Illumination 2 (d) Relit face using Illumination 2 of Fig 2(c)

Figure 2: Mirrored ball, representing illumination of an environment, used for relighting faces(Debevec et al., 2000).

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. (Masselus et al., 2003) exploit the richness in the angular and spatial variation of the incident illumination, and measure six-dimensional slices of the eight-dimensional reflectance field, for a fixed viewpoint. On the other hand, (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.

(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. (Koudelka et al., 2001) samples the surface's incident field to reconstruct a non-parametric apparent BRDF at each visible point on the surface. (Boivin and Gagalowicz, 2001) iteratively produces an approximation of the reflectance model of diffuse, specular, isotropic or anisotropic textured objects using a single image and the 3D geometric model of the scene.

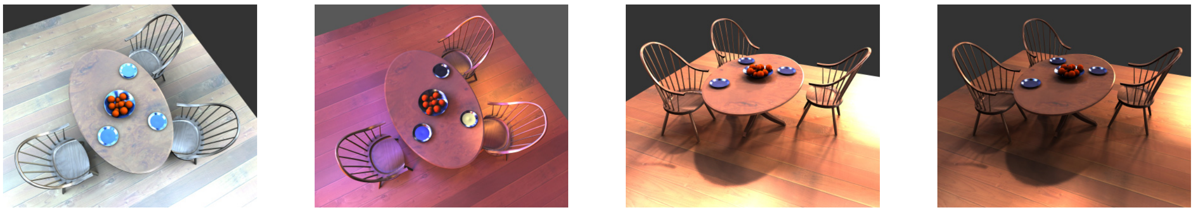
Techniques with **unknown** incident illumination information estimate it. (Nishino and Nayar, 2004) use eyes of a human subject and compute a large field of view of the illumination distribution of the environment surrounding a person, using the characteristics of the imaging system formed by the cornea 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. Some other techniques (Fuchs et al., 2005),(Tchou et al., 2004) indirectly compute the incident illumination information by using black snooker ball/non-metallic sphere. A very early work of IBRL, *Inverse Rendering* (Marschner, 1998), solves for unknown lighting and reflectance properties of a scene, for relighting purposes.

2.2 Inverse

The inverse problem of estimation of reflectance functions can be 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.

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, environ-



(a) View 1: Relit Scene 1 (b) View 1: Relit Scene 2 (c) View 2: Relit Scene 1 (d) View 2: Relit Scene 2

Figure 3: Pre-computed radiance transport based IBRL, depicting all-frequency shadows, reflections and highlights along with view variation (Ng et al., 2004).

ment 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.

2.3 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, self-interreflections, occlusion and scattering effects. When the actual lighting condition is substituted at run-time, the resulting model provides global illumination effects.

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 for changing illumination and viewpoint, while including all-frequency shadows, reflections and lighting (Fig. 3). They propose a novel triple product integrals based technique of factorizing the visibility and the material properties. Recently, (Wang et al., 2005) presented a method of relighting translucent objects under all-frequency lighting. They apply a two-pass hierarchical technique for computing non-linearly approximated transport vectors due to diffuse multiple scattering.

3 BASIS FUNCTION

Basis Function based techniques decompose the luminous intensity distributions into a series of basis functions, and illuminances are obtained by simply summing luminance from each light source whose luminous intensity distribution obey each basis function. 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 α.

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. Some desirable properties of a basis set of illumination functions are:

1. The basis functions should be general enough to form 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.

We classify the type of basis functions (used in Relighting) into five categories and 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) (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, 2004), (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 *optics*) (Adelson and Bergen, 1991). 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 scene.

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) discuss a new formulation of the plenoptic function, *Plenoptic Illumination Function*, which explicitly specifies the illumination component. They propose a *local illumination model*, which utilizes the rules of superposition for relighting under various lighting configurations. (Lin et al., 2002) on the other hand, propose a representation of the plenoptic function, the *reflected irradiance field*. 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 are:

1. **Directional Light Source (DLS)**: A DLS 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. For planar surfaces lighted by a DLS, the degree of shading will be the same right across the surface. The computations required for directional lights are therefore considerably less. Using a DLS is also more meaningful, because the captured pixel value in an image tells us what the surface elements behind the pixel window *actually 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 light source. But it poses practical difficulties for capturing real and large object/scene. They can be approximated with strong spotlights at a distance which greatly exceeds the size of the object/scene.
2. **Point Light Source (PLS)**: A PLS shines uniformly in all directions. Its 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 the presence of multiple light sources, this means that for every vertex, one has to determine the

direction of the light vector corresponding to a light source. This requires determination of the depth map of the images using computer vision algorithms, which though provide good approximations, make the lighting calculations computationally intensive. Point light source are usually close to the observer 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. 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, thus eliminating noticeable artifacts.

6 FUTURE DIRECTIONS

A lot of research remains to be done in IBRL. Some ideas are:

1. **Efficient Representation**: 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. Thus, a lot of research is required to find accurate and efficient representations of a scene, which capture all the complex phenomenas of lighting and reflectance functions. A related area which deserves 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) discuss 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) discuss the importance of 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/illumination information: Reflectance Function-based, Basis Function-based and Plenoptic Function-based. We have presented each of the categories 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 should motivate researchers to invent efficient Image-based Relighting techniques in future.

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