写実的な画像生成のための光源環境推定と物体表面の見えの標本化

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あらまし　一般に物体の見え方はシーンの光源環境の影響を受けて大きく変化することが知られており，物体認識および画像合成の分野では, 任意光源環境下での物体の見えを生成する技術の開発に注目が集まっている．本稿では, 実画像から撮影されたシーンの光学情報を獲得し写実的な画像を生成するイメージベースモデリング・レンダリングの研究分野において，実世界の複雑な光源環境を計測または推定する手法の提案と求められた光源環境下で物体の見えを現実感高くまた効率よく生成するための技術の開発を行う．

Illumination Recovery and Appearance Sampling for Photorealistic Rendering

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Abstract Conventional model-based rendering techniques synthesize the appearance of objects based on empirically or analytically given reflection models, and the geometric and the photometric information about the scene needs to be provided. Regardless of its great importance, the photometric information about a scene tends to be manually provided by a user. In order to make this input process more efficient and accurate, techniques for automatically providing the photometric models of a scene have been studied in the fields of both computer vision and computer graphics research. In particular, techniques that use a set of images of a scene provided under different viewing and/or lighting conditions for determining its geometric and photometric information are called image-based modeling. This thesis addresses two issues of image-based modeling for synthesizing photorealistic appearance of real objects under natural illumination conditions: capturing real-world illumination and modeling complex appearance of real objects for variable illumination.

1 Introduction

One of the important goals in computer graphics is achieving photographic realism of synthesized images. Techniques for rendering realistic computer graphics objects and seamlessly merging them into images of real scenes especially attract a great deal of attention in media industries such as film making, television broadcasting, game making, advertising, and so on.

For the purpose of synthesizing the realistic appearance of objects, conventional *model-based rendering* techniques have been intensively developed. Model-based rendering techniques synthesize the appearance of objects based on empirically or analytically given reflection models,[1] and the geometric and photometric information about the scene need to be provided: the shapes of objects in the scene, their surface reflectance properties, and the lighting condition of the scene where those objects are placed.

[1]Commonly used reflection models in the filed of computer vision and computer graphics include the Lambertian model, the Phong model, the Blinn-Phong model, the Torrance-Sparrow model, the Cook-Torrance model, the Beckmann-Spizzio model, the Ward model, and the Lafortune model.

Regarding the geometric information of a scene, the 3D shapes of objects are often manually produced by using well-designed CAD modelers, or a number of approaches have been developed for modeling more complex shapes that real objects have, e.g., range image merging techniques and 3D photography techniques. In contrast, providing the photometric information about a scene has been a difficult task.

Needless to say, the appearance of an object changes significantly depending on its surface reflectance properties: the appearance of a metallic surface is completely different from that of a matted surface even under the same lighting condition. In addition, the appearance of an object is greatly influenced by the lighting condition of the scene where it is placed. It is thus important to provide not only appropriate surface reflectance properties of an object in a scene but also natural illumination conditions of that scene so that realistic appearance of the object can be synthesized under the provided natural illumination conditions. Nevertheless, the photometric information about a scene tends to be manually provided by a user.

Since it is difficult to imagine the appearance of an object directly from reflectance parameters, the input process of manually specifying its reflectance properties is normally non-intuitive and thus time-consuming. As for providing lighting conditions, a scene generally includes both direct and indirect illumination distributed in a complex way, and it is also difficult for a user to manually specify such complex illumination distributions.

In order to overcome these difficulties, techniques for automatically providing the photometric information of a scene have been studied in the fields of both computer vision and computer graphics research. In particular, techniques that use a set of images of a scene provided under different viewing and/or lighting conditions for determining its geometric and photometric information are called image-based modeling. This thesis addresses two issues of image-based modeling for synthesizing photorealistic appearance of real objects under natural illumination conditions: capturing real-world illumination and modeling complex appearance of real objects for variable illumination. Regarding the first issue of capturing and modeling real-world illumination, both an image-based approach and an inverse lighting approach are studied.

2 Image-based Lighting for Measuring Real-World Illumination [39]

The image-based modeling techniques that measure real-world illumination conditions from photographically acquired images of a real scene are called *image-based lighting*. Image-based lighting techniques have been developed successfully with practical applications [11, 7, 3].

However, two difficulties in image-based lighting still remained to be solved: how to construct a geometric model of the scene, and how to capture a wide field of view of the scene. In this thesis, we confront these two difficulties and propose an efficient method for automatically measuring illumination distribution of a real scene by using a set of omni-directional images of the scene taken by a CCD camera with a fisheye lens.

Our proposed method automatically measures a radiance distribution of a real scene by using a set of omni-directional images taken by a CCD camera with a fisheye lens. There are three reasons why we use omni-directional images rather than images taken by a camera with an ordinary lens.

First, because of fisheye lens' wide field of view, e.g., 180 degrees, we can easily capture illumination from all directions from far less number of omni-directional images. Second, since a fisheye lens is designed so that an incoming ray from a particular direction is projected onto a particular point on an imaging plane, we do not have to concern ourselves with computing directions of incoming rays and considering a sampling frequency of the incoming rays. Third, we are also able to use the directions of the incoming rays for automatically constructing a geometric model of the scene with fisheye lens' wide field of view.

Based on our proposed omni-directional stereo algorithm, a geometric model of the scene is first

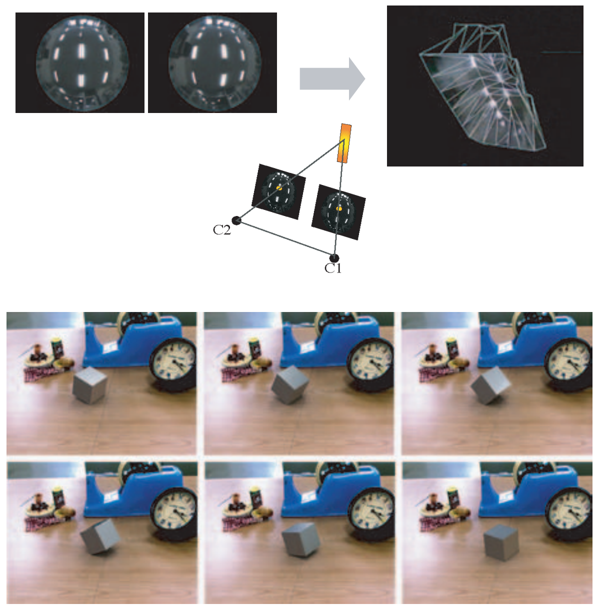

図 1: Measured illumination distribution based on the proposed omni-directional stereo algorithm and synthesized images under the captured illumination distribution.

constructed from a pair of omni-directional images taken from different locations. Then radiance of the scene is computed from a sequence of omni-directional images taken with different shutter speeds and mapped onto the constructed geometric model.

We refer to this geometric model with the radiance as a radiance map. The construction of a radiance map is necessary in order to compute a radiance distribution seen from any point in the scene. In other words, without constructing a radiance map, we can determine only the radiance distribution seen from the particular point where the omni-directional image was captured.

To overcome this limitation, our method measures the radiance distribution of the scene as a triangular mesh. Once a radiance map is constructed as a triangular mesh, an appropriate radiance distribution can be used for rendering a virtual object and for generating shadows cast by the virtual object onto the real scene wherever the virtual object is placed in the scene.

Figure 1 shows the obtained triangular mesh representing the radiance distribution as its color texture and synthesized images under the captured illumination distribution. In the images synthesized by our method, shading of the virtual object blends well into the scene. Also, the virtual object casts a shadow with a soft edge on the tabletop in the same way as do the other objects in the scene.

2.1 Image Synthesis under Dynamically Changing Illumination [46]

We also pursue the possibility of real-time rendering of synthetic objects with natural shading and cast shadows superimposed onto a real scene whose illumination condition is dynamically changing.

In general, high computational cost for rendering virtual objects with convincing shading and shadows, e.g., interreflections or soft shadows under area light sources, prohibits real-time synthesis of such composite images with superimposed virtual objects. From this limitation, simple rendering algorithms supported by commonly available graphics hardware needs to be used for the applications that requires real-time image synthesis. In general, computationally expensive rendering algorithms are not supported by such graphics hardware, and this leads to some restrictions on achievable image qualities.

Alternative approaches have been proposed for re-rendering a scene as a linear combination of a set of pre-rendered basis images of the scene [8, 29, 5]. These approaches are based on the linearity of scene radiance with respect to illumination intensities. Since this linearity holds for scenes with complex geometry and complex photometric properties such as interreflections between objects and cast shadows, photo-realistic appearance of a scene can be synthesized based on this simple linear combination operation.

Most of the previously proposed methods, however, have been developed for the task of interactive lighting design. Therefore, basis lights are intensionally positioned at the desired locations. so that a scene under desired lighting configurations can be efficiently synthesized. Recently, Debevec et

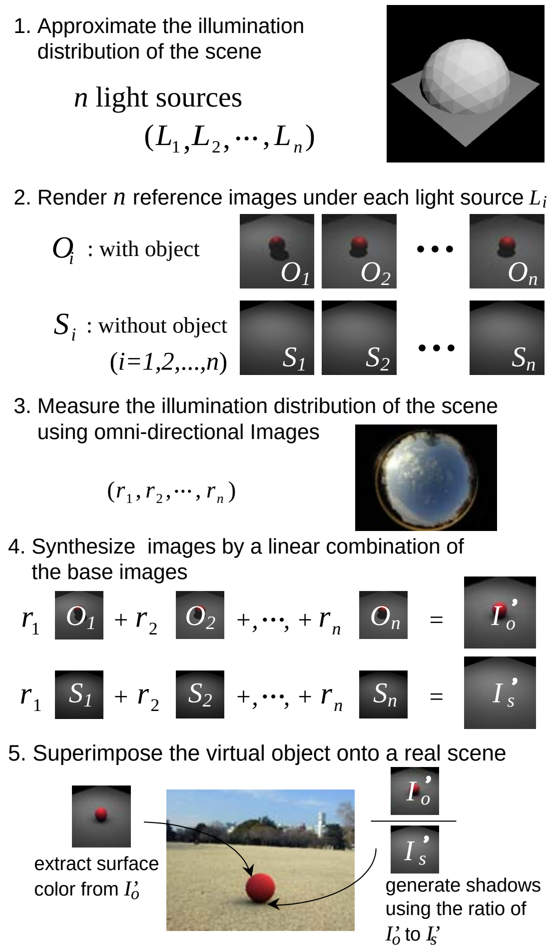

図 2: Basic steps of the proposed method.

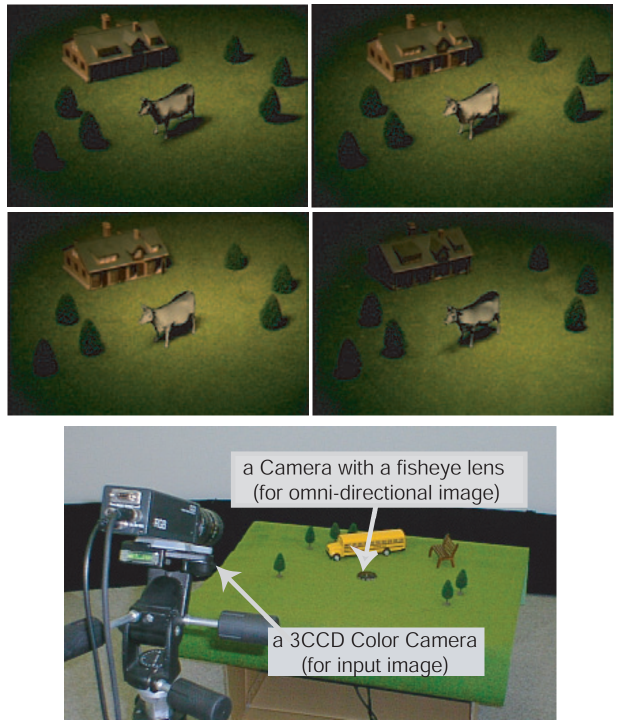

図 3: Image acquisition system and synthesized images by our method: a color camera with a fish-eye lens is used for capturing illumination of the scene.

al. introduced a method for re-rendering a human face based on a linear combination of face images taken under densely sampled incident illumination directions in [4]. This method further considered a model of skin reflectance to estimate the appearance of the face seen from novel viewing directions and under arbitrary illumination.

In this thesis, we generalize the approach based on the linearity of scene radiance with respect to illumination radiance and present an efficient technique for superimposing synthetic objects with natural shadings and cast shadows onto a real scene whose illumination is dynamically changing: we consider a scene consists of both real objects and synthetic objects with fixed scene geometry and synthesize the image of a scene viewed from a fixed viewing point under dynamically changing illumination.

Taking advantage of the linear relationship between brightness observed on an object surface and radiance values of light sources in a scene, the proposed method synthesizes a new image for novel lighting conditions as described in the following steps.

Step1: The entire illumination of a scene is approximated as a collection of area sources $L_i (i = 1, 2, \cdots, n)$ which are equally distributed in the scene (Figure 2.1).

Step2: Two images which are referred to as reference images are rendered under each area light source: one with a virtual object superimposed onto the scene O_i, and the other without the object S_i (Figure 2.2).

Step3: Scaling factors of the light source radiance values r_i $(i = 1, 2, \cdots, n)$ are measured by using an omni-directional image of the scene taken by a camera with a fisheye lens (Figure 2.3).

Step4: New images ${I_o}'$ and ${I_s}'$, which should be observed under the current illumination condition, are obtained as a linear combination of O_i's and

S_i's with the measured scaling factors r_i's, respectively (Figure 2.4).

Step5: Using I_o' and I_s', the virtual object is superimposed onto the image of the scene along with natural shading and shadows that are consistent with those of real objects (Figure 2.5). The ray casing algorithm is imposed here; if an image pixel corresponds to the virtual object surface, the color of the corresponding pixels in I_o' is assigned as the value of the pixel. Otherwise, the effects on the real objects caused by the virtual object, i.e., shadows and secondary reflection, are added by multiplying the pixel value by the ratio of I_o' to I_s'(Figure 2.5).

Image acquisition system and several examples of synthesized composite images are shown in Figure 3. In those composite images, appearance of the virtual object blends well into the scene, and the virtual object casts a shadow with a soft edge on the grass in the same way as the other objects such as trees in the scene do.

The main advantage of the proposed method is that image quality is not affected by the requirement for real-time processing, since reference images are rendered off-line. This enables us to employ computationally expensive algorithms for providing reference images, and this results in achieving high quality in the final composite images of the scene.

3 Inverse Lighting for Estimating Real-World Illumination [43]

There has been another approach in image-based modeling called *inverse rendering* that deals with an inverse problem of traditional model-based rendering. As described in model-based rendering, the image brightness of an object can be computed as the function of the shape of the object, its surface reflectance properties, and the illumination condition where the object is located [17, 16]. The relationship among them provides three research areas in inverse rendering:

- Shape-from-Brightness for recovering the shapes of the object from its reflectance properties and the known illumination condition,
- Reflectance-from-Brightness for recovering the surface reflectance properties of the object from its shapes and the known illumination condition, and
- Illumination-from-Brightness for recovering unknown illumination condition of the scene based on the knowledge of the shape and the surface reflectance properties of the object.

The third research area is also known as *inverse lighting*. One of the main advantages of inverse lighting over the former image-based lighting is that it does not require additional images for capturing illumination of a scene, but uses the appearance of objects located in a scene instead for recovering an illumination distribution of the scene.

In inverse rendering, the first two kinds of analyses, shape-from-brightness and reflectance-from-brightness, have been intensively studied using the shape from shading method [18, 20, 19, 34], as well as through reflectance analysis research [21, 30, 15, 1, 22, 25, 47, 53]. In contrast, relatively limited amounts of research have been conducted in the third area, inverse lighting.

This is because real scenes usually include both direct and indirect illumination distributed in a complex way and it is difficult to analyze characteristics of the illumination distribution of the scene from image brightness. As a consequence, most of the previously proposed approaches were conducted under very specific illumination conditions, e.g., there were several point light sources in the scene, and those approaches were difficult to be extended for more natural illumination conditions [19, 21, 47, 52, 56], or multiple input images taken from different viewing angles were necessary [24, 32].

Pioneering work in the field of inverse lighting for recovering natural illumination conditions of real scenes was proposed by Marschner and Greenberg [27]. This work introduced to approximate the entire illumination with a set of basis lights located in a scene and estimated their radiance values from

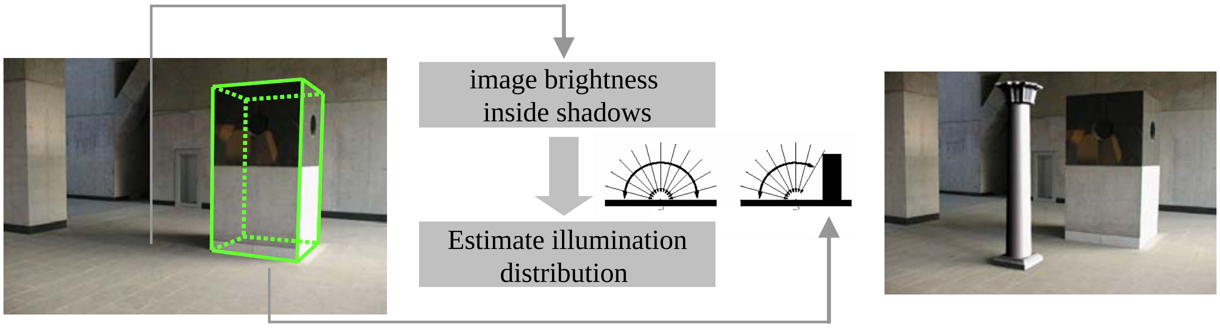

図 4: An inverse lighting approach for recovering an illumination distribution of a scene from image brightness inside shadows cast by an object of known shape in the scene.

shadings of objects observed in that scene.

Although this method had an advantage over the previous methods of not requiring knowledge about the light locations of the scene, the estimation relies on the appearance changes observed on an object surface assumed to be Lambertian, and therefore some restrictions were imposed on the shape of the object, e.g., the object must have a large amount of curvature.

Later, Ramamoorthi and Hanrahan showed under which condition inverse rendering could be done robustly based on their proposed signal-processing framework that described the reflected light field as a convolution of the lighting and the bidirectional reflectance distribution function (BRDF) [36]. It was shown through their analysis that appearance changes observed on lambertian surfaces were not suitable for estimating high frequency components of illumination distribution of a scene.

In this thesis, we demonstrate the effectiveness of using occluding information of incoming light in estimating an illumination distribution of a scene [40]. Shadows in a scene are caused by the occlusion of incoming light, and thus contain various pieces of information about the illumination of the scene. Nevertheless, shadows have been used for determining the 3D shapes and orientations of an object which casts shadows onto the scene [26, 23, 49, 6], while very few studies have focused on the the illuminant information which shadows could provide. In our method, image brightness inside shadows is effectively used for providing distinct clues to estimate an illumination distribution.

This study further addresses the following two issues in inverse lighting [41]. First, the method combines the illumination analysis with an estimation of the reflectance properties of a shadow surface. This makes the method applicable to the case where reflectance properties of a surface are not known a priori and enlarges the variety of images applicable to the method.

Second, an adaptive sampling framework for efficient estimation of illumination distribution is introduced. Using this framework, we are able to avoid unnecessarily dense sampling of the illumination and can estimate the entire illumination distribution more efficiently with a smaller number of sampling directions of the illumination distribution.

We also discuss the amount of the information obtainable from a given image of a scene about the illumination distribution of the scene in [42]. In general, the amount of information obtainable from an image is determined depending on how much of shadow surfaces are blocked by objects in a scene and how much of the scene are covered by the field of view of the camera taking the image of the scene. In particular, two main factors that control the stability of the illumination estimation from shadows are analyzed: blocked view of shadows; limited sampling resolution for radiance distribution inside shadows.

Then, based on the analysis, a robust method has been presented. For estimating the illumination distribution of a scene reliably by taking stability issues into considerations, we propose to change the sampling density of the illumination distribution depending on the amount of the information obtainable from a shadow image for a particular direction of the illumination distribution. For using radiance distribution inside penumbra of shadows correctly, we introduce a super-sampling scheme for examining occlusion of incoming light from each light source. We also explain the optimal sampling of image pixels and the selection of illumination distribution samplings for more stable computation.

All of these extensions contribute to improve stability and accuracy of illumination estimation from shadows, and illumination distribution can be estimated in a reliable manner with these proposed improvements regardless of types of input images such as the shape of an occluding object or a camera position.

In the bottom row of Figure 5, several synthetic objects were also superimposed onto the surface using the illumination distribution estimated from the input shadow image shown in this figure. It is worth noting that in this example, a relatively large area of the shadow surface is occluded by the occluding object, and it is often difficult to provide a correct estimate of the illumination distribution in such case.

Even in this challenging case, our proposed approach could reliably estimate the illumination distribution of the scene by taking stability issues into considerations. Shadows cast by those synthetic objects resemble well those cast by the real objects, and this shows that the estimated illumination distribution gives a good presentation of that of the real scene.

Recently, based on the signal-processing framework proposed by Ramamoorthi and Hanrahan, it was shown that high frequency components of the appearance of an object surface could retain significant energy by taking the occlusion of incoming light as well as its BRDF into account in [33]. This indicates that the use of shadows for the illumination estimation has the significant advantage of providing more clues to the high frequency components of illumination distribution of a scene.

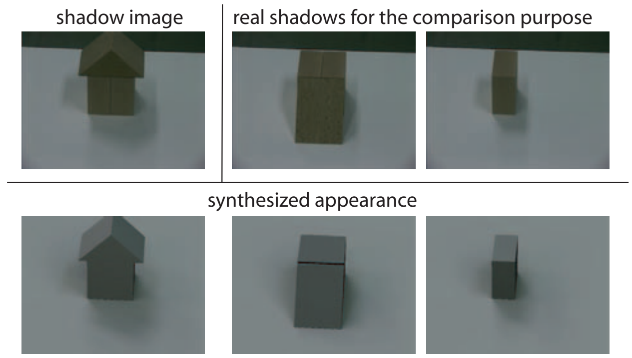

図 5: Synthesized appearance using the estimated illumination distribution.

3.1 Acquiring Shading Model For Artistic Shadings in [45]

As an application for the proposed inverse lighting approach we also present a new technique for superimposing synthetic objects onto oil paintings with artistic shadings that are consistent with those originally painted by the artists. In a colored medium such as oil painting, artists often use color shift techniques for adding some artistic tones to their paintings as well as for enlarging their dynamic ranges.

In this thesis, we attempt to determine the mechanisms for color shifts performed by artists and to automate their processes so that we can superimpose onto paintings synthetic objects that have consistent shadings. We first study characteristics of shadows observed both in real scenes and in paintings to discover how intrinsic color shifts were performed by artists. In particular, we analyze brightness distributions inside shadows ob-

図 6: Superimposing a synthetic chair into the painting by Rembrambt.

served in a painting. Then, we adapt the acquired mechanisms so that we can superimpose synthetic objects with consistent shadings onto oil paintings (Figure 6).

4 Image-Based Rendering under novel lighting conditions

Inverse rendering carries out the opposite procedures of model-based rendering to provide the models of a real scene from photographically available information of the scene. Once the models of a scene are acquired, new images of the scene under novel lighting and/or viewing conditions can be synthesized by using conventional model-based rendering techniques.

On the other hand, the approach called *image-based rendering* directly uses the original set of input images of a scene for producing new images of the scene under novel conditions [50]. Depending on which scene conditions should be modified, image-based rendering techniques are classified into three categories: image-based rendering under novel viewing conditions, image-based rendering under novel lighting conditions, and image-based rendering under novel viewing and novel lighting conditions. In this thesis, we consider the second category, image-based rendering under novel lighting conditions.

In contrast with model-based rendering techniques, image-based rendering techniques do not require full radiometric computation to synthesize the photorealistic appearance of objects in a scene. This makes the cost to produce new images of the scene independent of the scene complexity. Also image-based rendering techniques normally do not require the geometric and photometric models of a scene.[2] Image-based rendering, however, has a tendency to require many input images of a scene to synthesize reasonably realistic appearance of the scene. This results in the requirement for a large amount of both computer memory and data storage.

While there may seem to be a large variety of possible appearances for a given object, it has been demonstrated in previous research that the appearance changes of an object for varying illumination can be represented with a linear subspace spanned by a set of basis images of the object. For instance, in the case of a convex Lambertian object, its appearance seen under distant illumination without attached and cast shadows can be described with a 3-D linear subspace spanned from three input images of the object taken under linearly independent lighting conditions [28, 48, 55].

Even taking into account attached shadows, most of the image variation of a human face or other object under varying illumination was shown to be adequately represented by a low-dimensional linear subspace slightly higher than 3-D [14, 10, 54]. A similar observation was utilized for object recognition in [12, 13].

A set of basis images spanning such a linear subspace are often provided by applying principal-component analysis to the input images of an object taken under different lighting conditions. Since little is known about how to sample the appearance of an object in order to obtain its basis images correctly, a large number of input images taken by moving a point light source along a sphere surrounding the object are generally provided.

Recent investigations in frequency-space analysis of reflection have shown that the appearance of an object under varying complex illumination conditions can be well represented with a linear subspace spanned by basis images of the object, called *harmonic images*, each of which corresponds to an image of the object illuminated under *harmonic lights* whose distributions are specified in terms of spherical harmonics [36, 37, 2].[3]

Hence if harmonic lights can be physically constructed in a real setting, harmonic images of a real object can be obtained simply as images of the object seen under these light sources. However, harmonic lights are complex diffuse light sources comprising both negative and positive radiance and are

[2] Some image-based rendering techniques make use of the geometric models of a scene for better compression of its appearance.

[3] Harmonic images have been also used for the purpose of efficient rendering of an object under complex illumination [38, 51].

図 7: Hardware set-up and synthesized images of objects under natural illumination. The first row shows illumination maps. The second, third and forth rows shows synthesized appearance of objects under the corresponding illumination map.

thus difficult to physically construct in a real setting. Therefore, most of the previously proposed techniques synthetically compute harmonic images from the knowledge of an object 3-D shape and reflectance properties.

4.1 Appearance Sampling for Obtaining a Set of Basis Images [44]

This motivated us to develop a method for analytically obtaining a set of basis images of a convex object for arbitrary illumination from input images of the object taken under a point light source. The main contribution of our work is that we show that a set of lighting directions can be determined for sampling images of an object depending on the spectrum of the object's BRDF in the angular frequency domain such that a set of harmonic images can be obtained analytically based on the sampling theorem on spherical harmonics [9].

Using those sampling directions determined from the sampling theory, we are able to obtain harmonic images by using a significantly smaller number of input images than other techniques which do not take into account a relationship between a spectrum of BRDFs and a sampling density of illumination directions.

In addition, unlike other methods based on spherical harmonics, our method does not require the shape and reflectance model of an object used for rendering harmonics images of the object synthetically. Thus, our method can be easily applied for determining a set of basis images for representing the appearance change of a real object under varying illumination conditions.

An overview of our hardware set-up[4] used for obtaining the input images of the objects is shown in Figure 7; an array of light sources is mounted on a turntable. These light sources are equally spaced in elevation, and the set of light sources is rotated around the objects in azimuthal. By using this hardware set-up, input images of an object are taken under a point light source positioned at equiangular grid points [5] and used for obtaining a sets basis images of the object.

To evaluate the accuracy of the recovered harmonic images, we took images of those objects under normal lighting conditions in our laboratory and compared real appearance with the appearance of those objects synthesized by using the obtained harmonic images.

[4] *Surface Reflectance Sampler*, TechnoDream21 corporation

[5] 36 input images were used for the sheep and the venus examples, and 144 input images were used for the fish example

In Figure 8, the left column shows the real images of the objects and the right column shows the synthesized appearance. The synthesized appearance of the objects resembles that of the objects in real images, and this shows that the recovered harmonic images provide a good representation of the appearance of the objects.

To demonstrate how well the recovered harmonic images represent the appearance of those objects under varying illumination, we synthesize their appearance from the recovered harmonic images under several natural illumination conditions provided by high-dynamic range light probe measurements by [3]. In Figure 7, synthesized appearance changes dynamically depending on characteristics of the illumination, and one can say from this that the proposed method succeeded in providing a set of basis images representing appearance of those objects under varying illumination.

図 8: Comparison between real images and synthesized images under complex illumination

4.2 Anti-aliasing Framework in Appearance Sampling

Furthermore, we carefully study the issue of aliasing and extend the method based on the sampling theorem further for reducing the artifacts due to aliasing, by substituting extended light sources (*ELS*) for a point light source to sample the reflection kernel of a real object.

The use of ELS for modeling the shape and reflectance of an object was originally introduced in [31]. We extend their analysis further in the angular frequency domain so that the harmonic images of an object of arbitrary surface materials can be obtained without suffering from aliasing caused by insufficient sampling of its appearance.

The use of ELS has the following advantages. ELS have a radiance distribution that is similar to that of the Gaussian function, and this enables extended sources to function as a low-pass filter when the appearance of an object is sampled under them. This enables us to obtain a set of basis images of an object for varying illumination without suffering from aliasing caused by insufficient sampling of its appearance. In addition, ELS can reduce high contrast in image intensities due to specular and diffuse reflection components. This helps avoid saturation so that we are able to observe both specular and diffuse reflection components in the same image taken with a single shutter speed.

5 Conclusion

Conventional model-based rendering techniques have been intensively developed for synthesizing the realistic appearance of computer graphics objects. Model-based rendering techniques synthesize appearance of objects based on empirically or analytically given reflection models, and the geometric and the photometric information about the scene needs to be provided: the shapes of objects in the scene, their surface reflectance properties, and the lighting condition of the scene where those objects are placed.

Needless to say, the appearance of an object greatly changes depending on its surface reflectance properties. Also, the appearance of an object changes significantly under a different lighting condition. It is thus important to provide not only appropriate surface reflectance properties of objects in a scene but also appropriate illumination conditions so that realistic appearance of the objects can be synthesized under this illumination condition. Nevertheless, the photometric information about a scene tends to be manually provided by a user. Since it is difficult to imagine appearance of an object directly from reflectance parameters, this input process of manually specifying its reflectance properties is normally non-intuitive and thus time-consuming. As for providing lighting conditions, a scene generally includes both direct and indirect illumination distributed in a complex way, and it is also difficult for a user to manually specify such complex illumination distributions.

In order to overcome these difficulties in providing photometric information about a scene, techniques for automatically providing the photometric models of a scene have been studied in the fields of both computer vision and computer graphics research. In particular, techniques that use a set of images of a scene provided under different viewing and/or lighting conditions for determining its geometric and photometric information are called image-based modeling.

This thesis address two issues of image-based modeling for achieving photo-realistic appearance of an object under natural illumination conditions: capturing real-world illumination and modeling complex appearance of real objects for variable illumination. Regarding the first issue of capturing and modeling real-world illumination, both of an image-based approach and an inverse lighting approach have been studied in this thesis. As for the second issue of modeling the appearance of real objects for variable illumination, we present a novel method for analytically obtaining a set of basis images from input images of the object taken under a point light source or extended light sources.

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