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Creating Photorealistic Virtual Model with Polarization-based Vision System

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ABSTRACT

Recently, 3D models are used in many fields such as education, medical services, entertainment, art, digital archive, etc., because of the progress of computational time and demand for creating photorealistic virtual model is increasing for higher reality. In computer vision field, a number of techniques have been developed for creating the virtual model by observing the real object in computer vision field. In this paper, we propose the method for creating photorealistic virtual model by using laser range sensor and polarization based image capture system. We capture the range and color images of the object which is rotated on the rotary table. In geometry aspect, an object surface shape is reconstructed by merging multiple range images of the object. In optical aspect, color images are captured under fixed point light source. By using the reconstructed object shape and sequence of color images of the object, parameter of a reflection model are estimated in a robust manner. As a result, then, we can make photorealistic 3D model in consideration of surface reflection. The key point of the proposed method is that, first, the diffuse and specular reflection components are separated from the color image sequence, and then, reflectance parameters of each reflection component are estimated separately. In separation of reflection components, we use polarization filter. This approach enables estimation of reflectance properties of real objects whose surfaces show specularity as well as diffusely reflected lights. The recovered object shape and reflectance properties are then used for synthesizing object images with realistic shading effects under arbitrary illumination conditions.

Keywords: Model-based Rendering, Surface Reflection, Polarization

1. INTRODUCTION

It becomes more and more important to develop the easy method for getting the accurate reflectance information as the interest in virtual reality is growing. Currently, virtual reality system is used in a wide variety of applications including electronic commerce, simulation-and-training, and virtual museum walk-through. In spite of these many needs for virtual reality models, most of the virtual reality systems utilize models that are manually created by programmers. If we can build a system that automatically create the models for virtual reality system, we can drastically decrease modeling costs for virtual reality systems.

One major approach to building the virtual object model is the one which reconstructs the input images taken by camera. In recent several years, many techniques have been proposed for interpolating between views by warping input images, using depth information or correspondences between multiple images. The general notion of generating new views from pre-acquired imagery is called image-based rendering. Apple's QuickTime VR is one example. Gorter et al.[5] proposed the method for capturing the complete appearance of the real objects and scenes, and rendering the images of the objects from new view positions. Unlike the traditional shape capturing method which is used in computer vision, they don't use the fine geometric representation. Instead, they use the 4D function called Lumigraph. The Lumigraph is the subset of the complete plenoptic function which represents the complete flow of light in all position in all directions. Levoy et al.[7] also proposed the subset of the plenoptic

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function called Light Field. They interpretes the input images as two slices of 4-D function. This function can completely characterizes the flow of light through unobstructed space in a static scene with fixed illumination. Nishino et al.[10] proposed the another approach for image-based rendering. They used a fine geometric model and the eigen-texture which was texture-patches made of pictures taken from various point of view and was reduced its data set by principal-component analysis. Wood et al.[19] also proposed the method which used a fine geometric model and point-based color information called Lumisphere. Lumisphere also reduced information quantity with the use of principal-component analysis.Georghiades[4] proposed the method recovering BRDF to render under novel illumination and 3D shape of the object at the same time from a small number of photographs without information about the position and intensity of the light-source and the position of the camera. The method is under assumption that image is monochrome and the parameters are constant across the surface. Debevec et al.[2] proposed the method to acquire the reflectance filed of a human face and use these measurements to render the face under arbitrary changes in lighting and viewpoint. They acquire images of the face from a small set of viewpoints under a dense sampling of incident illumination directions using the setup named Light Stage. Then they construct a reflectance function image for each observed image pixel to generate images of the face from the viewpoints in any form of sampled or computed illumination. This method has been extended[3] to composite a live performance of an actor into a virtual set wherein the actor is consistently illuminated by the virtual environment using sphere of inward-pointing RGB light. And more, Wenger et al.[17] have extended it to time-multiplexed illumination and high-speed photography to capture time-varying reflectance properties of a live performance in a way that the lighting and reflectance of the actor can be designed and modified in postproduction.

The other approach to the problem is the one called model-based rendering. Usually, model-based rendering uses information of a fine geometry and a physical surface property. Sato et al.[13] build a virtual model which is made of a fine geometric model and reflectance parameters used in a particular reflectance model. They fixed the position of the camera and point light source and, then, putted the real object on the rotary table.

When we make a model of reflectance properties by observing real objects, we need to consider two reflection components: the specular reflection component and the diffuse reflection component. If we only map the observed image onto the object shape model as observed surface texture, we cannot reproduce the appearance of the object under different viewing and illumination conditions correctly. When highlights are observed in the original images, those highlights are fixed on a certain position of the object surface permanently regardless of illumination and viewing conditions. Therefore, in order to model the reflection properties correctly, we have to separate the specular reflection and diffuse reflection.
Several techniques to separate the reflection components have been developed. One major approach to the problem is the one that uses color as a clue. Most of color based methods are based on the dichromatic reflection model proposed by Shafer.[15] The dichromatic reflection model suggests that reflected lights from dielectric material have different spectral distributions between the specular and the diffuse reflection components. The specular component has a similar spectral distribution to that of the illumination. On the other hand, the diffuse component has an altered distribution by the colorants in the surface medium. Consequently, the color of an image point can be viewed as the sum of of two vectors with different directions in color space. Klinker et al.[6] observed that color histogram of a uniformly colored object surface makes the shape of *skewed T* with two limbs in the color space. One limb represents the purely diffuse points while the other represents highlight regions. Based on this observation, Klinker et al.[6] proposed an algorithm for automatically identifying the two limbs and using them to separate the diffuse and specular reflection components at each surface point. Sato and Ikeuchi[12] used a sequence of color images taken under actively varying light direction, and successfully separated the reflection components for each object surface point even if object surface is not uniformly colored.
Nayer et al.[9] used not only color but also polarization to separate the reflection components. Their proposed algorithm used the partial polarization included in the reflection in order to determine the color of specular component independently for each image point. The specular color imposes constraints on the color of the diffuse component and the neighboring diffuse colors that satisfy these constraints are used to estimate the diffuse color vector for each image point.
All of these separation methods based on the dichromatic reflection model suffers from the common weakness

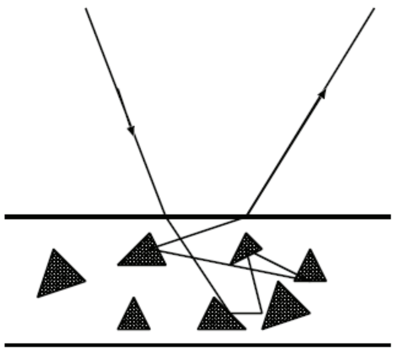


Figure 1. Diffuse reflection resulting from the internal scattering mechanism

in that they cannot work if the specular and diffuse reflection vectors have same direction in a color space. In this paper, we propose a new method for separating the reflection components using polarization. Unlike the previously proposed methods, our method does not require that the diffuse color and the specular color are different. In order to separate the reflection components in a robust manner, we use a controlled illumination which is linearly polarized, and we take the images of an object through a polarization filter. Our method is able to separate the diffuse and specular reflection components for each image pixel independently, and therefore, it can be applied to objects with complicated surface textures.

This paper is organized as follows: Section 2 describes the representative reflection models and especially, Torrance-Sparrow reflectance model which is used in this paper is described in detail. Section 3 explains polarization mechanism which is used to separate the reflection components is explained. In Section 4, data acquisition system which contains the CCD camera, the light stripe range sensor, polarization filter, point light source, and rotary table, is described. In Section 5, the details of the algorithm is described and the separation result is examined. In Section 6, the parameters of the Toraace-Sparrow are estimated, and the result is presented. In Section 7, by the estimated parameters, I synthesize the virtual images. Finally, Section 8 concludes the paper.

2. REFLECTION MECHANISM

A number of reflectance models have been proposed in the past by the researchers in the fields of applied physics and computer vision. In general, these models are classified into two categories: a specular reflectance model and a diffuse reflectance model.

2.1. Diffuse Reflection

A diffuse reflectance model represents reflected rays resulted from internal scattering inside surface medium. When light strikes an interface between two different medias, some percentage of the light passes through the boundary and the remaining portion of light is reflected. The penetrating light hits internal pigments of the objects, and is re-emitted randomly(Figure1). This re-emitted light is called diffuse reflection, and Lambert is the first who modeled this phenomenon. The formula Lambert deduced is:

$$\begin{aligned} I_{diff} &= C_{diff} \vec{N} \cdot \vec{S} \\ &= C_{diff} \cos \theta_i \end{aligned} \tag{1}$$

where I_{diff}, C_{diff}, $\vec{N}$, $\vec{S}$, θ_i are the brightness, a proportional constant, the surface orientation, the light source direction, the angle between the light source direction and the surface orientation, respectively. The diffuse component does not depend on the angle of reflection but depend on the incident light.

2.2. Specular Reflection

A specular reflectance model, on the other hand, represents light rays reflected on the surface of the object. The surface may be assumed to be composed of microscopic planar elements, each of which has its own surface orientation different from the macroscopic local orientation of the surface. The result is the specular reflection component that spreads around the specular direction and that depends on the surface roughness for the width of the distribution.

Specular reflectance model can be derived from the two completely different approaches: physical optics based and geometrical optics based. The physical optics based approach uses electromagnetic theory and Maxwell's equations to study the propagation of light. On the other hand, geometrical optics based approach uses assumption of the short wave length of light and treats the propagation of light geometrically. The representative physical optics based model is the Beckman-Spizzichino model, and the representative geometrical optics based model is the Torrance-Sparrow model.[16]

2.2.1. Physical Optics Based Model

The physical models are directly derived from electromagnetic wave theory by usig Maxwell's equations. Beckmann and Spizzichino deduced their reflectance model by solving the Maxwell's equations by using Helmholts integral with Kirchoff's assumption on a perfect conductor surface. They made some assumptions to make up their reflectance model, as follows:

- The surface height is assumed to be normally distributed.
- The radius of curvature of surface irregularities is large compared to the wavelength of incident light (Kirchoff's assumption).
- The surface is assumed to be a perfect conductor.
- The shadowing and masking of surface points by adjacent surface points is ignored.
- The light is assumed to be reflected only once and not to bounce between surface facets before scattered in the direction of the observer.
- The incident wave is assumed to be perpendicularly polarized.
- The incident wave is assumed to be a plane wave. This assumption is reasonable when the light source is at a great distance from the surface relative to the physical dimensions of the surface.

The Beckmann-Spizzino model consists of the specular lobe and specular spike component. The specular spike component is represented as a delta function and causes very sharp reflection when reflection angle equals to the incidence angle(specular angle). The specular lobe component is represented as a Gussian function and causes widely spreadding reflection.

2.2.2. Geometrical Optics Based Model

The geometrical models are derived from simplifying many of the light propagation problems. Torrance and Sparrow obtained their reflectance model by assuming as follows:

- The surface is modeled as a collection of planar microfacets, and the facet slopes are assumed to be normally distributed.
- The size of planar facets is much greater than the wave length of incident light. Therefore, it can be assumed that incident light rays are reflected by each facet in its specular direction only.
- Each facet is one side of a symmetric V-groove cavity.
- The light source is assumed to be at a great distance from the surface so that all incident rays are regarded to be parallel to one another.

The Torrance-Sparrow model is represented by a Gaussian function of the surface roughness parameters.

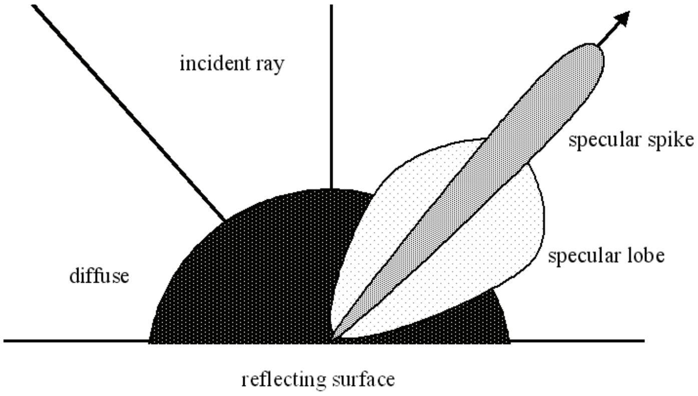


Figure 2. Diagram of the Unified Reflectance Model

2.3. General Reflectance Model

The Torrance-Sparrow model is aimed for modeling rough surface of any materials. The Beckmann-Spizzichino model describes the reflection from rough to smooth surface. The Torrance-Sparrow model is good approximation of the Beckmann-Spizzichino model when it is applied to the rough surface. So, physical optics based model is more general than the geometrical optics based. But, physical optics based model has very complex mathematical forms and is difficult to manipulate. Geometrical optics based model, however, has very simple function form, but it can not be applied to the smooth surface materials.

In order to combine the reflection models for the smooth surface and the rough surface, Nayer, Ikeuchi, and Kanade[8] proposed the general reflectance model. This model consists of three components: specular spike, specular lobe, and diffuse. Each of these components is represented by, respectively, these threee functions: the delta function, the Gaussian function, and the Lambertian's cosine function.
Let's assume that the surface is located at the origin of the coordinate frame, and that surface normal vector is in the direction of the Z axis. The beam illuminating the surface lies in the X-Z plane, and it's incident on the surface is at an angle, θ_i. The observer is located at (θ_r, ϕ_r).
Under this geometry, general reflectance model is represented as follows

$$I = C_{ss}\delta(\theta_i - \theta_r)(\phi_r) + C_{sl}\frac{\exp(-k\alpha^2)}{\cos\theta_r} + C_{diff}\cos\theta_i \tag{2}$$

C_{ss}, C_{sl}, C_{diff} are constants which respectively represents the strength of the specular spike, specular lobe, and diffuse components. The α is the angle between the surface normal and the bisector of the viewing and surface directions. The k is the parameter related to the Torrance-Sparrow surface roughness parameter.
The ratio C_{sl}/C_{ss} is dependent on the optical roughness of the surface. Mathematically, optical roughness is defined as

$$g = (2\pi\frac{\sigma_h}{\lambda}(\cos\theta_i + \cos\theta_r))^2 \tag{3}$$

where σ_h, λ are the root-mean-square of the height distribution, and the wavelength, respectively. For smooth surface $(g \ll 1)$, the spike component is dominant. As the roughness increase, however, the spike component shrinks rapidly, and for rough surface $g \gg 1$, the lobe component begins to dominate. It is only for a small range of roughness values that C_{sl} and C_{ss} are both significant. In this paper, the Torrance-Sparrow model is used for representing the diffuse and specular components.

$$I_m = I_{D,m}\cos\theta_i + I_{S,m}\frac{1}{\cos\theta_r}e^{-\alpha^2/2\sigma^2} m = R, G, B \tag{4}$$

where θ_i is the angle between the surface normal and the light source direction, θ_r is the angle between the surface normal and the viewing direction, α is the angle between the surface normal and the bisector of the light source direction and the viewing direction, $I_{D,m}$ and $I_{S,m}$ are the scaling factor for the diffuse and specular components, and σ is the standard deviation of a facet slope of the Torrance-Sparrow model.

In this model, the reflections bounced only once from the light source are considered. Therefore, this model is valid only for the convex objects. So, in this research, we use the objects for which inter-reflection does not affect our analysis significantly.

We refer to $I_{D,m}$ as the diffuse reflection parameters, and $I_{S,m}$ and σ as the specular reflection parameters.

3. POLARIZATION

Polarization has been used for several decades in the remote sensing research. Wolff and Boult[18] have proposed an algorithm which analyzes linear polarization states of highlights removal and material classification. Boult and Wolff[1] have also studied the classification of scene edges based on their polarization characteristics. Recently, Saito et al.[11] have proposed a method for measuring surface orientation of a transparent object using the degree of linear polarization in highlights observed on the object. Schechner et al.[14] have presented the method for classifying the transmitted image and the reflected image to the transparent sheet.
The method presented in this paper uses two linear polarization filters. One is placed in front of a point light source in order to polarize the light source linearly, and the other is placed in front of a camera to capture images through the linear polarization filter.
For an ideal filter, a light wave should be passed unattenuated when its electric field is aligned with the polarization axis of the filter, and the energy is attenuated as a trigonometric function when the filter is rotated.
As described in the previous section, the image brightness value taken by sensor is described as:

$$I = I_d + I_s \tag{5}$$

where I_d represents the diffuse component and I_s represents the specular component.
When incident light is linearly polarized, the diffuse component tends to be unpolarized due to its internal scattering. In contrast, the specular reflection component tends to remain linearly polarized. Therefore, the observed brightness of the specular component can be expressed as a trigonometric function for polarization filter angle, and that of the diffuse component can be expressed as a constant. Thus the image brightness observed through a linear polarization filter is described as:

$$I = I_c + I_v(1 + \cos 2(\theta - \beta)) \tag{6}$$

where θ is the angle of the polarization filter and β is the phase angle determined by the projection of the surface normal onto the plane of the filter.
It should be noted that in the above equation I_c is not equal to the real diffuse intensity, and $2 \times I_v$ is not equal to the real specular intensity. The diffuse reflection component which is unpolarized is always attenuated by the polarization filter and the specular reflection component is also attenuated by the difference of the reflectivity between the light waves which are parallel or perpendicular to the incidence plane. *

The polarization state of reflected light dependents on several factors including the material of the reflecting surface element, and the type of reflection component, i.e. diffuse or specular. In order to describe the state of polarization of the reflected light, the Fresnel reflection coefficients $F_\perp(\eta, \psi)$ and $F_{||}(\eta, \psi)$ are used.[18] The Fresnel reflection coefficients determine the polarization of reflected light waves in the directions perpendicular and parallel to the plane of incidence respectively, and determine the maximum and the minimum intensities which are observed when the angle θ of the polarization filter varies. The parameter η is the complex index of reflection of the surface medium and the parameter ψ is the incidence angle. Since we use a linearly polarized light source, we can assume that the intensity of the specular component observed through a linear polarization

*The incidence plane includes the surface normal and the illumination direction.

filter is guaranteed to become equal to zero at a certain angle. Hence, we obtain the following relation between I_v and specular reflection intensity:

$$q = \frac{F_{\perp}(\eta, \psi)}{F_{||}(\eta, \psi)} \tag{7}$$

$$2I_v = \frac{q}{1+q} I_s \tag{8}$$

where I_s equals the specular reflection intensity.

It is known that the diffuse component is also polarized when the viewing angle is close to 90 degrees, e.g., near the occluding contour of an object. However, the diffuse component becomes linearly polarized only in narrow region and the degree of polarization in the diffuse reflection component is generally negligible. Hence, we assume that the diffuse component is unpolarized in our analysis. The intensity of unpolarized light is attenuated by half when it passes a linear polarization filter. As a result, I_c and the diffuse component have a relation as below:

$$I_c = \frac{1}{2} I_d \tag{9}$$

where $\frac{1}{2} I_d$ is the intensity of the diffuse reflection.

Figure 3 shows the relation between the image brightness and the angle of the polarization filter.

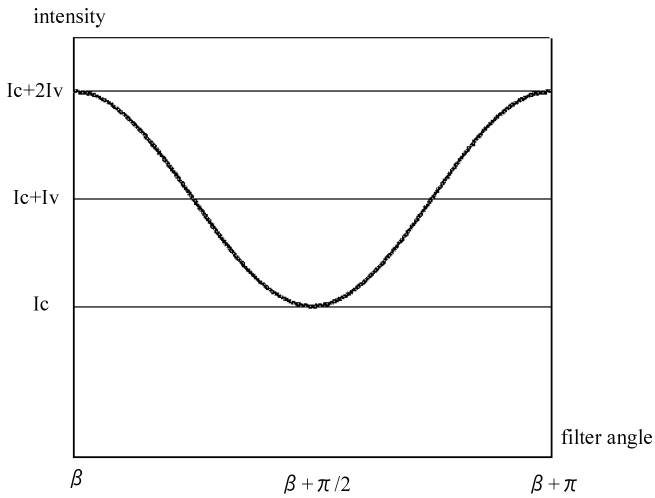


Figure 3. Imge brightness plotted as a function of the orientation of a polarization filter

4. DATA ACQUISITION SYSTEM

The experimental setup for the image acquisition system used in our experiment is illustrated in Figure 4. An object to be modeled in this experiment is placed on the rotary table. A sequence of range images and color images are captured as the object is rotated at a certain angle step. For each rotation step, one range image and thirty five color images, which are taken every five degrees polarization filter rotation in front of the CCD camera, are obtained.

A range image is obtained using a light-stripe range finder with a liquid crystal shutter and a color CCD video camera. Each range image pixel represents an (X, Y, Z) location of a corresponding point on an object surface. The same color camera is used for acquiring range images and color images. Therefore, pixels of the range images

and the color images directly correspond. Color images are taken through a polarization filter.
The range finder is calibrated to produce a 3×4 projection matrix which represents the translation between the world coordinate system and the image coordinate system. The location of the rotary table is with respect to the world coordinate system is calibrated before image acquisition. Therefore, object location is uniquely determined by the translation matrix.
A xeon lamp is used as a light source. The lamp is small and placed far enough from the object so that we can assume the lamp is a point light source. In order to illuminate the object with linearly polarized light, a linear polarization filter is placed in front of the lamp.

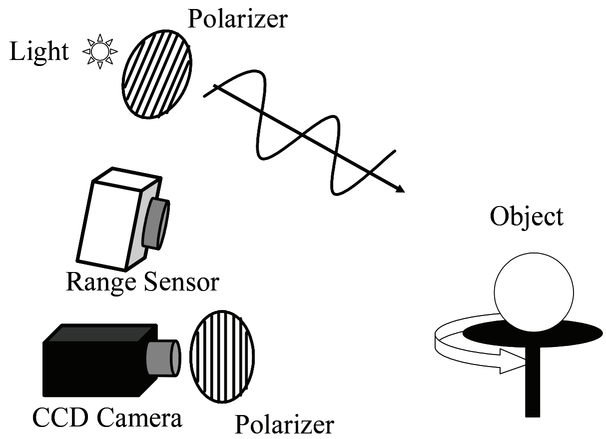


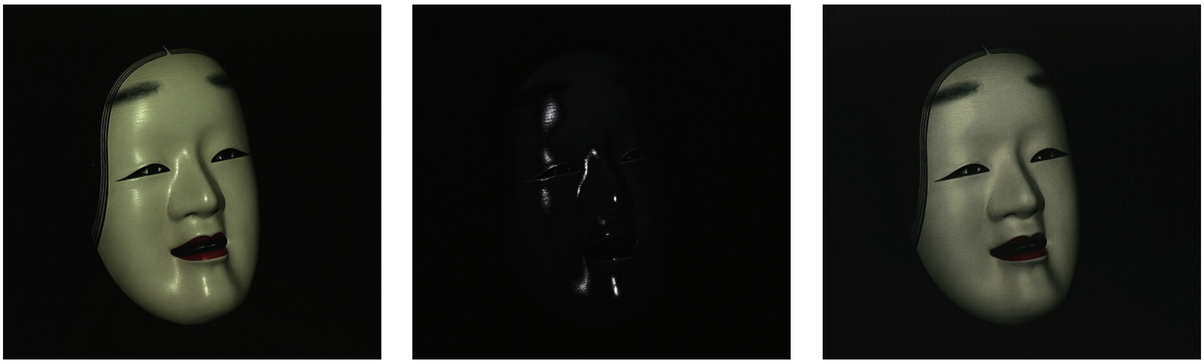
Figure 4. Image acquisition system

5. SEPARATION OF REFLECTION COMPONENTS

In our experiments, images of a target object are taken every five degrees filer rotation, i.e., 35 images in total. Then, the maximum intensity I_{max} and the minimum intensity I_{min} are determined for every image pixel. Theoretically, only three images are sufficient for determining I_{max} and I_{min}. However, for increasing robustness of estimation of I_{min} and I_{max}, we uses more images by rotating the polarization filter. If $I_{min} - I_{max}$ for a certain pixel is less than a threshold, we consider the pixel to contain only the diffuse component. If $I_{max} - I_{min}$ is larger than a threshold value, we consider that the pixel contains the specular component and that $I_{max} - I_{min}$ is equal to $2I_v$ and I_{min} is equal to I_c.
In summary, our separation technique is proceeded as follows. First, a linear polarization filter is placed in front of the light source and camera. Second, input images of an object are captured for every 5 degree rotation of the polarization filter in front of the camera. Third, I_{max} and I_{min} are determined for each pixel. If $I_{max} - I_{min}$ is larger than a threshold value, we determine the pixel contains the specular component and the intensity of the specular component is obtained from $I_{max} - I_{min}$. I_{min} is used for determining the intensity of the diffuse component.
Figure 5 shows an example of reflection component separation by using our proposed method. For comparison, we show another image which were captured without a polarization filter. It shows that the specular and diffuse reflection components were successfully separated even if they have the similar color.

6. PARAMETER ESTIMATION

After separating the reflection components, we determine the reflection parameters using the separated reflection component images.



(a) (b) (c)

Figure 5. (a)Original image, (b)Specular component, (c)Diffuse component

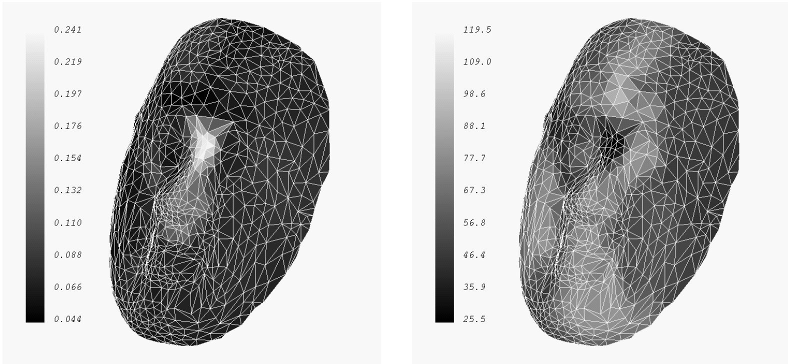
Figure 6. Estimated diffuse parameter image

6.1. Diffuse Parameters Estimation

Using the separated diffuse reflection image, we can estimate the diffuse reflection parameters $(I_{D,R}, I_{D,G}, I_{D,B})$ without undesirable effects from the specular reflection component. The incidence angle θ_i can be obtained by range sensor and camera calibration.
Figure 6 shows the estimated diffuse parameter image. We can see the object surface color which is not attenuated due to the incidence angle.

6.2. Specular Parameters Estimation

After estimating the diffuse parameters, we also estimate the specular parameters $(I_{S,R}, I_{S_G}, I_{S_B}, \sigma)$ using the angle α and the angle θ_r as a known information.
As described in the Section 3, separated specular images are attenuated by a certain ratio determined by Fresnel reflection coefficients. But attenuation ratio is constant overall highlight region, we can correctly estimate the specular parameters. More precisely, the Fresnel reflection coefficients are dependent on the incidence angle. However, the Fresnel coefficients are constant around the incidence angle of less than 30 degree, and the specular reflection is observed only near the surface normal direction in our experimental setup. Therefore, by setting the light and camera in the same direction, we can assume that the Fresnel reflection coefficients are constant.
There is a significant difference between estimation of the diffuse and specular reflection. Diffuse reflection can be observed overall the object surface where illuminated by a light. On the other hand, specular reflection is observed from a limited viewing direction, and is observed over a narrow area of the object surface. So, we have to select the sampling pixel carefully for specular parameters estimation. We used the same strategy described in.[13] Figure 7 shows the estimated σ and I_S which are projected on the mesh model.



(a) (b)

Figure 7. (a)Specular parameter(σ) image, (b)Specular parameter(I_S) image

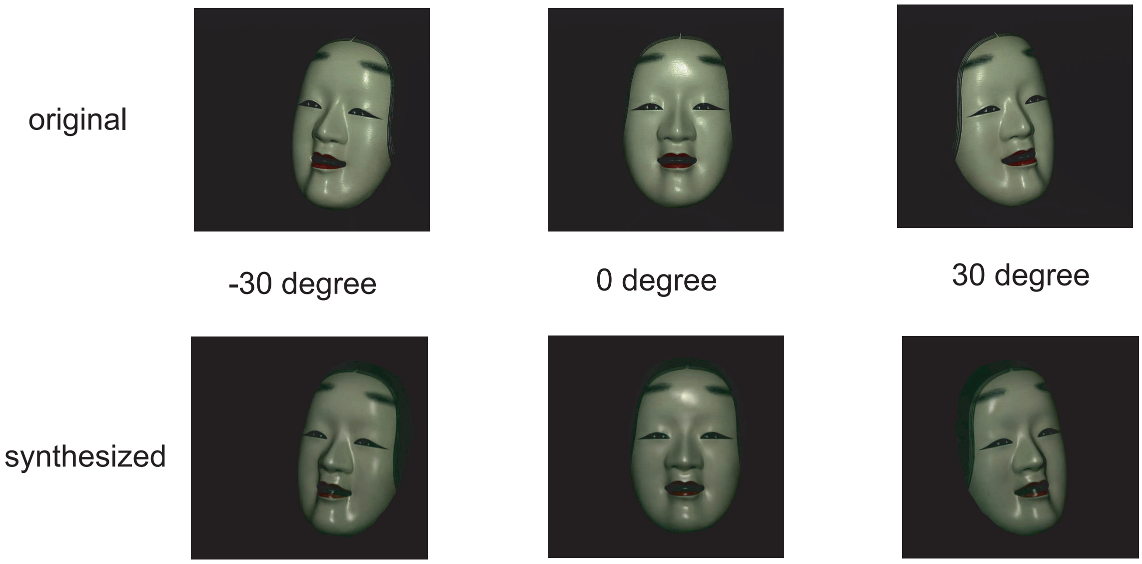


Figure 8. Comparison between input images and synthesized images

7. SYNTHESIZED IMAGES

Using the diffuse and specular reflection parameters estimated in the previous section, and the surface mesh model of the object, we synthesized virtual images of the object under different illumination and viewing conditions. Figure 8 shows the comparison between original images and synthesized images viewed from different directions.

Comparing the synthesized images with the original images, we notice that synthesized images are darker than the original images. I think this is caused by the variation of the polarizer's optical density with respect to the wavelength. In order to avoid this problem, we should have calibrated white balance every before capturing images without polarizer and before capturing images through polarizer.

8. CONCLUSION

In this paper, we proposed a new method for separating the reflection components using polarization. Unlike the previously proposed methods, our method does not require the difference of color between the specular reflection and diffuse reflection. So, our method can robustly separate the reflection components even if objects have a white texture and illumination color is white. After reflection components separation, we estimate the parameters of a reflection model by using the separated reflection components. By synthesizing virtual images under the arbitrary illumination and viewing, we have shown that the reflection parameters are successively estimated from the separated reflection components. Future work includes calibrating white balance because synthesized images are darker than the original images. And more, we should examine to use circuler polarizer for separating specular and diffuse components easier. For large scale data, we will consider data compression way to keep data efficiently.

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