Separating reflection components using polarization and Determining reflectance parameters

偏光による反射成分の分離および反射パラメタの決定

by

Toru Takahashi

高橋 徹

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Thesis Supervisor: Katsushi Ikeuchi　　池内克史

Title: Professor

ABSTRACT

This paper describes the method to separate the reflectance components and determine the reflectance parameters of optically rough surface from real images which are captured through polarization filter. The reflectance model which is used in this paper consists of two components: specular component and diffuse component. Specular component represents the surface reflection. On the other hand, diffuse component represents the reflection resulting from the internal scattering mechanism.

If polarization of light is used as a light source, specular component is polarized, but diffuse component is not polarized. So, we can separate the two components by capturing images through polarization filter. After separating the two components , we determine the reflectance parameters using least square method. To examine this method, I implemented this method and applied it to real object.

論 文 要 旨

本論文では、光学的に荒い表面を持つ物体について、偏光板を通して撮影された画像から反射光の成分分離および反射パラメータ決定を行う方法について述べる。この論文で使われる反射モデルは２つのコンポーネントからなる：specular component と diffuse component である。specular component は表面反射を表す。一方、diffuse component は内部乱反射の結果として生成される反射光を表している。

光源として偏光をもちいた場合、specular component は偏光するが diffuse component は偏光しない。よって、偏光板を通して画像を撮影することにより、２つのコンポーネントを分離することができる。２つのコンポーネントを分離した後、最小２乗法によって反射パラメータを決定することができる。この方法を検証するため実装を行い現実物体に適用してみた。

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Chapter 1

Introduction

Measuring reflection property from images is very important in computer vison research. Since surface reflectance is directly related to surface roughness and the polishness, surface reflectance is used as a imoprtant criteria in many industrial applications. In addition, 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-throughs. 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. The easy method for determinig reflectance properties will contribute to the automatic modeling system because if the reflectance parameters are previously measured for various materials, the time to manually adjust the reflectance parameters of virtual reality model can be left out.

Reflection is usually classified into two broad categories:specular and diffuse. There are many reseaches in saparating reflection comopnents, however, there are a few attempts to directly exract either or both of the raflectance parameters. This paper proposes the method for determinig reflectance parameters from images captured by CCD camera.

In order to determine the reflectance parameters, this study uses two polarization filter, one is used to produce linearly polarized light source, the other is used to measure the polarization in the reflection. Since specular and diffuse reveal diffferent properties from each other when polarization is used as a light source, we can separate the componets by capturing the images through polarization filters. After separatnig reflectance components, the parameters which effect the reflectance property are determined respectively.

In this paper, section2 describes the details of reflection model. Section3 describes the method for separating the reflectance components and determining the reflectance parameters. Section4 describes the experimental setup and the experimental results. The final section summaraize the experiment and discuss the room for improvement of the proposed method.

Chapter 2

Reflection Model

Various reflectance models have been proposed by the researchers in applied physics and computer vision. In general, these models are classified into two categories: Specular reflectance model and Diffuse reflectance model.

Diffuse reflectance model represents the rays resulted from the internal scatering mechanism. The rays penetrate the surface and encounter microscopic inhomogeneties in the surface. The rays are repeatedly reflected and some of the rays are re-emitted to the surface with a variety of directions.

Specular reflectance model, on the other hand, represents the rays reflected on the surface of the object. The surface may be assumed to be composed of several planner elements, each of which has its own orientation that differs from the large-scale local orientation of the surface. The result is a specular component that spreads around the specular direction and that depends on the surface roughness for the width of the distribution.

In the following subsections, first, the details of specular reflectance model and diffuse reflectance model are described . Next, genaral reflectance model, which is unified specular and diffuse reflectance model, is described.

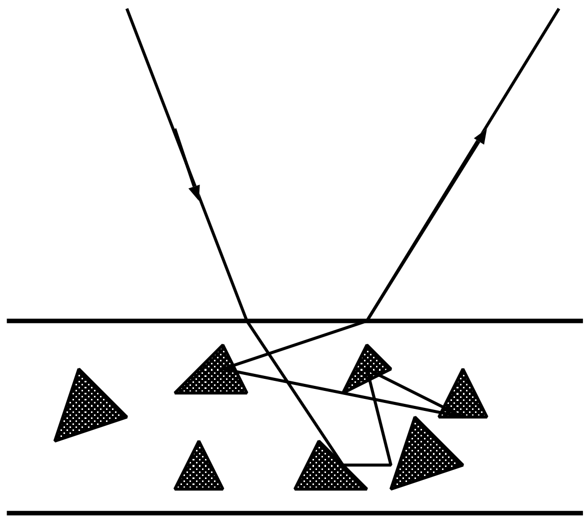

Figure 2.1: Diffuse reflection resulting from the internal scattering mechanism

2.1 Diffuse component

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 refleced. The penetrating light hits internal pigments of the objects, and is re-emitted randomly(Fig**??**). Lambert is the first who modeled this phenomenon. The formula Lambert deduced is:

$$\begin{aligned} I_{diff} &= C_{diff}\vec{N}\cdot\vec{S} \\ &= C_{diff}\cos\theta_i \end{aligned} \tag{2.1}$$

where I_{diff}, C_{diff}, $\vec{N}$, $\vec{S}$, θ_i are the brightness, a propotional 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 incident light but depend on the reflection angle.

2.2 Specular components

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.

2.2.1 Physical opticas 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 hight 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 palner microfacets, and the facet slopes are assumed to be normally distributed.

- The size of palnner facets is much greater than the wave length of inciednt 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 disatance 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.

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, pysical 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 opticas 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[**?**] proposed the general reflectance model. This model consits 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 coodinate 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 surafce 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

$$I = C_{ss}\delta(\theta_i - \theta_r)(\phi_r) + C_{sl}\frac{\exp(-k\alpha^2)}{\cos\theta_r} + C_{diff}\cos\theta_i \tag{2.2}$$

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 surce 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

$$g = (2\pi\frac{\sigma_h}{\lambda}(\cos\theta_i + \cos\theta_r))^2 \tag{2.3}$$

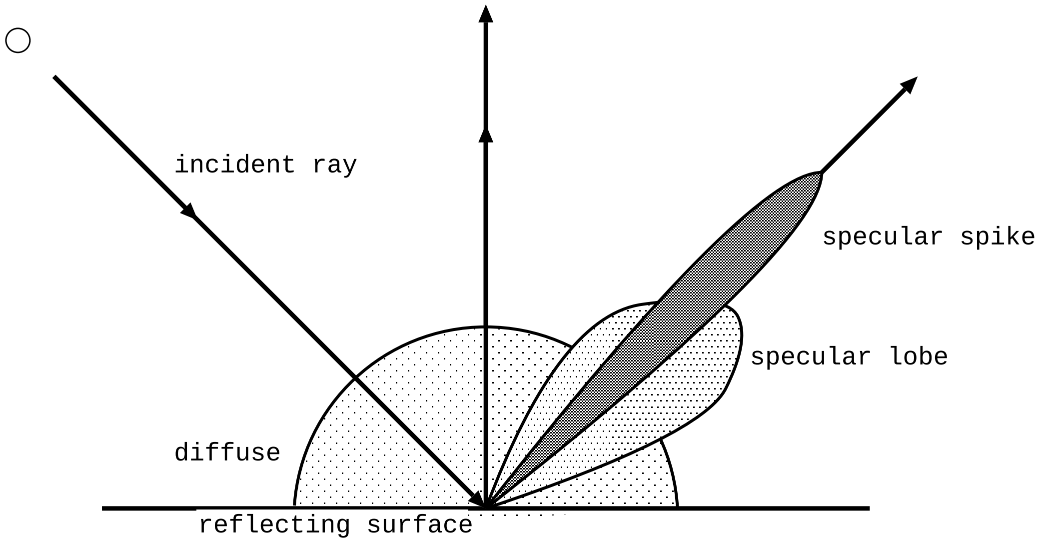

Figure 2.2: Diagram of the Unified Reflectance Model

where σ_h, λ are the root-mean-square of the height disrtribution, and the wavelength, respectively. For smooth surface ($g \ll 1$) , the spike component is dominant. As the roughness incrrease, however, the spike componet 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_{sb} are both significant.

Chapter 3

Method for extracting reflectance parameters

In this section, the detals of the method for determing reflectance parameters from the images are explained.

In this study, the surface of the observed object is assumed to be optically rough. For this assumption, the specular spike componet can be ignored and the follwing equation is obtained from the general reflectance model(Eq2.2)

$$I_{rough} = C_{sl} \cos \theta_i + C_{diff} \frac{\cos(-k\alpha^2)}{\cos \theta_r} \tag{3.1}$$

For the specular spike and specular lobe hardly can be dominat at the same time, it has little problem to completely omit the specular spike component by assuming that the surface is optically rough.

In order to determine the reflectance parameters, the following two steps are used. First, the image is divided into specular lobe component and diffuse component. The polarization filter is used in order to divide the components.

Next, for each component(diffuse and specular lobe), the reflectance parameters are dertermined by using the least-square-method.

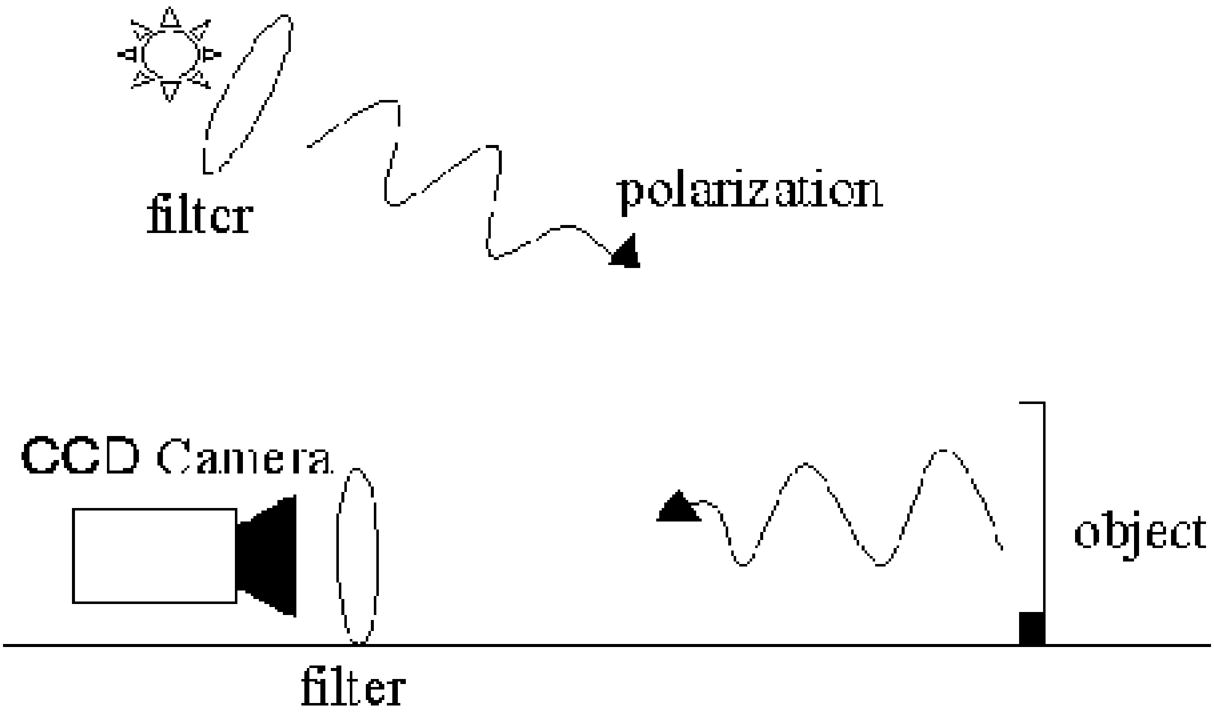

Figure 3.1: The image of the experimental setup

3.1 Separating the reflection components using polarization

For separating the reflectance components, two polarization filters are uesd. One of them is laid in front of the light source, and the other is in front of the camera. Fig ?? shwos the surface illuminated by the polarization and taken image through polarization filter. From the previous section, the reflection from surface is described as

$$I_{total} = I_d + I_s \tag{3.2}$$

where I_{total} represents the total intensity of the reflection and I_d, I_s represents the diffuse component and specular component respectively. The incident light is completely polarizaed by the polarization filter. For the reflection, the polarization state is dependent on several factors including the material of the reflecting surface element, and the type of reflection component(diffuse or specular). Diffuse comopnent tends to be unpolarized because of the internal random reflections. So, rotating the polarization filter laid in front of the camera does not alter the image brightness if the reflection includes only diffuse componet. In contrast, specular component tends to be polarized and rotating the polraization filter alter the image brightness. As a result, specular component can be expressed as a cosine function:

$$I_s = I_{sv} \cos 2(\theta - \beta) \tag{3.3}$$

where I_{sv} is an amplitude, θ is the angle of the polarization filter(in front of the camera), and the β is the phase angle. Substituting Eq **??** for Eq **??**, we can obtain the below equation:

$$I_{total} = I_d + I_{sv} \cos 2(\theta - \beta) \tag{3.4}$$

Fig.**??** shows the relation between the image brightness and the angle of the polarization filter.

Since only specular component is dependent on the polarization filter angle, the specular component is equal to the $I_{max} - I_{min}$(Fig. **??**), and the diffuse component is equal to the I_{min}. So that, we can separate the reflection components by using polarization. In this study, concretely, images are taken every five degrees filetr rotation. After that, I_{max} and I_{min} are extracted for every pixel.

To summarize the our separation technique, it is like the following steps. First, laying the polarization filter in front of the light source and camera. Second, capturing images with the every 5 degree rotaion of plarization filter. Third, detecting the I_{max} and I_{min} for each pixel. $I_{max} - I_{min}$ represents the intensity of the specular component, and I_{min} represents the intensity of the diffuse component.

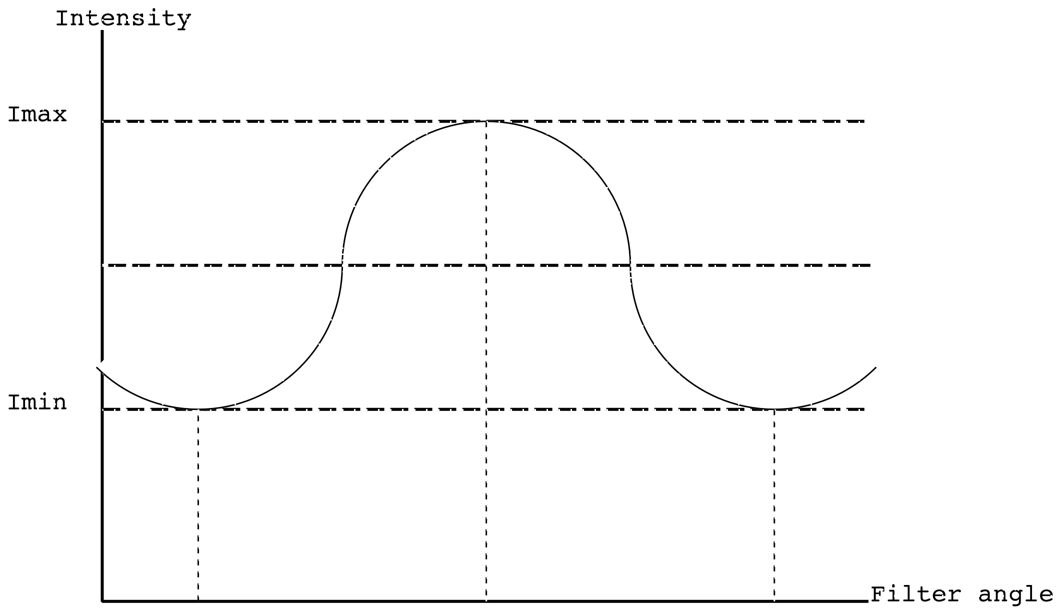

Figure 3.2: Image brightness plotted as a function of the filter angle

3.2 Determing the reflection parameters for each component

After separating the reflection components, reflectance parameters are determined. In this study, the assumption is made that information, such as surface orientation, surface patches coordinates, camera coordinates, and light source coordinates are already known. Ikeuchi, and Sato [?] use range sensor to obtain the surface geometric information. But, in this study, geomety is measured manually for the simplification.

3.2.1 Diffuse parameters

Diffuse parameters are determinned from the image of diffuse component which are obtained by the method of previous section. The theoretical brightness of each pixel is denoded as

$$I_{cldiff}(x,y) \quad = \quad A\cos\theta_i$$

$$= A\vec{N}(x,y) \cdot \vec{S} \tag{3.5}$$

where $\vec{N}(x,y)$, and $\vec{S}$ are surface orientation vector and light source direction vector, respectively. By the assumption, geometrical information is available. So, $\vec{N}(x,y)$, and $\vec{S}$ are already knwon, and, only A is needed to determine. In order to obtain A, least-square-method is used, that is, it is possible to obtain the diffuse parameter A by minimizing the following δ

$$\delta = \sum_{x,y} (A\vec{N}(x,y) \cdot \vec{S} - I_{obdiff}(x,y))^2 \tag{3.6}$$

where $I_{obdiff}(x,y)$ is the observed diffuse brightness.

3.2.2 Specular parameters

Theoretically, the specular brightness satisfies the following formula

$$I_{clsp}(x,y) = B \frac{\exp(-k\alpha(x,y)^2)}{\cos\theta_r(x,y)} \tag{3.7}$$

By using the surface orientation, the viewer, and the source direction, the parameters $\alpha(x,y)$, $\theta_r(x,y)$ are calculated for each pixel. Since Eq(3.7) is nonlinear, logarithm is used to apply the least-square-method. So, $\alpha(x,y)$ and $\theta_r(x,y)$ are obtained by minimizing the following δ

$$\delta = \sum_{x,y} (2k\alpha(x,y)^2 - \ln\cos\theta_r(x,y) - \ln B - \ln I_{obsp})^2 \tag{3.8}$$

where I_{obsp} is the observed specular brightness.

Chapter 4

Experiments

The experiment is conducted with the proposed method. As a sample object, green-cup is selected. The cup is made of plastic, and the shape is , approximately, regarded cylindrical. The image is taken by SONY DXC-960MD COLOR CCD CAMERA. After reflectance parameters are calculated, the cylinder image is synthsized usinig the obtained reflectance parameters.

4.1 Separating components

The images of green cup are taken every five degrees polarization filter rotation(from 0 degree to 175 degree). After that, one of the images is separated into specular component and diffuse component. Fig?? is an original image before separated into reflection components. Fig?? is the separated specular comonent. It is obvious that the specular component is separated. Fig?? is the separated diffuse cup. The image does not have highlight, and only green reflection can be observed. It can be said that the diffuse component is well extracted.

Fig ?? is the separated specular component. Only white highlight is extracted. So, it seems that diffuse reflection is not included in this image.

Figure 4.1: Original Image

Figure 4.2: Separated diffuse component

Figure 4.3: Separated specular component

4.2 Determining parameters for each component

From the separarted component images, reflectance parameters are calculated. In order to examine these calculated parameters, images of circular cylinder, which has the reflectance property calculated by using general reflectance model and the obtained parameters, are created.

4.2.1 Diffuse parameters

Fig.?? is the synthesized cylinder which does not have specular component. Its color tone is similar to the separated diffuse image??.

4.2.2 Specular parameters

Fig.?? is the synthesized specular component. It seems that obtained specular parameters are almost correct, but synthesized image is a little redder than the

Figure 4.4: Synthesized lambert component

Figure 4.5: Synthesized specular component

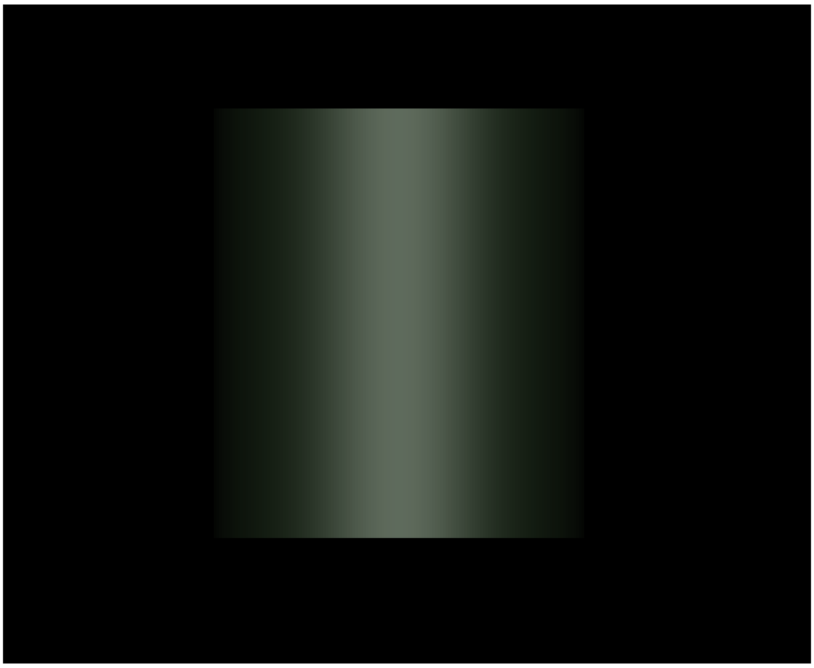

Figure 4.6: Synthesized image

Table 4.1: Obtaine reflectance parameters

Variable	RED	GREEN	BLUE
C_{diff}	2.481×10	4.059×10	2.299×10
C_{sp}	4.298×10	2.347×10	2.393×10
k	2.260×10	2.556×10	$1.852\times$

separated specular image. Table **??** is the list of parameters obtained in this experiment. Fig.synthesize is the complete synthesized image which includes both specular and diffuse components.

Chapter 5

Conclusion

From the experimetal results, the reflectance parameters are obtained correctly by the proposed method. This method requires only three devices (polarization filter, light, and CCD camera)to obtain reflectance parameters. So, it satisfies the purpose to develop the simple method for determining reflectance parameters. Using this method, we can easily make up the color model from real world.

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