Estimation of Reflection Parameters from a Single Image for a Free-form Object

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Abstract

Specular reflectance is important in creating a realistic CG model. This paper describes a method for estimating reflectance parameters for an object with free-form surface from a single image using readily available equipments: a PC, a digital camera, and a lighting unit. The object surface is classified according to texture color. The reflection property is estimated for each color region. The camera is directed to a relatively even or flat region to form a highlight. Then reflection parameters are estimated based upon the pixel values of an HDR (High Dynamic Range) image. Experiments were conducted for two objects. Good agreement between the actual photograph and the corresponding synthetic image with the Torrance-Sparrow reflection model was obtained.

Keywords: *3D CG, 3D geometric object, Reflection property, BRDF, Torrance-Sparrow reflection model.*

1. Introduction

In the field of Computer Graphics (CG), it is an important task to generate a CG model from a real-world object. For a virtual museum application, for instance, it is desired to truely preserve not only its shape but also the optical property of its surface. Generally, an object shape can be readily acquired by a scanner as geometrical data, and surface color can be acquired by a digital camera as texture data. The remaining optical property is the reflection property, which is the topic of this paper. Generally a number of camera images with tilting a camera are required to measure the reflection property of a point on the surface.

This paper describes an estimation method for measuring the reflection property using readily available equipments.

1.1 Related works

Various reflection models such as the Phong reflection model[14], the Torrance-Sparrow reflection model[18], the Cook-Torrance reflection model[2], The Oren-Nayer reflection model[13], and the Ward reflection model[19] have been proposed, and it is now possible to create a realistic 3D CG image based upon one or more of these reflection models.

Sato et al.[7,16] proposed a method for estimating reflection parameters from a sequence of photographs by rotating an object of interest with a robot arm. The parameters of specular reflection and diffuse reflection were separately estimated, while the 3D geometric data were acquired with a range finder.

Tominaga et al.[17] proposed a method for estimating the reflection parameters of the Phong reflection model for a cylindrical object based on a single color image.

Debevec et al.[4] developed a two-axis rotation system with a directional light to measure the reflectance field of a human face. Gardner et al.[6] developed a specially designed linear light spectrometry apparatus to estimate the diffuse color, specular color, and specular roughness at each point of the object surface.

Dana et al.[3] introduced the BTF for textures and BRDF (bidirectional reflection distribution function) for specular reflectance. They investigated the dependence of appearance on the geometry of viewing and illumination directions. Ramamoorthi and Hanrahan[15] presented a signal processing framework that described the reflected light field as a convolution of the lighting and BRDF. They introduced inverse rendering as a deconvolution. Jensen et al.[10] introduced a model for subsurface light transport in translucent materials and developed measurement techniques for determining the optical properties of translucent materials.

Boivin et al.[1] proposed a method for approximating the BRDF of object surfaces from a single image and a 3D geometric model. Their photometric method is based on Ward's BRDF model. It iteratively compares the original photographic image and a synthetic image generated based upon adjusted BRDF parameters until the difference between the two images becomes smaller.

Lensh et al.[11,12] proposed a method for estimating a basis of the BRDF's for deriving a spatially varying BRDF representation from a small number (generally 15

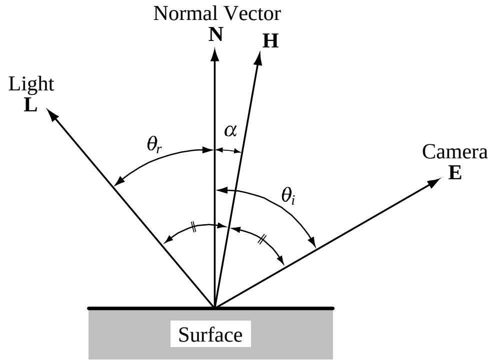

Figure 1. Parameters involved in the reflection model. **E**, **N**, **L** are camera direction, surface normal, light direction vectors. $\mathbf{H} = (\mathbf{E} + \mathbf{L})/2$.

to 25) of photographic images. The surface of an object is segmented by a texel based clustering process.

The method to be presented utilizes only affordable components (i.e. a digital camera with a commercially available illuminating light). It is assumed that the surface reflection properties depend on the surface color of an object.

2. Method of Estimating Reflectance

2.1 General Principle

The reflected light from an object consists of two components: diffuse reflection and specular reflection. The first is known to obey Lambert's cosine law which has the property of equal intensity in all directions. The second component appears on a surface as a highlight. The specular reflection can be observed at the direction of reflection angle on the surface of object which is on the opposite direction of the incident angle. The Phong model is widely used, but the Cook-Torrance model or the Torrance-Sparrow model which utilizes more precise physical law has been used more often recently.

This paper is concerned with reflection parameters of the Torrance-Sparrow model. The equation to represent the Torrance-Sparrow model given by Sato et al.[16] is as follows (see Figure 1):

$$I = K_D \cos(\theta_r) + \frac{K_S}{\cos(\theta_i)} \exp\frac{-\alpha^2}{2\sigma^2} \tag{1}$$

where I is the pixel value (R, G, B), K_D is the diffuse reflectance coefficient, K_S is the specular reflectance coefficient, and σ is the roughness of surface. Let **N** represent the normal vector of the polygon, and **E** the view vector from the camera to the polygon, and **L** the incident light vector to the polygon from the light source. Then the following relationships hold.

$$\cos(\theta_i) = \mathbf{N} \cdot \mathbf{E} \tag{2}$$

$$\cos(\theta_r) = \mathbf{N} \cdot \mathbf{L} \tag{3}$$

$$\cos(\alpha) = \mathbf{N} \cdot \mathbf{H} \tag{4}$$

$$\textit{where } \mathbf{H} = (\mathbf{E} + \mathbf{L})/2 \tag{5}$$

where θ_i is the angle between the normal vector and a view vector (Eq. (2)), θ_r is the angle between the normal vector and the light vector (Eq. (3)), and α is the angle between the normal vector and the average of the view vector and the light vector (Eq. (4)).

The values of I, θ_r, θ_i, and α are obtained based on observation data. Three parameters of K_D, K_S, and σ are likewise estimated. The method of deriving these parameters is the main topic of this paper.

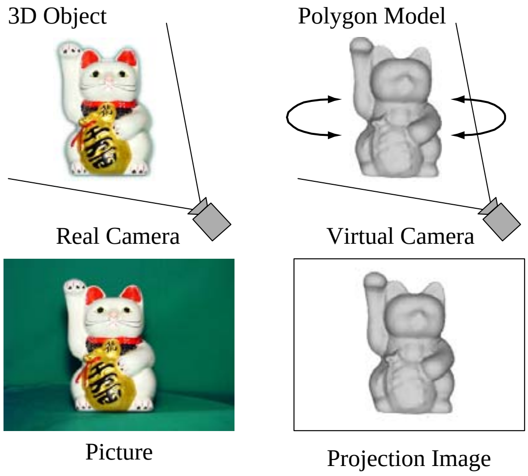

Figure 2. Real and virtual optical system.

2.2 Outline of our Method

In order to estimate reflection values from a single image, the specular highlight appearing on the surface is utilized. In addition, the camera position is estimated from a photograph, and each pixel of the photograph can be located on the 3D geometric model that is assumed to be known by other means such as a laser scanner or a CT scanner. The relationship among the camera, the light, and surface of the object needs to be identified for each pixel of the image to derive the reflection property.

The camera position is estimated by using silhouettes of an object of interest[9]. Hence it is possible to make precise correspondence between the 3D geometric model and the photograph. A lighting unit is attached to the top of the camera with an attachment. Therefore its precise position can be derived based upon the known geometrical relationship between the camera and the lighting unit. Three parameters of θ_r, θ_i and α (see Eq. (1)) are obtainable based upon this relationship.

It is pointed out here that our proposed method requires only commercially available equipments which are readily affordable.

Usually there is a very wide range in highlight values. Over saturation or under saturation can frequently take place with any setting of a single shutter speed. In order to broaden the the dynamic range of a camera, a scheme called high dynamic range(HDR)[5] is utilized. It limits the incoming light energy by controlling the shutter speed. A detailed description is given in section 3.2.

2.3 Estimation of Camera Position

The problem of estimating the camera position from a photograph is described here. We consider two optical systems shown in Figure 2: a real system and a virtual system. The real system consists of a real-world object and a real digital camera. The virtual system is a counterpart in a computer.

For estimating the camera position from a photograph, it is required to identify six unknown camera parameters (three parameters in a translation matrix **T** and three parameters in a rotation matrix **R**). It is carried out in the virtual optical system so as to, with varying the six parameters, minimize the difference between the

Figure 3. Photograph (front and back view).

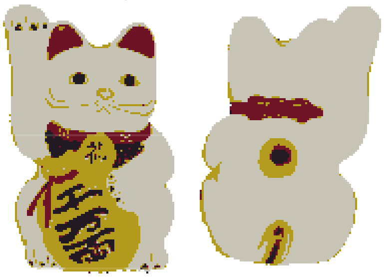

Figure 4. Classification result (front and back view) where the surface is classified into four colors (white, red, gold and black).

silhouette derived from the photograph taken with the real camera and that from the virtual camera photograph. A simplex method is applied to this minimization problem[8,9].

2.4 Locations for Estimation

It is assumed that reflection parameters of our object of interest depend upon the color of surface region. This is generally applicable to painted objects such as wood works and earthenwares (pottery). Hence the reflection property is estimated for each color region.

(1) Region classification based on color

The pottery cat shown in Figure 3 has four colors on its surface. Since each color is due to a glaze or enamel, it may be assumed that the region with a color have an identical reflection property. Several photographs were taken and mapped on the surface of the 3D model. A diffused light source should be used to avoid specular reflection. Classification based on color was applied to the entire surface. The result is shown in Figure 4.

(2) Selection of even surface areas

Even or flat surface areas are preferred because rugged surface areas reflect light in a complicated manner. Therefore the degree of curvature that indicates surface flatness is examined at every surface point. This is done as follows. Consider all the surface polygons with a same color which are within a distance of d from a given point. (For our examples, d is set to be 1[cm].) Then curvature c at the point (or pixel) is defined as the maximum of the difference between the normal direction of the center polygon which contains the pixel and that of every polygon within distance d. It is to be noted that $c = 0$ for completely flat surface and c becomes larger for more rugged surface. Then a threshold of 30[degrees] is selected to determine whether a surface point is suitable for measurement. For the pottery cat, dark gray areas of Figure 5 show suitable regions with curvature smaller than 30[degrees]. It is required to direct the camera to suitable part other than the dark gray areas to measure specular parameters.

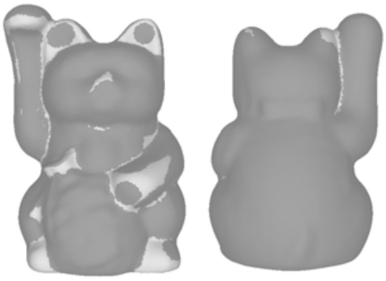

Figure 5. Dark gray areas show relatively even or flat regions suited to measurement while Light gray regions show unsuitable rugged regions.

2.5 Estimation of Reflection Property

The reflection property is estimated based upon HDR images. The details of obtaining HDR images will be described in section 3 (Experiment).

It is necessary to observe a specular highlight in order to estimate the reflection parameter. The camera is directed toward suitable areas (as mentioned in the previous subsection) so as to observe a highlight. An HDR image is a composite image of photographs with different shutter speeds, while the camera is kept stationary. Estimation is based on pixel values of the HDR image. The center of the highlight which is usually circular or oval is detected. Then the polygon to which the highlight center belongs is identified.

Values θ_i, θ_r, and α are obtained in each vertex of each polygon. Values of an internal point are interpolated based upon the values at three corners.

The derivation of reflection parameters is based on an X-Y plot where X-axis represents α and Y-axis the pixel value, I, of the HDR image. Finally reflection parameters K_D and K_S with σ in Eq. (1) are derived based on this plot. Details are in subsequent subsections.

2.6 Estimation of Diffuse Reflection Parameter

The first task is to determine K_D, the diffuse parameter in Eq. (1). Following the method of Sato et al.[16], a slowly varying part excluding the sharply projected parts near the origin is utilized. The diffuse parameter K_D is estimated from the following equation:

$$K_D = \frac{\sum I}{\sum \cos(\theta_r)} \qquad (6)$$

2.7 Estimation of Specular Reflection Parameters

Once the diffuse parameter K_D is estimated based on Eq. (6), the next task is to estimate specular parameter K_S and the degree of sharpness σ using Eq. (7).

$$I_{specular} = I - K_D \cos(\theta_r) \qquad (7)$$

Actually, the process of estimating K_D and that of K_S and σ are iterated several times to minimize the total estimation error.

2.8 Texture Mapping

Textures acquired for the reflection property may not be used for texture mapping. The main reason is that the textures of highlighted areas are difficult to estimate or recover. Therefore, non-saturated photographic images taken under defused fluorescent lamps are mapped to the 3D surface of the object with the process described in reference[9].