Simple Surface Reflectance Estimation of Diffuse Outdoor Object using Spherical Images

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Abstract

This paper proposes a new, efficient method to estimate reflectance parameters of diffuse outdoor objects from only one measurement with a spherical camera. The camera we used captures nearly 75 percent of a 360-degree field of view; thus, it captures the radiance of an object and illumination environment at one shot. By taking the known object's shape into account, the illumination effect is calculated and the surface reflectance is derived. Measurement and data-processing cost will be greatly decreased by this method compared to previous methods that need elaborate procedures. Neither specific apparatus nor calibration of the camera gain factor is needed.

1 Introduction

Computer vision and graphics techniques to create a realistic model of a real world object have attracted interest from a wide range of research fields and industries in recent years. To simulate the accurate appearance of an object, we have to know the object's (1) shape and (2) surface reflectance properties. Acquiring shape information has been facilitated by the development of sensors and the progress of data processing algorithms.

For calculating surface reflectance properties, one would need (1) the shape of a target object, (2) the actual appearance of the object, and (3) illumination environment. Shape information and actual appearance can be obtained by range and image sensors, respectively.

The illumination environment can be acquired in several ways. Yu et al., the first who handled outdoor objects, took photographs of the sun and sky to measure their radiance distribution [1]. As they used a normal camera, they included landmarks in each photograph so that they could use them to recover the camera pose later. The position of the sun was calculated by the time and date, and the sky radiance was fitted to the CIE (International Commission on Illumination) standard model to extrapolate the missing portion of the sky. They first recovered diffuse reflectance from measured sky irradiance and from appearance, and then they acquired specular properties by fitting multiple photographs to the Lafortune model. Debevec et al., the second and the latest to tackle the outdoor problem, used a specific apparatus to measure the outside illumination [2]. They used a mirrored sphere to image the sky and clouds, a shiny black sphere to indicate the position of the sun, and a diffuse grey sphere to indirectly measure the intensity of the sun. They decided the reflectance parameters of the previously obtained BRDF (Bidirectional Reflectance Distribution Function) by an iterative calculation using the object's photographs from multiple views.

This paper proposes a new, efficient method to estimate reflectance parameters of diffuse outdoor objects from only one measurement with a spherical camera. The spherical camera we used captures nearly 75 percent of a 360-degree field of view [4]; thus, it captures the radiance of an object and illumination environment at one shot. By taking the known shape of the object into account, the illumination effect is calculated and the surface reflectance is derived. Measurement and data-processing cost will be greatly decreased by this method. Neither specific apparatus nor calibration of the camera gain factor is needed. However, the camera should cover a high dynamic range in order to measure both the intensity of the sun and the object. The shape of the object and the pose of the spherical camera are assumed to be known. We also assume that the target object only has diffuse reflection, and outdoor illumination is at infinity.

2 Scene Radiance Acquisition with a Spherical Camera

The radiance distributions of the object and surrounding illumination can be captured at one shot by using a spherical camera which has nearly 360-degree field of view.

Illumination radiance As Fig.1 shows, the camera records the spherical radiance distribution of illumination at the camera center C. Let us denote the incident radiance distribution of illumination as $L(\lambda, \theta, \phi)$, where λ is the wavelength, θ and ϕ are the polar and zenith angles.

When recorded by a camera, the light will be multiplied by the camera sensitivity function $q_k(\lambda)$, then integrated over the visible spectrum Ω. Thus, image intensity I_k will be; $I_k(\theta, \phi) = \tau \int_{\Omega} L(\lambda, \theta, \phi) q_k(\lambda) d\lambda$, where k and τ are

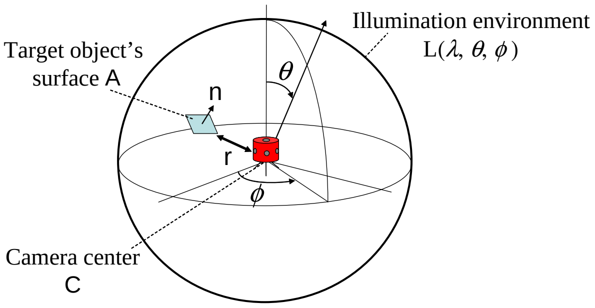


Figure 1: Scene radiance acquisition by the spherical camera.

the type of sensors and the camera gain. Assume that the camera sensitivity can be approximated by a Dirac's delta fuction (*narrow-band camera assumption*), the wavelength λ can be considered as a constant;

$$I_k(\theta, \phi) \simeq \tau L(\lambda_k, \theta, \phi) \qquad k = \{r, g, b\}. \tag{1}$$

Surface radiance The camera also records the radiance of the object's surface. Let us consider the irradiance E, at the surface point A in Fig.1. As shown in Fig.2(a), the irradiance E is the sum of the incident radiance $L_i(\lambda, \theta_i, \phi_i)$ from the hemisphere whose north pole is at the surface normal direction [3];

$$E(\lambda) = \int_{-\pi}^{\pi} \int_{0}^{\frac{\pi}{2}} L_i(\lambda, \theta_i, \phi_i) \cos\theta_i \sin\theta_i d\theta_i d\phi_i. \tag{2}$$

$\sin\theta_i d\theta_i d\phi_i$ is the solid angle $d\omega_i$ at the direction (θ_i, ϕ_i), as shown in Fig.2(b).

The radiance I of the point A will be the multiplication of irradiance E and the surface reflectance S;

$$I(\lambda) = \int_{\omega} S(\lambda) L(\lambda, \theta_i, \phi_i) \cos\theta_i d\omega_i = S(\lambda)E(\lambda) \tag{3}$$

as we assume a Lambertian surface. $S(\lambda)$ and $I(\lambda)$ are uniform regardless the viewing direction.

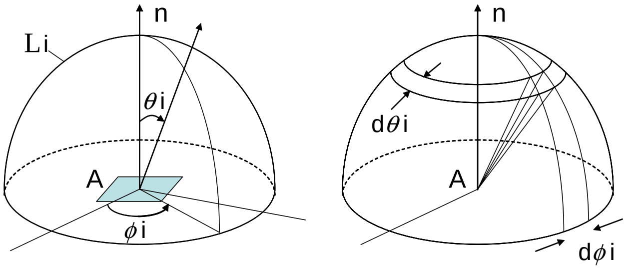
The light $I(\lambda)$ will be filtered when recorded by a camera. By using the narrow-band camera assumption, the wavelength λ becomes a constant;

$$I_k = \tau S_k E_k. \tag{4}$$

3 Reflectance Estimation from Scene Radiance and Object's Shape

Let us consider again the irradiance which the point A in Fig.1 receives. Owing to the assumption that the illumination is at infinity, the r in Fig.1, the distance between the camera and the point A, can be approximated as zero compared to the distance to the illumination. For this reason, surrounding illumination seen from the camera and the object surface is nearly equal;

$$L(\lambda, \theta, \phi) \simeq L_i(\lambda, \theta_i, \phi_i). \tag{5}$$



(a) (b)

Figure 2: (a) the direction of incident light rays. (b) solid angle at the direction (θ_i, ϕ_i).

The irradiance E at the point A (Eq.2) can be rewritten using Eq.5;

$$E(\lambda) = \int_{\Phi} \int_{\Theta} L(\lambda, \theta, \phi) \cos\psi \sin\theta d\theta d\phi \tag{6}$$

where ψ is the angle between the surface normal and the incoming light direction. The new integral ranges Θ and Φ are introduced to reflect the change of the coordinate system. By introducing the narrow-band camera assumption to Eq.6,

$$\tau E_k = \tau \int_{\Phi} \int_{\Theta} L(\lambda_k, \theta, \phi) \cos\psi \sin\theta d\theta d\phi. \tag{7}$$

By substituting Eq.1,

$$\tau E_k = \int_{\Phi} \int_{\Theta} I_k(\theta, \phi) \cos\psi \sin\theta d\theta d\phi. \tag{8}$$

The camera pose and the object shape are known, hence, we know the value of ψ, Θ, Φ. Thus, we can calculate τE_k from the aquired illumination radiance $I_k(\theta, \phi)$.

We let the rendering software to render the object appearance seen from the camera postion under the aquired illumination distribution $I_k(\theta, \phi)$, where the surface reflectance $S(\lambda)$ was set to 1.0 for all wavelengths. Then, an image of τE_k can be obtained. We denote this image as I'_k. By dividing the aquired image I_k by the rendered image I'_k, (Eq.4/Eq.8), the surface reflectance value can be obtained.

$$S_k = I_k / I'_k \tag{9}$$

4 Experiment

4.1 Measurement of the scene radiance We used a Point Grey Research Ladybug2, a spherical digital video camera. To capture the wide level of intensity, we took images with ND filters and multiple shutter speeds, then generated an HDR (High Dynamic Range) image. At this point, we eliminated pixels which had values of brightness less than 10 or more than 210, because those pixels could be under camera dark or saturated.

4.2 Measurement of the object's shape We measured the shape of a diffuse outdoor object using a Cyrax 2500,


(a) (b) (c) (d)

Figure 3: (a) the captured image at 14:35, illuminated by cloudy daylight. (b) the image taken on the other day at at 9:40, illuminated by sunny daylight. (c) the estimated surface reflectance image derived from the image (a). (d) the other surface reflectance image from the image (b).

a range sensor. We chose a planar convex object to avoid ineter-reflection. The shape of surrounding environment was included to make the calibration easier.

We calibrated the object and the camera coordinates using Tsai et al.'s method [5]. We found corresponding points between the shpae of the object and the images taken, then we calculated the view point and the projection matrix using those coordinates.

4.3 Estimation of the surface reflectance We rendered the object's shape, of which the surface reflectance was set to be 1.0, under the lighting environment captured by the Ladubug2. The view point was set to the estimated camera position. We used the rendering system software RADIANCE.

We generated the surface reflectance image by dividing the original HDR image by the rendered object image, where its surface reflectance was set to be white; $S(\lambda) = 1.0$.

4.4 Evaluation We conducted the experiment twice, with different time and day. Figs.3(a) and 3(b) are the captured radiance images. They were taken at 14:35, illuminated by cloudy daylight, and at 9:40, illuminated by sunny daylight, respectively. Figs.3(c) and 3(d) are the estimated images of surface reflectance, derived from (a) and (b), respectively.

Nevertheless there is much difference between the images (a) and (b), the two estimated surface images, the (c) and (d), look similar to each other. The median RGB values of the part of the tower were (118, 110, 109) in (c), and (134, 117, 115) in (d). The intensity is slightly different, whereas the chromaticity is surprisingly similar.

However, we can see there are much noise in Fig.3(d). This is partly because the sky was so bright, that some portion of the sky could not be captured correctly. We used a single ND filter, Fujifilm ND-4.0 that reduces incoming light to 1/10000. While we carefully tuned the shutter speeds to cover the entire dynamic range in conjunction with this filter, the discrepancy appeared in the images taken. Further investigation will be conducted by the authors.

Further improvements could be achieved by the more accurate acquisition of the scene radiance, by overcoming the narrow-band camera assumption, and by taking into account the shape of the surrounding environment.

5 Conclusion

We have proposed a new, efficient method to estimate diffuse reflectance parameters by using a spherical camera. Measurement and data-processing cost will be greatly decreased by this method.

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