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Spectral Measurement of Ambient Lighting and Its Application to Image Rendering

Shoji Tominaga[1]
Department of informatics
Osaka Electro-Communication University

Norihiro Tanaka[2]
Department of informatics
Osaka Electro-Communication University

Abstract

A method is described for estimating the illuminant spectra of an omnidirectional light distribution from the images of a camera aiming at a mirrored ball. First, we introduce an imaging system using a spherical steel ball and a normal color CCD camera. The parameters including the optical axis and the focal length of the camera lens are estimated to determine the mapping between coordinates on the ball and light rays in the world. We create images to represent the omnidirectional light distribution in the world. Next, algorithms are presented for estimating the illuminant spectra from the image data. In experiments, the spectral radiance distributions are estimated in an outdoor scene including strong direct sunlight. Finally, a CG image is demonstrated using the estimated illuminant distribution.

1 Introduction

Knowing the scene illumination is very important for realistic image rendering and image understanding. Many illumination sources are present in natural scenes. The case of one source seldom happens. This paper discusses estimation of the illuminant spectra of an omnidirectional light distribution from camera data.

Previous works related with omnidirectional measuring systems used a mirrored ball, a fisheye lens, and a mirror with a hyperbolic curve. Debevec [1] developed a technique for using a mirrored ball in CG, called a light probe, to acquire an omnidirectional image that records the illumination conditions at a particular point in space. Such images were used for composing objects into actual photography of a scene. However he did not calibrate the camera system that is needed to precisely determine the illumination distribution [2]. The fisheye lens is mounted directly on a camera, but the viewing range is narrower than the ball. In using the mirror with a hyperbolic curve, viewing the sky is often neglected. In a previous work [3] we presented a method for measuring an omnidirectional light distribution with a simple camera calibration.

However, all these works did not intend to estimate illuminant spectra, but only to estimate RGB illumination colors. Also the works had a certain inaccuracy in estimating the spatial illumination vectors. Note that 3D RGB data of light sources are not used for precise spectral-based image rendering.

In this paper, we propose a method for estimating the illuminant spectra of an omnidirectional light distribution from the images of a camera aiming at a mirrored ball. Two essential points are (1) illuminant spectral estimation of an omnidirectional light distribution, and (2) illumination directional estimation based on the perspective projection.

First, we show the imaging system using a spherical steel ball and a normal color CCD camera. Several camera parameters are estimated to determine the mapping between coordinates on the ball and light rays in the world. We create images to represent the omnidirectional light distribution. Next, algorithms are presented for estimating the illuminant spectra from the image data. In experiments, the spectral radiance distributions are estimated in an outdoor scene. The accuracy of the spectral estimation is discussed. Finally, a CG image is created using the estimated omnidirectional illuminants.

2 Measuring system

A Canon RGB digital camera EOS D30 is used for estimating illuminant spectra. Each channel is represented in 12 bits, and an image is sampled in 2160x1440 pixels.

First we examined the linearity of the camera response. Uniform color patches were measured with both the camera and a radiometer. It had a good linearity. Next we measured the camera sensitivities by using a monochrometer. Figure 1 shows the spectral sensitivity functions. Note that the spectral bands are much broader than those of a multi-channel camera with more than three sensors. Therefore, the RGB camera acquires spectral information less accurately than the multi-band camera. On the other hand, the RGB camera is quite easy to measure outdoor scenes.

Figure 2 shows the geometric model for the measuring system using a mirrored ball. A camera aims at a spherical mirror, placed at any location in a natural environment. The camera photographs the spherical mirror to obtain an omnidirectional radiance map around the location. In the figure **N** is the surface normal, **L** is the light directional vector, and **V** is the viewing vector. Moreover, $\mathbf{V_r}$ is **V** mirrored about **N**. We assume that the ray beams from a light source are parallel. So the mirrored vector $\mathbf{V_r}$ is the same directional vector as the light vector **L** from the spherical center.

[1] Address:18-8 Hatsu-cho Neyagawa, Osaka 572-8530 Japan. E-mail: shoji@tmlab.osakac.ac.jp

[2] Address: 18-8 Hatsu-cho Neyagawa, Osaka 572-8530 Japan. E-mail: norihiro@tmlab.osakac.ac.jp

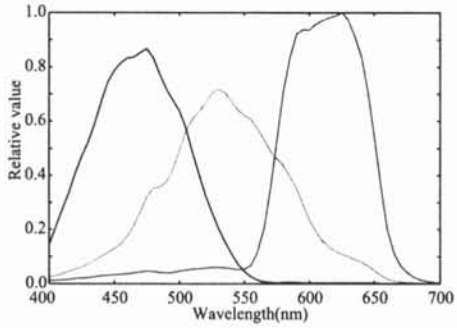

Figure 1. Spectral sensitivity functions of the camera.

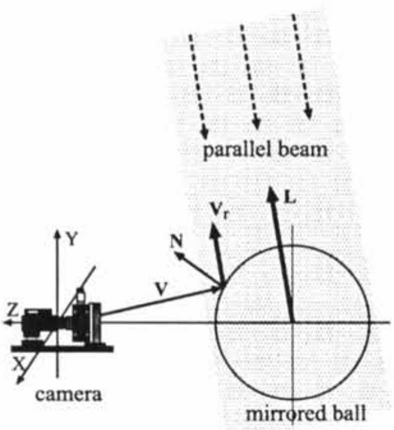

Figure 2. Geometric model of the observation.

3 Estimation of light-directional vectors

The illumination direction is estimated from an image projected on the mirrored ball. This computation requires such camera parameters as the focal length and the principal point. In a previous paper [3] we described a camera calibration method for measuring these parameters. Let (a_x, α_y) and (x_0, y_0) be the focal length of the lens and the optical axis on the image plane.

From Figure 2, the light directional vector is described as

$$\mathbf{L} = \mathbf{V}_r = \mathbf{V} - 2(\mathbf{N}\cdot\mathbf{V})^t\mathbf{N}. \tag{1}$$

In the above equation, the viewing vector **V** and the surface normal **N** are unknown, which are calculated using the spatial coordinates of the mirrored ball and the coordinates of the viewing direction on the image plane. Let (x, y) be the coordinates on the image plane.

First, **V** is calculated by .

$$\mathbf{V} = \frac{[(x-x_0)/\alpha_x,\ (y-y_0)/\alpha_y,\ 1.0]^t}{\left|[(x-x_0)/\alpha_x,\ (y-y_0)/\alpha_y,\ 1.0]^t\right|}. \tag{2}$$

Second, we calculated the surface normal **N** at (x, y). For this computation, we determine the spatial coordinate vector **M** of the ball center. Figure 3 shows the geometry for calculating the spatial position of the ball, where unit vectors **C** and **B** indicate a pointing vector from the camera center to the ball center and to the any point at the ball edge, respectively. Let ξ be an angle between **C** and **B**. Moreover let d and r be the distance from the viewpoint to the ball center and the radius of the ball. Then d is calculated as $d = r/\sin(\xi)$. Hence the coordinate **M** is determined as $\mathbf{M} = d\mathbf{C}$. The intersection of **V** and the ball is judged by using an index

$$t = (\mathbf{V}\cdot\mathbf{M}) - (\mathbf{M}\cdot\mathbf{M}) + r^2. \tag{3}$$

If $t \geq 0$, **V** intersects the ball. The distance from the viewpoint to the intersection point is calculated as

$$d_p = \min\left((\mathbf{V}\cdot\mathbf{M}) - \sqrt{t},\ (\mathbf{V}\cdot\mathbf{M}) + \sqrt{t}\right). \tag{4}$$

Finally the normal vector **N** can be calculated as

$$\mathbf{N} = (d_p\mathbf{V} - \mathbf{M}) / \left\| d_p\mathbf{V} - \mathbf{M} \right\|. \tag{5}$$

The Omnidirectional light-directional vectors are calculated by repeating the above procedure for all pixels of the ball image

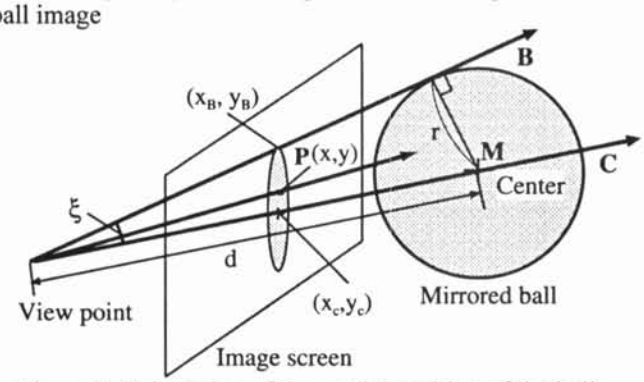

Figure 3. Calculation of the spatial position of the ball

4 Creation of Omnidirectional image

4.1 Polar coordinate representation

In order to represent the spatial distribution of ambient lighting, we create an omnidirectional image in a polar coordinate system. A set of the light vectors **L** points in all directions from the spherical center. Therefore, assuming a camera at the spherical center, we can produce an omnidirectional image observed at the center point. Let (x_s, y_s, z_s) be the rectangular coordinates on the spherical ball the axis z_s of which is coincident with the optical axis Z as shown in Figure 4. The light vector is expressed in the polar coordinates (θ, ϕ) by transformation

$$\theta = \tan^{-1}\left(y_s \middle/ \sqrt{x_s^{\,2} + z_s^{\,2}}\right), \quad \phi = \tan^{-1}\left(x_s / z_s\right) \tag{6}$$

Calculation of the radiance values looking in all directions of (θ, ϕ) provides the omnidirectional image mapped on a sphere.

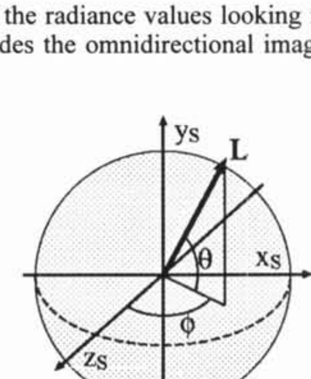

Figure 4. Polar coordinate system.

4.2 Image composition

We should note that the resolution of an image projected onto the mirrored ball. That is, the central part of the image corresponding to the spherical center is sampled finely, but the outer part corresponding to the edge is sampled roughly. In order to eliminate low resolution in the omnidirectional image, in this study, we acquired three images by observing the ball from three different positions with the rotational angle of 120-degree as shown in Figure 6.

Each of the observed images of the ball is transformed into the omnidirectional image in the polar coordinates. Next, the central part in the range $[-60 \le \phi \le 60]$ is cut out from each of the three images. These cutout parts are then combined into one image as shown in Figure 5.

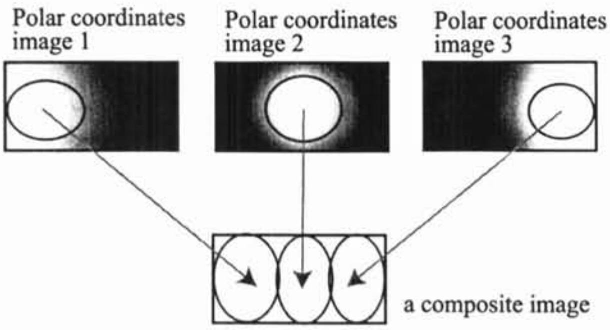

Figure 5. Composition of three images.

5 Estimation of illuminant spectra

5.1 Illuminant recovery from RGB camera data

A finite-dimensional linear model is used for describing the spectral function of illuminants. This model is effective in the sense that the number of unknown parameters in the spectral functions estimation can be reduced significantly. As a result, the linear model with a small number of parameters makes it possible to recover the spectral functions from camera data. We assume that the illuminant spectrum $E(\lambda)$ can be expressed as a linear combination of *three* basis functions as

$$E(\lambda) = \sum_{i=1}^{3} \varepsilon_i E_i(\lambda), \tag{7}$$

where $\{E_i(\lambda)$, i=1, 2, 3$\}$ is a statistically determined set of basis functions for the illuminant, and $\{\varepsilon_i\}$ is a set of scalar weights.

The camera output at spatial location x is described as

$$\begin{bmatrix} R(x) \\ G(x) \\ B(x) \end{bmatrix} = \int_{400}^{700} S(x,\lambda)E(\lambda) \begin{bmatrix} r(x) \\ g(x) \\ b(x) \end{bmatrix} d\lambda, \tag{8}$$

where $S(x,\lambda)$ the surface-spectral reflectance of the mirrored ball, and $\{r(\lambda), g(\lambda), b(\lambda)\}$ are the spectral sensitivity functions of the camera. The surface-spectral reflectance was determined by the Fresnel reflectance for the polished metal as

$$S(x,\lambda) = F(\theta_i, n(\lambda), k(\lambda)) / \cos(\theta_i), \tag{9}$$

where θ_i is the angle of incidence, $k(\lambda)$ is the absorption coefficient, $n(\lambda)$ is the index of refraction.

The illuminant weight vector can be solved in the form

$$\boldsymbol{\varepsilon} = \boldsymbol{\Lambda}_{S(x)}^{-1}\boldsymbol{\rho}(x), \tag{10}$$

where $\boldsymbol{\rho}(x)$ is the camera output vector define by $\boldsymbol{\rho}(x) = [R(x), G(x), B(x)]^t$ and $\boldsymbol{\Lambda}_{S(x)}$ are a 3x3 matrix with the element $[\int E_i(\lambda)S(\lambda)r(\lambda)d\lambda \; \ldots]$. Finally, the estimated curve of the illuminant $E(\lambda)$ is obtained by substituting the estimate of $\boldsymbol{\varepsilon}$ into Eq.(7).

5.2 Reflectance of the mirrored ball

We used the mirror ball, which was made from stainless steel (SUS304). The SUS304 steel is an alloy of iron(74%), chrome(18%), and nickel (8%). Generally, the reflectance of a segregation alloy is described as a weighted mean of the contained materials. Consequently, the spectral reflectance $S(x,\lambda)$ can be described as a function of the incident angle of illumination as follows:

$$\begin{aligned} S(x,\lambda) = {} & 0.74 \cdot F(n_{F_e}(\lambda), k_{F_e}(\lambda), \theta_i) \\ & + 0.18 \cdot F(n_{C_r}(\lambda), k_{C_r}(\lambda), \theta_i) \\ & + 0.08 \cdot F(n_{N_i}(\lambda), k_{N_i}(\lambda), \theta_i) \end{aligned} \tag{11}$$

where θ_i is the incident angle, that is calculated from $\theta_i = \cos^{-1}(\mathbf{N} \cdot \mathbf{L})$. The optical constants $n_{F_e}(\lambda)$, $k_{F_e}(\lambda)$ $n_{C_r}(\lambda)$, $k_{C_r}(\lambda)$, $n_{N_i}(\lambda)$, $k_{N_i}(\lambda)$ are the reflective indices and absorption coefficients for iron, chrome, nickel, respectively.

6 Image rendering

The omnidirectional spectral radiance distribution estimated in the above can be used as a light source for precise image rendering in natural scenes. Use of the illuminant spectral distributions for image rendering has the advantage that the physical interaction between light ray and object surfaces are accurately calculated, and the human color perception to natural scenes is realized as color images.

A realistic image of virtual objects existing in the real lighting environment is rendered using the ray tracing algorithm. We use the Torrance-Sparrow model for describing spectral reflection on any object surface. The spectral radiance $Y(\lambda)$ is then represented as

$$\begin{aligned} Y(x,\lambda) = \int_{\Omega} & [\alpha \cos(\theta_i) S(x,\lambda) E(\lambda) \\ & + \beta \frac{D(\varphi,\gamma) F(\theta_Q, n(\lambda), k(\lambda)) G(\mathbf{N},\mathbf{V},\mathbf{L})}{\cos(\theta_r)} E(\lambda)] d\Omega \;, \\ & + \beta' (\mathit{mirrored\ reflection\ term}) \end{aligned} \tag{12}$$

where the first term in the right hand side is diffuse and specular components, and the second term is a perfect mirror component. The constants α, β and β' are the weights of the respective components. Moreover θ_i is the incident angle, θ_r is the viewing angle, φ is the angle between global surface normal and micro-facet normal, and θ_Q is the angle of incidence to a micro-facet. The specular reflection component consists of several terms, *D*: function providing the index of surface roughness defined as $\exp\{-\ln(2)\varphi^2/\gamma^2\}$, where the γ is constant, G : geometrical attenuation factor, and *F*: Fresnel spectral reflectance of the material consisting of an object surface.

7 Experimental results

We estimated illuminant spectra of an omnidirectional light source in the open air. Figure 6 shows the steel ball, which was placed on the roof of our building under a clear sky. The scene includes strong specular high light by direct reflection of sunlight. Figure 7 shows synthesized omnidirectional image. Figures 8 shows the estimation results of illuminant spectra for direct sun. In the figures the dashed curves show the direct measurements by using a spectro-radiometer. The comparison between the estimates and measurements suggests the reliability of the proposed method. It should be noted that a normal color camera is available for estimating the spectral curves of the entire light sources in the sky. Figure 9 shows the chromaticity distribution of the light sources on the CIE-xy chromaticity diagram.

Finally, Figure 10 demonstrates an image rendered under the estimated omnidirectional illumination distribution. The four metallic objects with different materials of gold, silver, and copper are virtual objects in the scene. These objects are illuminated with the real ambient light sources. The ray-tracing image rendering was done based on spectral computation over the visible range of 400-700 nm in 5 nm increments. Note that the realistic appearance of the object materials is created by the present technique for precise spectral estimation and rendering.

Figure 6. Steel ball in an outdoors scene.

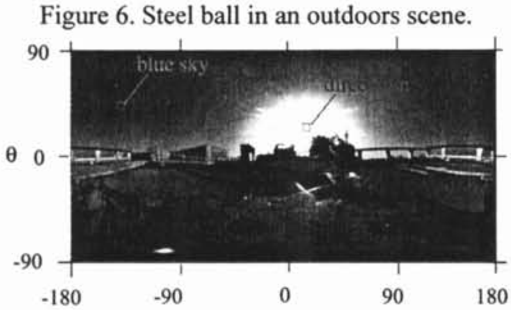

Figure 7. Synthesized omnidirectional image.

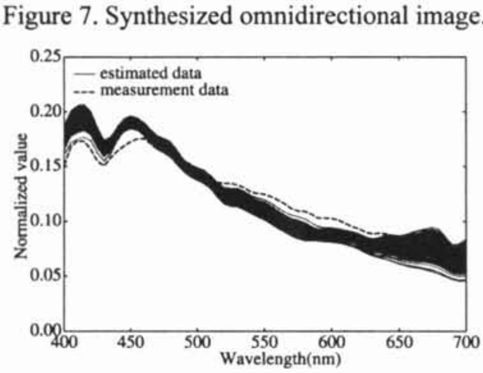

Figure 8. Estimated illuminant spectra for direct sun

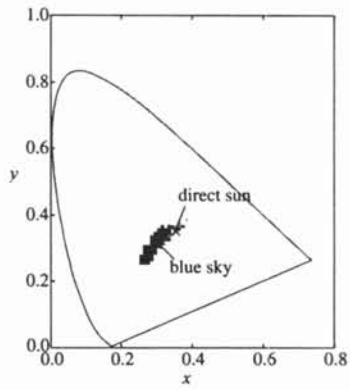

Figure 9. Distribution of light source on the CIE-xy chromaticity diagram.

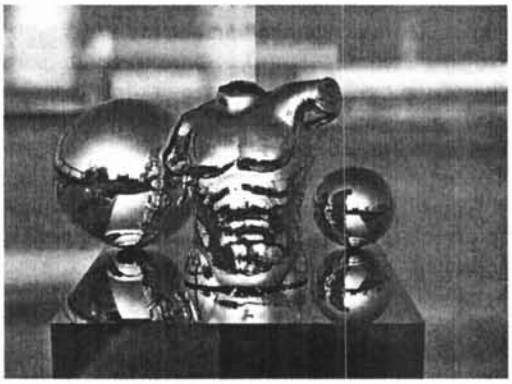

Figure 10. Image rendered under the estimated omnidirectional illumination distribution.

8 Conclusions

We have described a method for estimating the illuminant spectra of an omnidirectional light distribution from the images of a camera aiming at a mirrored ball. Our imaging system used a spherical steel ball and a normal color CCD camera. The camera parameters were estimated for determining the mapping between any coordinates on the specular surface and light rays in the world. An image in polar coordinates was created for representing the omnidirectional light distribution. We presented for estimating the illuminant spectra from the image data. The estimated omnidirectional spectral distribution was used as a light source for image rendering in natural scenes. Finally the feasibility of the proposed method was shown in an experiment.

Reference

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