Simplified Light Probe using Minimal Number of Photodiodes

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Abstract—Many display system users have strongly desired that a superimposed virtual object of computer graphics (CG) have optical consistency with a real object at a scene. For this study, we model a real-world light environment as one point light source at infinite distance and an environmental light, which has only three parameters: the point light direction and intensity ratios of the two light sources. We propose a simplified light probe sensor that has five photo IC diodes on each surface of a square pillar, except at its bottom, to estimate the three parameters. The five outputs of the photo IC diode under specific model parameters are obtainable analytically because the directivity characteristics of photo IC diode are approximated as a cosine of the incident angle. The three parameters are then derived from the five outputs. The parameter estimation entails very low computational cost. Experimental results demonstrate sufficient estimation accuracy to render a CG object without a feeling of strangeness.

I. INTRODUCTION

Computer graphics (CG) and CG animation are widely used in many fields, including augmented reality (AR) and mixed reality. The AR technology is anticipated for wider use not only in entertainment fields but also in fields of communication, transportation, and education. The CG objects are rendered and superimposed in a live and real-world environment captured by a camera in the AR. The superimposed CG objects require three consistencies: geometric, optical, and temporal.

Figure 1 presents example images with and without optical consistency. The right figures of Miku Hatsune in the images are CG objects superimposed over real images. The CG object in the upper image has optical consistency with the real figure of an anime character. The lighting environment for the CG object is approximately the same as that of the real image. However, the CG in the lower image has a different light environment from the real image. The optical consistency in the upper image makes the CG object appear to be more natural.

The optical consistency composes the brightness and the light environment for the CG object. The CG object brightness is determinable with, for example, average image intensity, but the light environment including the main light source direction and its size or ambient light intensity must be estimated one way or another.

Many methods to estimate the light environment can be found, for example, in a survey paper describing a study of inverse rendering [1]. As a direct measurement of the light environment, methods using a fisheye lens camera [2][3] or methods using a mirrored sphere [4][5] have been proposed. However, the method using a fisheye lens camera requires another image processing resources to estimate the light environment, entailing high computational costs. Methods to estimate the light environment from the captured image with modeling of the indoor structural circumstance [6][7] have been proposed, but they cannot be used in unknown situations. Methods using information in shade and shadow [8][9][10] estimate a complicated lighting distribution stably and accurately through analysis of the intensity distribution in the shadow based on linearity of the intensity. Methods using a
calibration object [11][12] use a Lambertian surfaced ball with reflection properties that can be approximated by a uniform diffuser. A method using a cylinder as a calibration object [13] has also been proposed.

A probe to measure the light environment is designated as a light probe [4]. Mirrored or Lambertian surfaced balls are often used as light probes, almost always with high dynamic range image processing. However, ideally, the light environment should be estimated solely from an image of a real object. Methods of using a human face as the light probe [14][15] have also been proposed. Furthermore, methods to estimate the light environment solely from indoor or outdoor scenes [16][17] have been proposed.

As described in this paper, we propose a light environmental sensor for enabling optical consistency in AR. The proposed method can estimate the lighting environment, while entailing only a very small computational cost using a simple dedicated light probe sensor for the light source environmental model described with only three parameters. The proposed method aims at lighting the CG object with great reduction of a feeling of strangeness instead of a detailed light environment model and precise parameters.

II. PROPOSED METHOD

A. Light Source Environmental Model

Figure 2 depicts the light source environmental model consisting of one point light source of intensity $L_0$ with direction $(\theta_0, \phi_0)$ at infinite distance and ambient light of intensity $\alpha_0$. All light sources are assumed to exist above the horizontal plane ($z > 0$). The three model parameters are the point light source direction $(\theta_0, \phi_0)$ and the intensity ratio $L_0/\alpha_0$.

B. Light Probe Sensor

The light probe sensor consists of five photo IC diodes (S9648-200SB; Hamamatsu Photonics K.K.) arranged in different directions.

The photo IC diode (PID) has a spectral sensitivity characteristic close to a human visual system. It outputs photocurrent proportional to illuminance. The acceptance surface of PID is located 0.75 mm behind the tip of a transparent plastic package with 5 mm diameter. The photocurrent output varies depending on the incident angle with respect to the acceptance surface.

The appearance of PID and directivity characteristic are shown, respectively, in Fig. 3 and Fig. 4. The directivity characteristic is modeled as shown below.

$$x = kL_0 \cos \phi,$$

Here, $\phi$ denotes the incident angle of the point light direction with respect to the optical axis of PID, as shown in Fig. 5. In that equation, $L_0$, $k$, and $x$ respectively denote the intensity of point light source, the gain of PID, and the output current.

Figure 6 shows our prototype light probe sensor and its coordinate system. The simplified light probe sensor has five PIDs on the respective surfaces of the square pillar, except its bottom, to estimate the three parameters. The optical axes of PID are placed orthogonally to the square pillar surfaces.

The five PIDs are numbered from $s_0$ to $s_4$. The normal vectors of each square pillar surface are set as follows, as
shown in Fig. 7.

\[
\begin{align*}
\mathbf{n}_0 &= (0, 0, 1), \\
\mathbf{n}_1 &= (1, 0, 0), \\
\mathbf{n}_2 &= (0, 1, 0), \\
\mathbf{n}_3 &= (-1, 0, 0), \\
\mathbf{n}_4 &= (0, -1, 0).
\end{align*}
\]  

(2)

Sensitivity of PID at an incident angle of greater than or equal to 90 deg. comes to zero, as presented in Fig. 4. The minimal number of PIDs is five if the point light source direction is assumed to exist above the horizontal plane \( z > 0 \) because estimation of the azimuth angle requires at least two PIDs with orthogonal placement.

C. Light Probe Sensor Outputs

First, we examine the output of the light probe sensor for the point light source. The output current of PID can be expressed by the inner product of the surface normal and the direction vector of the point light source from Eq. (1) as

\[
x_i = k \mathbf{n}_i \cdot \mathbf{p}.
\]  

(3)

Here, \( i \) denotes the corresponding PID number, and \( \mathbf{p} \) denotes the component of the point light source as

\[
\mathbf{p} = L_0 (\cos \phi_0 \sin \theta_0, \sin \phi_0 \sin \theta_0, \cos \theta_0).
\]  

(4)

Secondly, we examine the light probe sensor output for ambient light. The PID \( s_0 \) (top surface) output is obtainable by integrating Eq. (1) for all directions as

\[
x_0 = kao \int_{-\pi/2}^{\pi/2} \int_0^{\pi/2} \cos \theta \sin \theta d\theta d\phi = \pi kao_0.
\]  

(5)

The outputs of PID from \( s_1 \) to \( s_4 \) are the same, but the integration range for the azimuth angle \( \phi \) is halved as

\[
x_1 = x_2 = x_3 = x_4 = kao \int_{-\pi/2}^{\pi/2} \int_0^{\pi/2} \cos \theta \sin \theta d\theta d\phi = \frac{1}{2} \pi kao_0.
\]  

(6)

In summary, the output currents of PID are obtainable as shown below. As shown in Fig. 7, the azimuth angle \( \phi_0 \) of the point light is divided into four cases because the outputs on the shadow side surface come to zero. The output of PID \( s_0 \) (top) is independent from the azimuth angle \( \phi_0 \) as

\[
x_0 = kL_0 \cos \theta_0 + \pi kao_0.
\]  

(7)

1. When \( 0 \leq \phi_0 \leq \pi/2 \),

\[
\begin{align*}
\mathbf{x}_1 &= kL_0 \cos \phi_0 \sin \theta_0 + \frac{1}{2} \pi kao_0, \\
\mathbf{x}_2 &= kL_0 \sin \phi_0 \sin \theta_0 + \frac{1}{2} \pi kao_0, \\
\mathbf{x}_3 &= \frac{1}{2} \pi kao_0, \\
\mathbf{x}_4 &= \frac{1}{2} \pi kao_0.
\end{align*}
\]  

(8)

2. When \( \pi/2 \leq \phi_0 \leq \pi \),

\[
\begin{align*}
\mathbf{x}_1 &= \frac{1}{2} \pi kao_0, \\
\mathbf{x}_2 &= kL_0 \sin \phi_0 \sin \theta_0 + \frac{1}{2} \pi kao_0, \\
\mathbf{x}_3 &= -kL_0 \cos \phi_0 \sin \theta_0 + \frac{1}{2} \pi kao_0, \\
\mathbf{x}_4 &= \frac{1}{2} \pi kao_0.
\end{align*}
\]  

(9)

3. When \( \pi \leq \phi_0 \leq 3\pi/2 \),

\[
\begin{align*}
\mathbf{x}_1 &= \frac{1}{2} \pi kao_0, \\
\mathbf{x}_2 &= \frac{1}{2} \pi kao_0, \\
\mathbf{x}_3 &= -kL_0 \cos \phi_0 \sin \theta_0 + \frac{1}{2} \pi kao_0, \\
\mathbf{x}_4 &= -kL_0 \sin \phi_0 \sin \theta_0 + \frac{1}{2} \pi kao_0.
\end{align*}
\]  

(10)
When $3\pi/2 \leq \varphi_0 \leq 2\pi$,
\[
x_1 = kL_0 \cos \varphi_0 \sin \theta_0 + \frac{1}{2} \pi k\alpha_0,
\]
\[
x_2 = \frac{1}{2} \pi k\alpha_0,
\]
\[
x_3 = \frac{1}{2} \pi k\alpha_0,
\]
\[
x_4 = -kL_0 \sin \varphi_0 \sin \theta_0 + \frac{1}{2} \pi k\alpha_0. \tag{11}
\]

### D. Parameter Estimation

The three parameters of the light environment model are obtainable using the five PID outputs from $x_0$ to $x_4$, as described below.

First, we find the azimuth angle $\varphi_0$ of the point light by sorting the four values of $x_1$, $x_2$, $x_3$, and $x_4$. Secondly, we compute the following according to the case to obtain $\alpha$, $\varphi_0$, and $kL_0 \sin \theta_0$.

1. When $x_3 \approx x_4 < x_1, x_2$,
\[
\alpha \equiv \frac{1}{2} \pi k\alpha_0 = \frac{1}{2} (x_3 + x_4),
\]
\[
\varphi_0 = \frac{\tan^{-1} x_2 - \alpha}{x_1 - \alpha},
\]
\[
kL_0 \sin \theta_0 = \frac{(x_1 - \alpha) \sin \varphi_0 + (x_2 - \alpha) \cos \varphi_0}{\sin 2\varphi_0}. \tag{12}
\]

2. When $x_4 \approx x_1 < x_2, x_3$,
\[
\alpha \equiv \frac{1}{2} \pi k\alpha_0 = \frac{1}{2} (x_4 + x_1),
\]
\[
\varphi_0 = \frac{\pi - \tan^{-1} x_2 - \alpha}{x_3 - \alpha},
\]
\[
kL_0 \sin \theta_0 = \frac{(x_2 - \alpha) \cos \varphi_0 - (x_3 - \alpha) \sin \varphi_0}{\sin 2\varphi_0}. \tag{13}
\]

3. When $x_1 \approx x_2 < x_3, x_4$,
\[
\alpha \equiv \frac{1}{2} \pi k\alpha_0 = \frac{1}{2} (x_1 + x_2),
\]
\[
\varphi_0 = \frac{\pi + \tan^{-1} x_4 - \alpha}{x_3 - \alpha},
\]
\[
kL_0 \sin \theta_0 = \frac{-(x_3 - \alpha) \sin \varphi_0 - (x_4 - \alpha) \cos \varphi_0}{\sin 2\varphi_0}. \tag{14}
\]

4. When $x_2 \approx x_3 < x_4, x_1$,
\[
\alpha \equiv \frac{1}{2} \pi k\alpha_0 = \frac{1}{2} (x_2 + x_3),
\]
\[
\varphi_0 = \frac{2\pi - \tan^{-1} x_4 - \alpha}{x_1 - \alpha},
\]
\[
kL_0 \sin \theta_0 = \frac{-(x_4 - \alpha) \cos \varphi_0 + (x_1 - \alpha) \sin \varphi_0}{\sin 2\varphi_0}. \tag{15}
\]

Here, the function $\tan^{-1}$ returns a value from $-\pi/2$ to $\pi/2$. Finally we compute the following using the obtained $\alpha$ and $kL_0 \sin \theta_0$ as shown below.

\[
\theta_0 = \tan^{-1} \frac{kL_0 \sin \theta_0}{x_0 - 2\alpha},
\]
\[
L_0/\alpha_0 = \frac{\pi(x_0 - 2\alpha)}{2\alpha \cos \theta_0}. \tag{16}
\]

### E. Calibration of the Light Probe Sensor

We assume that the five PIDs respectively have different dark currents and gains. The five outputs $x_i$ described previously are obtainable using the following, normalized from the PID raw outputs $\tilde{x}_i$.

\[
x_i = \frac{\tilde{x}_0(*) - \tilde{x}_0(0)}{\tilde{x}_0(*) - \tilde{x}_0(0)}(\tilde{x}_i - \tilde{x}_i(0)). \tag{17}
\]

Here, $\tilde{x}_i(*)$ and $\tilde{x}_i(0)$ respectively denote the PID output under a specific illuminance and completely dark condition, which are both measured in advance.

### III. EXPERIMENTAL RESULT

#### A. Estimation Accuracy under Controlled Environment

We conducted measurements to assess the light probe sensor accuracy in a controlled environment using a dark chamber, as shown in Fig. 8.

The ambient light component is zero in this dark chamber. The light probe sensor is mounted on a rotary stage, as shown at the bottom of Fig. 8. The zenith and azimuth angles are determined respectively by the tilt base angle and the rotary stage. The light source is an LED lamp, which outputs 7 W power and which is driven by a stabilized DC power supply. The LED lamp is set 1100 mm distant from the center of the light probe sensor through a pipe with 20 mm inner diameter. The light source is regarded as a 20-mm-diameter surface light source at a distance of 1100 mm. The current outputs

![Fig. 8. Dark chamber to eliminate ambient light.](image-url)
of PID are measured using a USB-connected AD converter (AI-1608AY-USB; Contec Co., Ltd.) as voltages across load resistors.

Figure 9 presents outputs from \( x_1 \) to \( x_4 \) at the zenith angle of 90 deg. Dotted lines in the figure represent the computed cosine of incident angle. The outputs can be regarded approximately as the cosine of incident angle.

Figure 10 shows the light direction estimation results. The zenith and azimuth angles of the light source direction are set respectively every 15 and 10 deg. The intersection points of silver grids on the blue sphere correspond to the specified light source directions; the black dots denote the estimated directions. The average of angular distance error between the given and estimated directions on the sphere is 3.98 deg., using total 216 estimations.

B. Rendering CG using Estimation Results

An experiment was conducted in an indoor environment with an ambient light component. The light source was a hand-held LED lamp at a distance of about 2 m from a real object. The intensity ratio of main and ambient light is unknown in this experiment. Figure 11 shows CG objects rendered using the estimated lighting parameters superimposed over real scenes, which demonstrate the optical consistency between real and CG objects.

IV. CONCLUSIONS

We have proposed a simplified light probe sensor that has five photo IC diodes in each surface of the square pillar, except its bottom, to estimate the three parameters of the point light direction and intensity ratio of main and ambient lights. The proposed method can estimate the lighting environment at a very small computational cost. Experimental results demonstrate the estimation accuracy to render a CG object with adequate optical consistency to the real object in the scene.

REFERENCES

[4] Paul E. Debevec, “Rendering Synthetic Objects into Real Scenes: Bridging Traditional and Image-based Graphics with Global Illumination and
Fig. 11. Example of CG rendered using the estimated parameters: left, real object; right, CG.


