# Estimating the directions to light sources using images of eye for reconstructing 3D human face

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## Abstract

This paper proposes a technique to estimate the direction of light sources based on the image of eye where the light source is imaged as reflection. The estimated directions of light sources are used to reconstruct 3D shape of face based on the photometric stereo technique. By using the reconstructed 3D shape, we can reproduce faces under various illuminants and from various viewing points. Without knowing the standing position of the subject, we can estimate the directions of light sources on human face from there images of eye for three light sources. In the process of this estimation, it is assumed that human eye is the sphere, and the geometrical constrains for reflection are used in the imaging system. The position and the size of human eye are also estimated as a result of the process. Since the standing position of the subject taken is not restricted in capturing the images, our imaging system is very practical to be used. The effectiveness of the proposed techniques are demonstrated by experiments.

## Introduction

Reconstructing shape of human face has been required to reproduce faces under various illuminants and from various viewing points. In order to obtain the shape of human face, without using the expensive 3D scanner, the photometric stereo[3], which is a method for shape estimation that uses some intensity images obtained under different lighting conditions, has been used. However, with photometric stereo method, it is impossible to estimate the surface normal and the surface reflectance without *a priori* knowledge of the light source direction and the light source intensity. Therefore, in order to get the direction of light sources on human face exactly, it is necessary to determine the relation between the positions of light sources and subject.

In this paper, we propose a method for estimating the direction of light source on human face by using the image of eye where the light source is imaged as reflection. Since the shape of human eye is almost sphere, and can reflect light, we can assume that human eye is used as mirrored ball to capture the environmental illuminants. According to mirrored ball technique[1,2], using the position of highlight peaks in the image of mirrored ball, where the light sources are reflected by on mirrored ball, the direction of light sources can be calculated correctly. However, this method requires the accurate position and radius of the mirrored ball. Since the radius of eye belongs with people, we cannot measure it easily. Moreover, the position of both subject and his human eye are not decided. Therefore it is difficult to estimate the direction of light sources without knowing the position and the radius of the human eye. In this paper, the position and the radius of the human eye is also estimated from the image of eye. In this estimation, we assumed that the position of three light sources in the camera coordination is known. However, we do not know where the subject stands or sit in front of the imaging system.

By using the estimated direction of light sources, we can estimate the surface normal and the surface reflectance of human face by photometric stereo method. We can reconstruct 3D human face by integrating the estimated surface normal in the view coordinate. The effectiveness of this method is demonstrated by experiments.

## Geometry model of mirrored eye

Figure 1 show the geometry model of proposed imaging system. This imaging process is based on the process of mirrored ball techniques [1,2]. Since the position of human face is not restricted, the human eye will be placed at any location in a natural environment. The camera is assumed to be a pinhole camera. Therefore, we can assume the process of imaging as if a screen is placed in front the camera. The distance of camera and screen is focal length. Figure 1 shows the projection of a human face in a 3D space onto a screen by the camera in perspective. In this figure, **N** is the surface normal at highlight peak, **L** is the light source directional vector on human eye, and **V** is the directional vector of camera at highlight peak. $D$ is the distance between the camera and human eye, $(x_0, y_0)$ is the center of screen.

The directional vector of camera at the i[th] highlight peak $(x_i, y_i)$ on the image can be expressed using the focal length $\alpha$ and $(x_0, y_0)$ as follow,

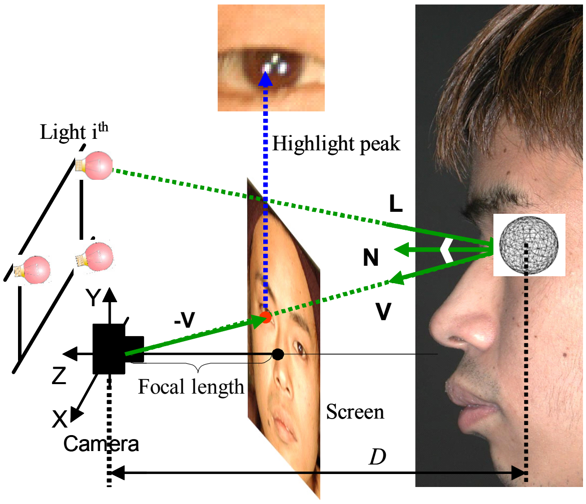



*Figure 1. Geometry of the proposed imaging system*

$$\mathbf{V} = [x_i - x_0\ ,\ \ y_i - y_0\ ,\ \ -\alpha]^T\ . \tag{1}$$

The coordinates of highlight peak $(x_i, y_i)$ can be obtained from image since the center coordinates of image is known. The focal length $\alpha$ of camera is also obtained by camera calibration. The directional of camera is easily calculated as is shown in Figure 1.

The surface normal vector $\mathbf{N}$ is determined using the sphere property. Let $r$ be the radius of eye and $(x_c, y_c)$ be the center coordinates of eye on the image. The surface normal vector at the i^th highlight peak $(x_i, y_i)$ can be calculated by

$$\mathbf{N} = \left[ x_i - x_c\ ,\ \ y_i - y_c\ ,\ \ \sqrt{r^2 - (x_i - x_c)^2 - (y_i - y_c)^2} \right]^T . \tag{2}$$

The surface normal vector is unknown at this stage, since the radius of eye and the center coordinates of eye on the image belong to anatomical property for individual and the distance from camera.

Relation of $\mathbf{N}, \mathbf{L}, \mathbf{V}$ is described as

$$\mathbf{L} = \mathbf{V} - 2(\mathbf{N}^T \cdot \mathbf{V})\mathbf{N}\ . \tag{3}$$

Therefore, we can describe the direction of light source on human eye at the i^th highlight peak $(x_i, y_i)$ by defining the function $\mathbf{G}_i$ of the eye radius $r$ and the eye center coordinates $(x_c, y_c)$ on the image as follow,

$$\mathbf{L}_i = \mathbf{G}_i(x_c, y_c, r)\ . \tag{4}$$

Therefore, in order to calculate the direction of light source on human eye, we must know the position and radius of human eye. The next section describes how to estimate the position and radius of human eye by solving optimization problem. The distance of camera and human eye in the image is also estimated in the next section.

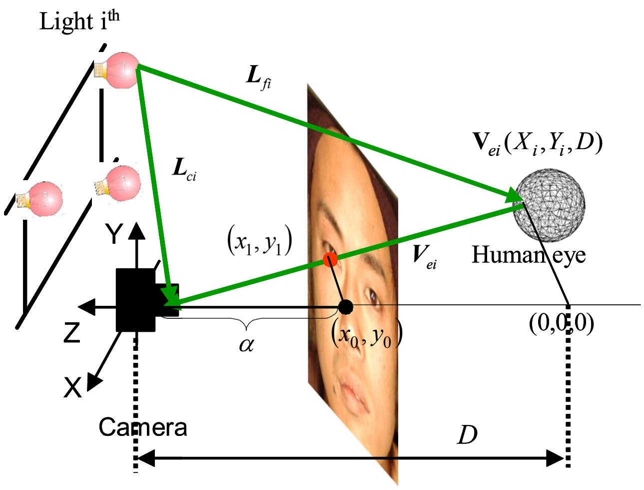



*Figure 2. Perspective projections and geometry*

## Estimating the direction of light source

Figure 2 shows the relation between the coordinates in the 3D space and in the 2D image by using perspective camera. In this figure, $\mathbf{L}_{fi}$ is the vector of light i^th to highlight peak on eye, $\mathbf{V}_{ei}$ is the vector to camera from highlight peak and $\mathbf{L}_{ci}$ is the vector from light i^th to camera. According to the Figure 2, the relation of $\mathbf{L}_{fi}, \mathbf{V}_{ei}, \mathbf{L}_{ci}$ is shown as follow,

$$\mathbf{L}_{fi} = \mathbf{L}_{ci} - \mathbf{V}_{ei} \tag{5}$$

In order to calculate the vector of light $\mathbf{L}_{fi}$, we must calculate the position of highlight peak $\mathbf{V}_{ei}$. However, $(X_i, Y_i)$ of $\mathbf{V}_{ei}$ are described by the function of the direction of camera and eye by using perspective camera as follow,

$$X_{ei} = \frac{(x_i - x_0)D}{\alpha} \qquad Y_{ei} = \frac{(y_i - y_0)D}{\alpha} \tag{6}$$

Therefore, the vector of light i^th on eye can be described as follow,

$$\mathbf{L}_{fi} = \mathbf{L}_{ci} - \left[ \frac{(x_i - x_0)}{\alpha} \quad \frac{(y_i - y_0)}{\alpha} \quad 1 \right]^T \cdot D \tag{7}$$

If we assume that the vector of light $\mathbf{L}_{ci}$ be known, according to the equation (7), we can describe the vector of light source on human eye at the i^th highlight peak $(x_i, y_i)$ by defining the function $\mathbf{K}_i$ of the distance between camera and human eye.

$$\mathbf{L}_{fi} = \mathbf{K}_i(D)\ . \tag{8}$$

Since the left of the equation (4) is the direction of

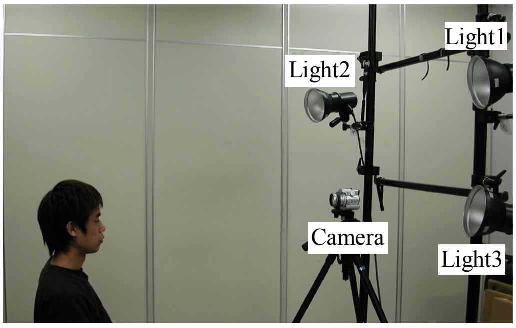



*Figure 3. Imaging system*

light source and the left of the equation (8) is the vector of light source on human eye, the relation between function $\mathbf{G}_i$ and $\mathbf{K}_i$ is describes as equation (9).

$$\mathbf{G}_i(x_c, y_c, r) = \frac{\mathbf{K}_i(D)}{\|\mathbf{K}_i(D)\|}. \qquad (9)$$

According to the equation (9), in order to calculate four parameters: the eye radius $r$ and the eye center coordinates $(x_c, y_c)$ on the image, the distance $D$ between camera and human eye, we solve the optimization problem $\sum\|\mathbf{F}_i^2\| = 0$, $i = 1,2,3$. Here, function $\mathbf{F}_i$ is described as follow,

$$\mathbf{F}_i(x_c, y_c, r, D) = \mathbf{G}_i(x_c, y_c, r) - \frac{\mathbf{K}_i(D)}{\|\mathbf{K}_i(D)\|}. \qquad (10)$$

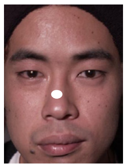
The reason why we use three light sources is that we must estimate four unknown parameters. Since for one light source we have two equations in the 2D image coordinate, therefore for three light sources we have six equations, which are enough to estimate four unknown parameters. Using the estimated parameters, we can calculate the direction of light source on eye by using the equation (4) or (8). Since we can assume that the direction of light source on human eye is the direction of light source on human face, the direction of light source on human face is calculated.

## Experiments

Figure 3 shows the scene of measurement. In this figure, three light sources 1,2,3 are fixed against the camera. The standing or sitting position of subject is not restricted. By using the method of this paper, at first the radius of eye and the center coordinates of the eye on the image, the distance of camera and human face were estimated. Next, the directions of light sources on human face are estimated.

The experiment was performed for some people at different position. At first, Figure 4 shows errors of the estimated directions of four light sources on four subjects. The errors of estimated directions of light sources were below $3^o$. Therefore, we can say that the direction of light source be estimated enough. Moreover, these results did not depend on subjects who have contact lens or not.

**Table 1 The estimated positions and the radius of human eye in 3D space (cm)**



| | $x_c$ | $y_c$ | $r$ |
|---|---|---|---|
| Subject 1 | -3.7 | -2.4 | 1.048 |
| Subject 2 | -3.9 | -3.5 | 1.052 |
| Subject 3 | -3.3 | -2.3 | 1.032 |
| Subject 4 | -4.0 | -2.9 | 1.042 |

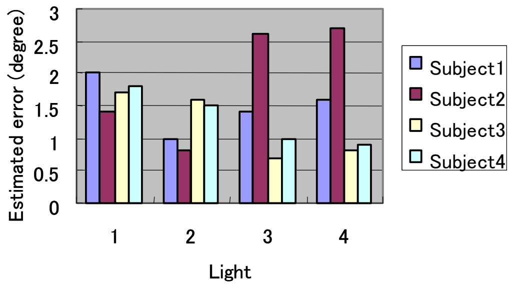



*Figure 4. Errors of estimated direction for light sources*

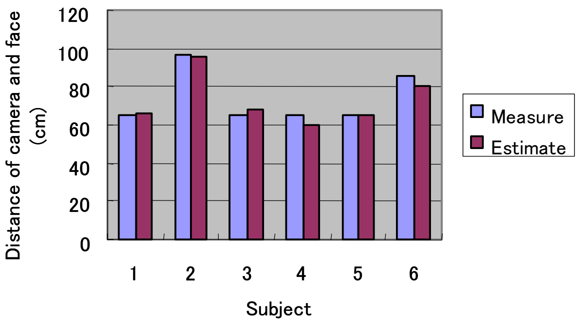



*Figure 5. The measured and estimated distance between camera and human face*

Figure 5 show results of the estimation and the measurement of the distance of camera and human face. In this figure, the difference between the measurement and estimation is very small. Therefore, we can say that the distance of camera and human face was also estimated enough. Since the position and the radius of human eye on the image, the distance of camera and human eye were estimated, we can estimate the position of eye and the radius of eye in 3D space by using the perspective projection. Table 1 shows the position and the radius of human eye in 3D space. The center point $(x_0, y_0)$ is shown in the figure as a white spot in the image put beside the Table 1. The accuracy of these results was not checked because we cannot measure the real radius of eye in 3D space. The mean of radius of human eye is known as 1.0-1.1 cm, therefore the estimated radius eye is in the available range.

Using the estimated direction of light source and photometric stereo method, we estimated the normal vector of surface and the reflection on the human face. We can

(a) Measured image (b) Predicted image (c) Difference

*Figure 6. Predicted and measured facial images under a new light source and their difference image*

reconstruct 3D human face by integrating the estimated surface normal in the view coordinate[3]. We can predict the human face image, which is taken under an arbitrary direction of light source by using the estimated normal surface and the absolute reflection of human face. We can also predict the human image, which is taken under an arbitrary viewing point, by using the reconstructed shape.

In order to check the validity of the estimated image, we estimated the picture under a direction of light source and took the picture under the same direction of light source. The position of light is just between Light 1 and Light 2 in Figure 3. Figure 6 shows the estimated, the real human face image and their difference under the light source. As shown in the different image, the difference between real image and estimated is very small. Therefore, we can conclude that the estimated image is valid for estimating image under various illuminants.

Figure 7 shows the predicted images under direction of light source with azimuth from $-60^0$ to $60^0$, and inclination from $-30^0$ to $30^0$. Figure 8 shows the predicted images under viewing point with azimuth from $-45^0$ to $45^0$, and inclination from $-20^0$ to $20^0$. As is shown in Figure 7 and 8, the predicted images are valid enough for some applications

## Conclusion and Discussion

This paper proposed a method for estimating the direction from light source on human face by using the reflection of light source on human eye. We also estimated the position, the radius of eye and the distance between camera and human face. By performing experiments with subjects who have or have not contact lens at different standing position , the direction of light source and the distance of camera and human face were estimated well. These results showed that the method of this paper is effective without depending people, their standing positions or contact lens. We reconstructed the shape of human face by using the estimated direction of light sources and photometric stereo method, and also we could show the faces under various illuminants and from various viewing points.

This technique will be expanded for area source instead of point source if the geometry of area source is known against the camera. After the estimation of coordinates and radius of eye, it is possible to use the reflected image on eye

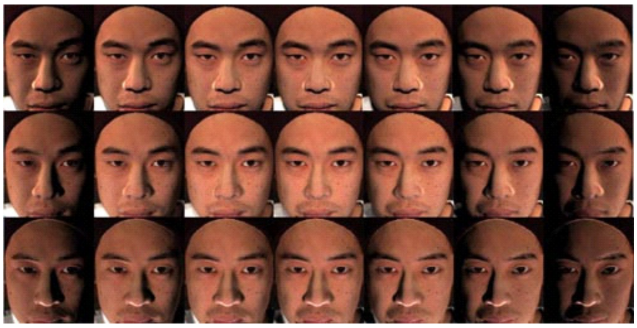


*Figure 7. Predicted images under different direction of light*

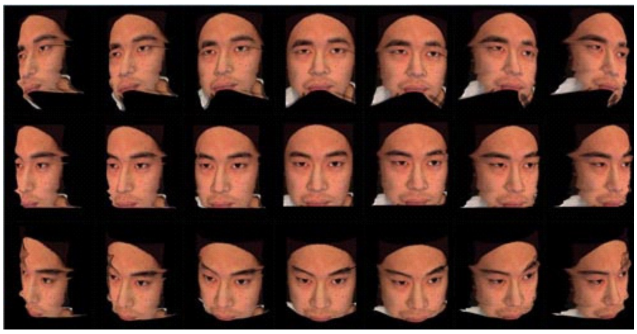


*Figure 8. Predicted images under different viewing point*

to obtain the environmental map for other applications[2]. The eye is not ideal spherical. Therefore, estimated radius is considered as a local curvature. The accuracy of the estimation for shape reconstruction will be examined in details in our future research. The accuracy will be affected depending on the geometry of imaging system, facing direction, position of the human.

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## Biography

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