Position Estimation of Near Point Light Sources
using a Clear Hollow Sphere

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Abstract

We present a novel method for estimating 3-D positions of near light sources by using highlights on the outside and inside of a single clear hollow sphere. Conventionally, the positions of near light sources have been estimated by using observed highlights on multiple reference objects, e.g. mirror balls.

1. Introduction

The estimation of 3-D positions of near light sources is one of the fundamental problems in photometric computer vision research, e.g. BRDF estimation, virtual object re-lighting and shape-from-shading. Conventional studies on the estimation of the positions of near light sources can be grouped into several categories. Unlike these approaches, geometric calibration of multiple reference objects is not required for our method, and this results in easy setup for measuring the 3-D positions of light sources. In the experiments, the accuracy of estimated light positions by the proposed method is evaluated using both simulation and real data.

The most straight-forward approach is to use a calibrated stereo camera system. Sato et al.[4] used stereo cameras with fisheye lenses to estimate the positions of near light sources that are widely distributed in a target scene. To reduce the complexity of the stereo camera system, reference objects are often used. Some methods use multiple reference objects to estimate 3-D light positions by triangulation of multiple rays corresponding to highlights from the reference objects[2, 3, 5]. To avoid a process of geometric calibration between multiple reference objects, some methods use a single reference object. Takai et al.[6] used a single diffuse sphere to estimate the 3-D position of a light source from the distribution of an isophote on the sphere. They also proposed a skeleton cube to use the self-shadow as an indicator of 3-D information [7]. These methods[6, 7],
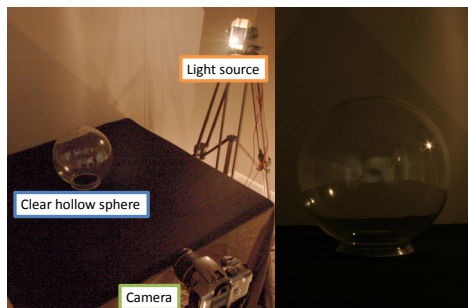

Figure 1. Clear hollow sphere. Left: setup for estimating the 3-D positions of the light sources. Right: an example of the captured image.

which use a single reference object, estimate 3-D positions based on the distribution of intensities over an input image. This sometimes gives unstable results owing to difficulty on estimating an accurate isophoto and self-shadow.

To achieve easy setup and accurate estimation of measuring positions for near light sources, we propose a method that uses highlight positions on the outside and inside of a single clear hollow sphere. Figure 1 shows an example of highlight positions on the clear hollow sphere. The primary contributions of our work are as follows; (1) Geometric calibration for multiple reference objects is not required., (2) Positions of near light sources can be accurately estimated by minimizing re-projection errors., (3) Corresponding pairs of highlight positions under multiple light sources can be easily determined.

2. Position estimation of near light sources

2.1. Problem setting

We estimate near light source positions under the following conditions. The intrinsic camera parameters and size of a clear hollow sphere are known. The relative 3-D positions of the sphere and a camera have already
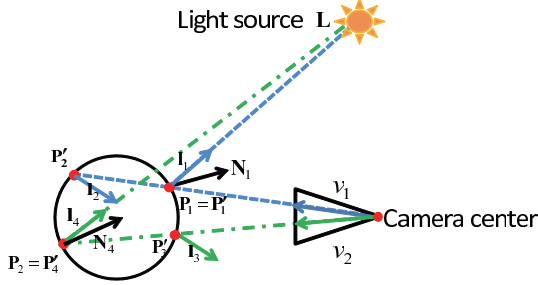
Figure 2. Rays reflected on a clear hollow sphere.

Figure 3. Re-projection errors.

been estimated, e.g. by the method[8]. We ignore inter-reflection and refraction. Multiple light sources can be treated simultaneously except for the critical conditions detailed in Section 2.4.

2.2. Position estimation of near light sources

The proposed method estimates the 3-D positions of near light sources in a camera coordinate system from a single image using a single clear hollow sphere. Figure 2 illustrates the geometric relationship of rays emitted from a light source L and rays reflected at the positions (P_1, P_2) on the sphere. These reflected rays are observed as two highlights of the positions (v_1, v_2) on the image plane. As shown in this figure, the 3-D position L of the light source can be determined by the triangulation of two different paths of rays reflected from the inside and outside of the sphere.

Initially, four intersection points P'_n $(n = 1, \cdots, 4)$ of two rays (v_1, v_2) from the camera center and the sphere are computed. The directions of the light l_n $(n = 1, \cdots, 4)$ from P'_n are then computed by:

$$l_n = \frac{v_m}{\parallel v_m \parallel} - 2(N_n \cdot \frac{v_m}{\parallel v_m \parallel}) \cdot N_n, m = \lfloor \frac{n}{2} \rfloor, \quad (1)$$

where N_n is a unit normal vector of the sphere at P'_n. Using the four rays from P'_n in the direction l_n, candidates for the light position L can be computed as the four intersection points of these rays. True 3-D position of L can be selected from these candidates using following constraints: (i) the light source does not exist in the opposite direction of l_n from P'_n; (ii)the light source does not exist in the clear hollow sphere.

2.3. Minimization of re-projection errors

For computing light source position L using triangulation of rays, there is the problem that typically two corresponding rays do not actually intersect in 3-D space owing to errors of quantization, calibration, and detection. Although minimization of re-projection errors is regarded as a reasonable way of computing a 3-D position in computer vision field, this approach has not been employed in conventional methods that use mirror
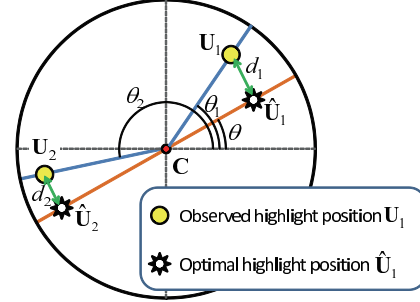
balls. This is due to the difficulty of direct computation of a 3-D reflected position P_n on the sphere from the fixed 3-D light position. In this study, we exploited the ability to directly minimize re-projection errors using the interesting characteristic of epipolar geometry on this system. More specifically, as shown in Fig. 1, all the highlights corresponding to a single light source are observed on the epipolar line that is the intersection line between the image plane and the epipolar plane that passes through the light source, camera center, and center of the clear hollow sphere in 3-D space. By using the constraint of the epipolar line as show in Fig. 3, the sum of re-projection errors E is defined as follows

$$E = d_1^2 + d_2^2, \quad d_i = \parallel U_i - \hat{U}_i \parallel, \quad i = 1, 2, \quad (2)$$

where U_i is the observed reflected light position on the image plane and $\hat{U}_i$ is the nearest positions from U_i on the epipolar line. E can be deformed as a function of θ, which is the angle of the epipolar line from a scan line, as follows:

$$E(\theta) = \sum_{n=1,2} (\parallel U_n - C \parallel \sin(\theta - \theta_n))^2, \quad (3)$$

where C is the center position of the sphere in an input image and θ_i is the rotation angle of the vector $U_i - C$ from a scan line. In our system, the re-projection error can be minimized using a one dimensional search for θ. After determining optimal θ, the 3-D position of the light source can be computed as a unique intersection point of the two rays $\hat{U}_i$.

2.4. Position estimation of multiple light sources

As mentioned in the previous section, reflected lights from a single light source are observed on a unique epipolar line in the proposed system. In this case, searching for corresponding pairs of highlights is quite easy even under multiple light sources, i.e. we can find pairs of highlights on an epipolar line that passes through these highlights and center of the sphere C. It should be noted that if there exist multiple light sources on a single epipolar plane, four or more highlights will be observed on a single epipolar line. Although it may

(a) by minimizing re-projection errors ($\sigma = 0$)

(b) by minimizing re-projection errors ($\sigma = 1.0$)

(c) by estimating middle point of rays ($\sigma = 1.0$)

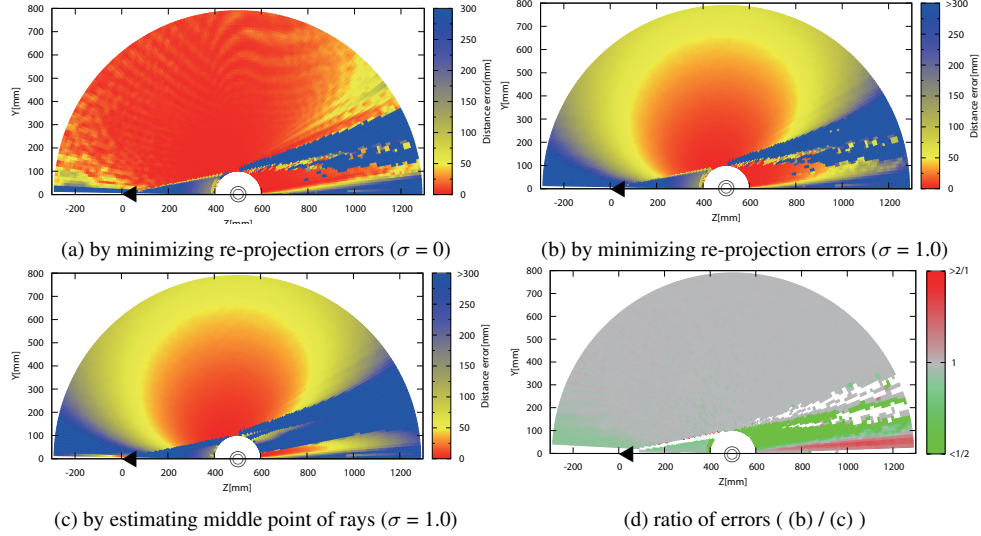(d) ratio of errors ((b) / (c))

Figure 4. A map of median errors for variable 3-D positions of a light source. The triangle and double circle indicate the position of the camera and the sphere.

possible to find pairs even in this case with some constraints, we do not discuss this problem in this paper.

3. Experiments

To evaluate the performance of the proposed method, we conducted three experiments. First, we quantitatively evaluated the accuracy of the estimated 3-D positions using the proposed method in both simulation and real scenes. The feasibility of our method was then demonstrated in real scene using a desk lamp. For all the experiments, we used a calibrated camera with a resolution of 1024×768 pixels, and a clear hollow sphere of radius 100 mm. The highlight positions on an input image were determined automatically by detecting the centroids of the highlighted regions.

3.1. Quantitative evaluation in a simulation

We evaluated the accuracy of the estimated results for variable light positions. In this experiment, the sphere was placed 500 mm from the camera, and the center of the sphere on the optical axes of the camera. The 3-D position of the single light source was changed on the Y-Z plane of the camera coordinates that passed through the camera position and the center of the sphere. Input images were generated using ray tracing software POV-Ray[1] for each position of the light source at variable distances from the center of the sphere (100 mm to 800 mm, at 10 mm intervals) and variable angles from the optical axis ($0°$ to $180°$, at $1°$ intervals).

Figure 4 shows the median of the estimation errors, which is computed as the distance between the estimated position and ground truth, over 10,000 trials for each light position. (a) and (b) indicate the results from

minimizing the re-projection errors with different levels of detection errors that are the Gaussian errors of the standard deviation (σ[pixels]). From (a) and (b), we see that the proposed method can accurately estimate the 3-D light positions for large parts of the positions close to the sphere except for the regions around the optical axis (A) and the lines that connects the camera position and surface of the sphere (B). We confirmed that the corresponding highlight positions were too close in the image for region A, and the estimation of the normal vector N of the highlight position was unstable around the boundary of the sphere for region B. (c) shows the result from computing the 3-D position as the middle point of the rays. (d) shows the ratio of the estimation errors for (b) and (c). As we can see in (d), minimizing the re-projection errors has an advantage over conventional methods that use the middle position of the rays as the 3-D position.

3.2. Quantitative evaluation in a real situation

The accuracy of the estimated light source positions was from the optical axis evaluated in a real situation. In this experiment, a halogen light source was placed at eight different distances from the center of the sphere. All the positions were placed roughly on the line that passed through the center of the sphere about $70°$ from the optical axis. Figure 5 shows the relationship between the estimation errors and the distance from the center of the sphere. In this experiment, ground truths for the light positions were measured using Total Station. The relationship between these errors and distances was similar to that evaluated in the simulation. We confirmed that we can estimate accurate light positions if they are not too far from the sphere.
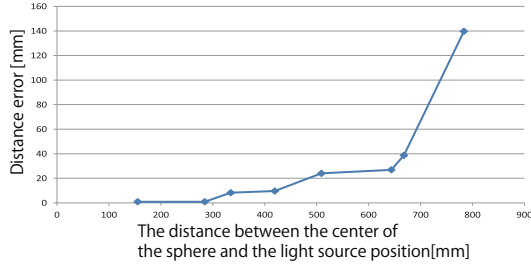
Figure 5. Position errors in real scene

3.3. Light position estimation for desk lamp

Our method has the significant advantage that we can find corresponding pairs of highlights using epipolar lines. To validate the effectiveness of this feature, we conducted a 3-D reconstruction of the linear light source on the desk lamp. Figure 6 shows the input image and appearance of the target scene. In this experiment, by finding pairs of highlights on epipolar lines, we have estimated 3-D position of the light for each epipolar plane. Figure 6 (c) shows the estimated 3-D light source of the desk lamp that is reconstructed as clouds of point light sources.

4. Conclusions

In this study, we have proposed a method for estimating positions of near light sources using a clear hollow sphere. In the experiments, the performance of the proposed method was quantitatively evaluated using both simulation and real data. We demonstrated the advantage of our method in a real situation by reconstructing the 3-D shape of a straight desk lamp. In future work, we will consider inter-reflection and refraction to achieve a more stable and accurate estimation.

Acknowledgment

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(a) Input image
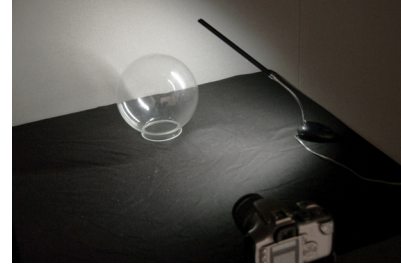
(b) Appearance of the target situation
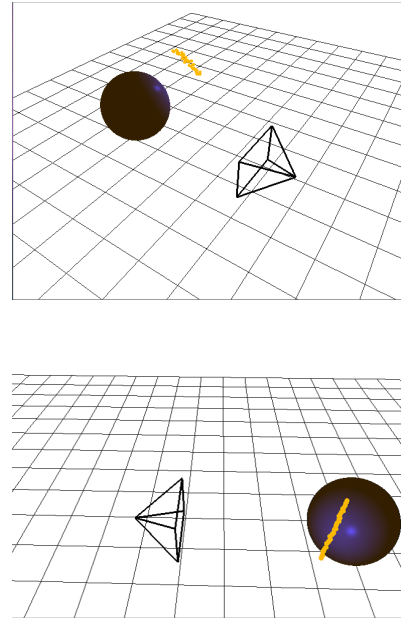
(c) Estimated light positions

Figure 6. Light position estimation for the desk lamp.

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