Near Surface Light Source Estimation from a Single View Image

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Abstract

Several techniques have been developed for estimating light source position in indoor or outdoor environment. However, those techniques assume that the light source can be approximated by a point, which cannot be applied safely to, for example, some case of Photometric Stereo reconstruction, when the light source is placed quite close to a small-size target, and hence the size of light source cannot be ignored. In this paper, we present a novel approach for estimating light source from single image of a scene that is illuminated by near surface light source. We propose to employ a shiny sphere and a Lambertion plate as light probe to locate light source position, where albedo variance of the Lambertian plate is used as the basis of the object function. We also illustrate the convexity of this object function and propose an efficient way to search the optimal value, i.e. source position. We test our calibration results on real images by means of Photometric Stereo reconstruction and image rendering, and both testing results show the accuracy of our estimation framework.

Introduction

Acquiring the knowledge of light sources is important in the field of computer vision and computer graphics with the recent advent of photometric modeling techniques of the real object. Once the parameters of light source are obtained, the illumination information can be effectively utilized not only for rendering images but also 3D reconstruction, like Shape from Shading (SFS) and Photometric Stereo (PS), both of which rely on illumination conditions and shading information to reconstruct the shape of the object. In this paper, we consider the problem of estimating near surface light source from an image of a shiny sphere and an image of a Lambertian plate, and orientation of the surface sources are unknown, and we deal with all those unknown factors during the estimation process, so that the outputs results would have increasing application.

The problem of estimating illuminate directions arises in the context of shape from shading [1], and traditional work [2-3] focuses on recovering a distant point light source under the assumption that the target object has Lambertian surface and uniform albedo. However, the assumption of distant point sources is not always true, especially in the indoor environment, when the light sources is placed not far away from the target; Besides, by assuming light source as a point it is risking of lack of rigor when the target is small and hence the sources cannot be regarded as a tiny point any more. It is believed that near surface light source can better model the indoor illumination environment. Even so, relative works develop slowly in recent years.

Early in 90s, there already have successful attempts to recover a more general illumination condition [4]. Marschner and Greenberg [5] use a least-squares method to estimate directions and radiant intensity of light sources from the surface intensity functions. Yang and Yuille [6] exploit the occluding boundary constrains to solve the light sources. Zhou and Kambhamettu [7] estimate the direction by the positions of highlights and shading detected on the stereo images of reference sphere. Similarly, Miyazaki et al. [8] utilize the object under single view to determine the illumination direction from the specular component but compute surface normal by shape from polarization. However, none of these approaches have made account for near surface light sources that have varying illumination effect depending on the distance and surface source's orientation.

Hara et al. [9] use target object under single view to estimate near point light source by linearizing Torrace-Sparrow specular reflection model, and they have good results for image rendering. Takai et al. [10] estimate position of near point light source by exploiting shading information of the stereo images of Lambertian sphere. Although both these two methods achieve sound calibration results for near light source, they are still limited to the point one, which would require the size of the source should be far smaller than the size of the target.

In this paper we propose a novel method for estimating parameters of surface light source, i.e.,

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orientation, distance, and in particular near surface light source including their surface area which is necessary to affect its radiance intensity. Assume indoor scenes where the target is put very close to the light source and hence can not be seem as point one. We first estimate the possible orientation of the source from the specular component of a shiny sphere, and second we estimate the distance and surface area by exploiting the irradiance of a Lambertian plate with known shape. Our key idea is illustrating how the uniformity of theoretically calculated albedo of Lambertian plate is affected by position of surface light source, and use such a relation to estimate the optimal position of the source. We show the results by means of using them on rendering the real image and using it on photometric stereo reconstruction, and both two test results prove accuracy of our calibration method.

The paper is organized as follows. Section 2 defines the lighting and reflectance model, and gives the assumptions used in the whole context. Section 3 describes detailed algorithm of estimating light source position, in particular, we come up an efficient optimum searching approach for a convex object function. Section 4 shows our calibration results on real images through Photometric Stereo and image rendering techniques. Section 5 gives discussion and future works.

Model Definition

1.1. Assumptions

For our light source estimation two images are employed, one is of a shiny sphere with known radius, and it is called **reference sphere** here; another one is of a Lambertian plate with known flat shape, and is called **reference plate**, and has uniform Lambertian albedo. Figure 1 illustrates the configuration for our light source estimation. The reference sphere is placed in a way that it is not occluded or casted shadows, and its center position can be estimated by the method mentioned in [11] provided sphere contour is known, and the reference plate can be fixed exactly on the sphere center and parallel to image plane of camera. It is also assumed the camera is accurately calibrated and the camera gain can be ignored so that image intensity can be referred to as image irradiance. Because the light source is placed quite near to the target in our configuration, we consider the possible diffuse-interreflection in the scene is minor and can be ignored.

1.2. Coordinates

As shown in Figure 1, the camera coordinates is taken as the **scene coordinates**, where the original is optical center, XOY plane is parallel to image plane, and Z axis is perpendicular to image plane and pointing to the target.

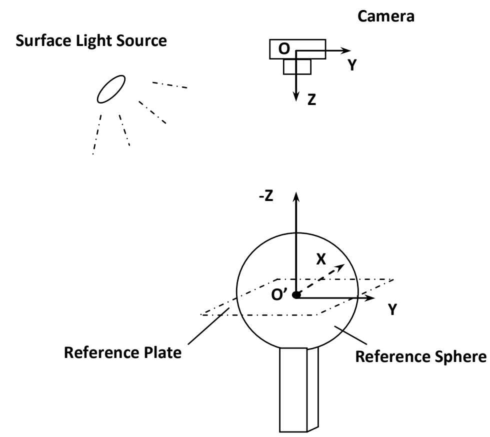


Figure 1: Configuration for our light source estimation.

1.3. Light Sources

The light source used here is LED, and the front contour of its emitting chip can be approximated by an ellipse. Suppose such a light source is denoted with S, and a target P is illuminated under S. As illustrated in Figure 2, each sources point s_i on $S = \{s_i\}$ radiates the beam along any radius centered at s_i, and, simultaneously, each target surface point p_j on $P = \{p_j\}$ receives the beam from every s_i. If the target is a shiny sphere, its surface normal vectors would uniformly distribute on the sphere surface and orient from the common point, i.e. sphere center. Suppose the sphere contains specular reflection only, hence, among all those normal vectors, there must be at least one vector, like $\mathbf{n}_j$ on p_j (Figure 2 (a)), would reflect one beam, l_{ij} from some source point, s_i to the camera, and hence an image of s_i would appears on the camera CCD. By tracing all the reflection beam of the bright spot detected on the sphere image, we would obtain a beam cone which gives the possible position range of source S (Figure 2 (b)).

The relation between incident light $\mathbf{l}$ and reflection light $\mathbf{l}'$ is given as,

$$\mathbf{l} = 2(\mathbf{n} \cdot \mathbf{l}')\mathbf{n} - \mathbf{l}' \quad (1)$$

where "$\cdot$ "denotes dot product, $\mathbf{n}$ is normal vector. If the shiny sphere has known radius and sphere center position, then $\mathbf{n}$ of any point on the sphere is known too. Suppose we have detected a spot area $\Omega = \{g_i\}$ on the sphere surface and their corresponding image pixel set $\Omega' = \{g_i'\}$, and assume the angle between viewing direction and reflection direction on any spot point g_i is small and can be ignored, so that we can use the viewing direction as the reflection to trace the incident light for all spot points $\{g_i\}$ through Eqn.(1). The resulting incident light directions of $\{g_i\}$ would form a cone shape, let us call it **range cone** and denote it as Θ. Range cone is important for the coming calculation of sources position.

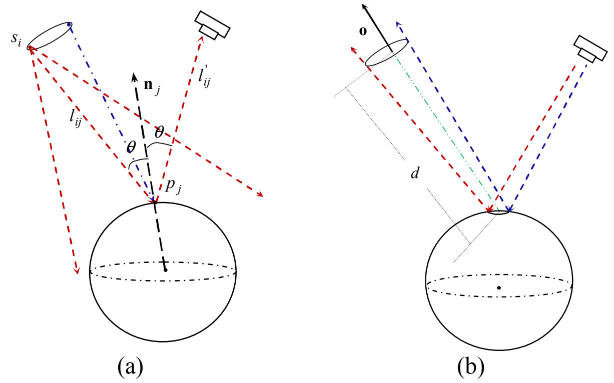


Figure 2: Illumination of surface light source on a shiny sphere.

Light Sources Estimation

As described in Section 2.3, we already have the range cone Θ that gives a possible position range for the source, but we still need a distance d and orientation $\mathbf{o}$ to locate the source position, as illustrated in Figure 2 (b), distance d is from some spot point g_k to the source plane S, and orientation direction $\mathbf{o}$ is the surface normal of S. Because S is assumed as flat plane, $\mathbf{o}$ must be one vector among $\{\mathbf{l}_i\}$,or in other words, the incident light directions of some element in $\{g_i\}$. In this paper, we temporarily choose the incident light $\mathbf{l}_k$ that has the smallest angle between the corresponding normal vector $\mathbf{n}_k$ and itself as $\mathbf{o}$, and we mainly focus on how to estimate d under such an orientation $\mathbf{o}$.

1.4. Radiance

As stated in Section 2.1, a reference plate is flat and exactly placed on the reference sphere center and parallel to image plane, which implies positions of all surface points of reference plate are known, let us denote these positions as $P = \{p_j\}$. Given the surface light source $S = \{s_i\}$, the radiance I_p (or say, the corresponding pixel value) of a particular $p \in \{p_j\}$ is equal to,

$$I_p = \rho_p \sum_{i=1}^{M} \frac{1}{|s_i - p|^2} \left(\frac{s_i - p}{|s_i - p|} \cdot \mathbf{n}_p \right) \tag{2}$$

where ρ_p is the albedo of p, M is total number of $\{s_i\}$, and $\mathbf{n}_p$ is the unit surface normal vector of p. Note that, due to the property of reference plate, all $\mathbf{n}_p, p \in P$ is equal to $[0 \quad 0 \quad -1]$. Let us use a unit direction vector $\mathbf{l}_{ip}$ to denote $(s_i - p)/|s_i - p|$, and assume affection caused by the difference between $\{|s_i - p|\}$ is minor, so that we can use a common scalar l_p to replace all $\{|s_i - p|\}$ in Eqn.(2), then we rewrite Eqn.(2) as,

$$I_p = \rho_p \frac{1}{{l_p}^2} \left(\sum_{i=1}^{M} \mathbf{l}_{ip} \right) \cdot [0 \quad 0 \quad -1] \tag{3}$$

Note that $\mathbf{l}_{ip}$ is actually the projection of s_i on the surface of a unit sphere centered at p, as illustrated in Figure 3. Besides, considering M is determined by the discrete interval λ on S (or S', the projection on the unit sphere), and it is approaching to equal to the area of S' along λ decreasing to an infinite small number, we use the area size of S', δ to replace M in Eqn.(3). According to the definition of **solid angle** [12], δ is actually the solid angle of S subtending at p, and it can be calculated once S and p are given (c.f. Appendix).

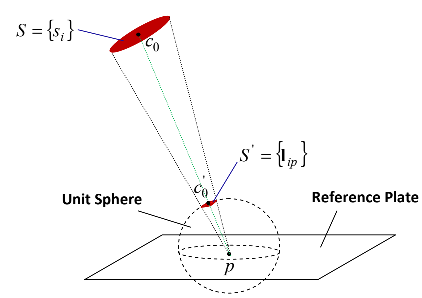


Figure 3: Radiance of reference plate under illumination of surface source.

It is worth to note that S' must have a regular shape due to the regularity of S ,i.e., the front cross contour of S is an ellipse, and according to the definition of gravity center C of an object with regular shape, that is C is equal to the mean value of all coordinate values of surface points, $C = [\sum x \quad \sum y \quad \sum z]/M$,here M denotes total number of surface points. Hence, the component $\sum_{i=1}^{M} \mathbf{l}_{ip}$ in Eqn.(3) can be described by c'_0, the gravity center of S', as below:

$$\sum_{i=1}^{M}\mathbf{l}_{ip} = \sum_{i=1}^{M}\frac{s_i - p}{|s_i - p|} = M(c_0^{'} - p)$$

Suppose S is given, then $c_0^{'}$ can be calculated as the projection of c_0, the ellipse center of S on the unit sphere. We further replace M with δ, and l_p with $|c_0 - p|$, and then the resulting radiance of reference plate based on Eqn. (3) would like as,

$$I_p = \rho_p \frac{1}{|c_0 - p|^2}\delta(c_0^{'} - p)\cdot[0 \quad 0 \quad -1] \tag{4}$$

Or,

$$\rho_p = I_p \frac{|c_0 - p|^2}{\delta(c_0^{'} - p)\cdot[0 \quad 0 \quad -1]} \tag{5}$$

Eqn. (4) and (5) are the basis of our object function to estimate light source.

1.5. Algorithm to Light Source Estimation

Considering albedo uniformity of reference plate, if the given position of S is correct, then variance of ρ_p calculated from Eqn. (5) over the whole surface of reference plate should have the smallest value, i.e.,

$$E = \sum_{p\in P}\left|\rho_p - \sum_{p\in P}\rho_p\right| \qquad d^* = \min_d\{E\} \tag{6}$$

where d^* is the optimal value of d which is used to locate S (see Figure 2). However, there is no way to express an explicit form of E about d due to the implicit expression of δ. Hence, we decouple the whole estimation process of d^* into following steps:

Now suppose we have a possible range of d, one image of reference plate, I_{plate}, and another image of reference sphere, I_{sphere}, both of which are taken under the illumination of S, the steps of d^* estimations are,

Step 1. Estimate sphere centre s_0 of the reference sphere through [11].

Step 2. Estimate the range cone Θ and sources plane normal $\mathbf{o}$ *from I_{sphere} (c.f. Section 2.3 and Section 3).*

Step 3. *Given a possible d and* $\mathbf{o}$ *obtained in Step2, calculate the corresponding cross section with Θ, i.e. S, fit S into an ellipse and find its center c_0.*

Step 4. For each surface point p of reference plate,

Step 4.1. Calculate its solid angle δ subtended at p, and projection $c_0^{'}$ of c_0 on the unit sphere centered at p (c.f. Appendix).

Step 4.2. Substitute δ, $c_0^{'}$, and the pixel value of p, $I_p \in I_{plate}$ into Eqn. (5) to calculate ρ_p (c.f. Section 3.1).

Step 5. Combine all ρ_p together to calculate E of the albedo variance through Eqn. (6) (c.f. Section 3.2).

Step 6. *Repeatedly run Step3 to Step5 until the optimal d^* that satisfies constraints in Eqn. (6) is found.*

1.6. Improvement of Algorithm to Light Source Estimation

We have empirically found the object function of Eqn. (6) is continuous and convex, but if we directly estimate d^* by calculating the partial differential, it would become very complex and time-consuming due to implicit expression of d in Eqn. (6). In following context, we come up a simple but efficient approach to find d^*, which is based on the slope change between two neighboring data segment.

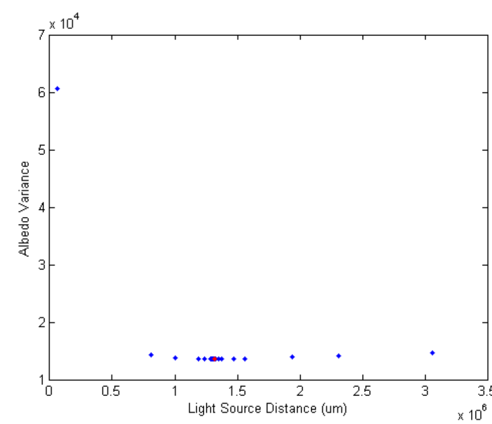
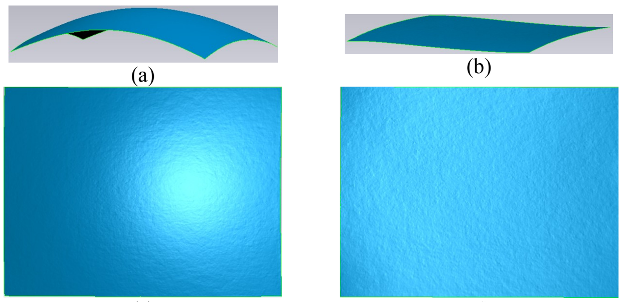


Figure 4: Relation between albedo variance of reference plate and light source distance.

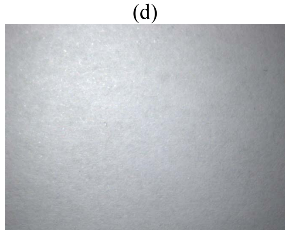
Consider Eqn.(6) is a convex function, so the minimum value should not appear on the two ends, but must appear on some point between them. Besides, Eqn.(6) is continuous and contains no local minimum. Hence, provided the data line was cut into many small segments beforehand, the minimum point must be surrounded by such two neighboring points, p_l and p_r, where the corresponding slopes have the opposite sign. Once p_l and p_r are found, they are used as two new ends, and cut into smaller segments again to find new p_l and p_r to replace the old ones. We repeatedly run such step until error difference between p_l and p_r is lower than a given threshold, and then return the middle point between p_l and p_r as the minimum point p^*, i.e. X axis coordinate of p^* is d^*. Figure 4 illustrates the mapping relation of Eqn. (6): the blue points indicate the above searching process for p^*, the red point, and there are total 45 points which imply only 45 repeats are needed to find the minimum. Figure 5 is the outputs of MATLAB 2011(a) running on the computer of 4GB memory with input image of 659×493 pixel resolution, and the total time cost is 2 min.



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

Light Source Assumption	Relative Depth Error (um)
Surface's	173.2034
Parallel	23.5617

(e)



(f)

Figure 5: Comparison in PS reconstruction: the left of the first two rows, (a) and (c), are the reconstruction results based on parallel source assumption, while the right ones, (b) and (d) ,are the counterparts based on surface source assumption. Results from the same row are set to the same view angle and illumination for observation. Table (e) gives the relative depth error of these two assumptions, and (f) is the original target which is a white flat cardboard.

Experimental Results for Real Image

We calibrate seven surface light sources one by one, and test the calibrated parameters on PS reconstruction with a real known-shape object as the target, and we also test them on image rendering. Both of the tests are compared to their counterparts that are based on parallel light source assumption [11]. All experimental results are output from MATLAB 2011(a) running on the computer of 4GB memory, and all input images are real and have the same pixel resolution of 659×493. Figure 5 illustrate the comparison in PS reconstruction of a flat Lambertian, obviously, surface light sources yields better reconstruction results than parallel ones.

Figure 6 illustrate the comparison in image rendering for real objects. We select a flat cardboard as the targets with known shape. We calculate its albedo through PS method, and render it by Lambertion Model. By comparison, as in Figure 6, the rendering result of surface source (middle column) look closer to the original one (the most left column) than far point source's (the most right column).

Discussion

In this paper, we present a novel but simple technique for estimating near surface light source. We mainly concerned the indoor scene, especially in the case of some PS application, where LED is placed quite close to the object to ensure enough irradiance to the target, and hence they cannot be regarded as point source anymore. We employ single view images of reference sphere and reference plate to estimation surface light source position: we first estimate a possible position range cone of the source from the image of reference sphere, and second we further locate the exact source position from the image of reference plate. In order to demonstrate the practicality of this technique, we also come up an efficient approach to find the optimal source position from the object function. Although we have obtained good calibration results, in particularly for PS reconstruction, there are some aspects we would like to address in future work, for example, we would like to further estimate the exactly orientation of the source plane rather than just assume a known one, and also, we are more interested in how to extend our calibration results in SfS and PS, where the shape of target is unknown, that is to say, p in Eqn. (4) is unknown, and hence would cause a very complex object function to solved.

Appendix: Calculation Solid Angle of an Ellipsoid

Due to pages limits, we just briefly give calculation formula here, and details please refer to [13].

Given the source plane J with ellipse contour, as illustrated in Figure 7, its solid angle δ subtended to point p can be calculated as:

$$\begin{aligned}\omega &= \int d\omega \\ &= kh\int_0^{2\pi}\int_0^{b}\frac{\rho_b}{\left(k^2\rho_b^2\cos^2\theta+\rho_b^2\sin^2\theta+h^2\right)^{3/2}}d\rho_b d\theta\end{aligned} \tag{8}$$

where a is the semi-major axis, b is the semi-minor axis of S, $k=a/b$, h is the distance between the center of S and the point p. Notice that there is no explicit form of Eqn. (12), but we can still calculate ω from J and p, i.e. k, b, h ,using the MATLAB command of numerical integration.

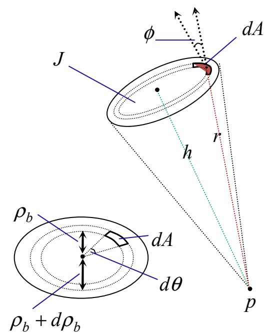


Figure 7: Geometric illustration of solid angle of an ellipsoid S subtend to a point p .

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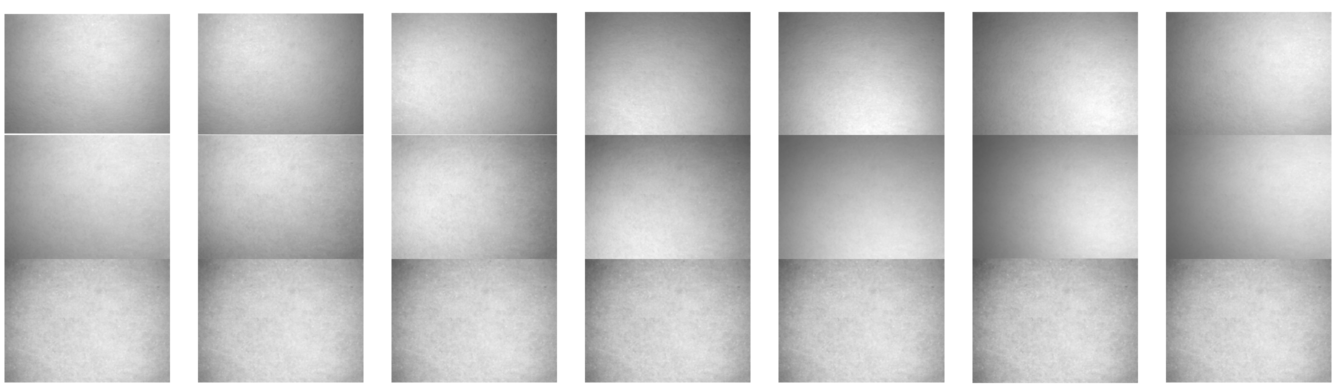

Figure 6: Comparison in image rendering for real objects: The most upper row are seven input original images; The middle row are the rendering results by near surface light source model assumption; The most bottom row are the rendering results by parallel (far point) light source model assumption. Picutures from the first column's to the last column's are under seven different LED illumination respectively.