Calibrating light sources by using a planar mirror

Hui-Liang Shen
Yue Cheng
Zhejiang University
Department of Information and Electronic Engineering
Hangzhou 310027, China
E-mail: shenhl@zju.edu.cn

Abstract. *Light source calibration is an important issue in many computer vision fields such as photometric stereo and shape from shading. Spheres, with either diffuse or specular reflections, are frequently deployed as calibration objects to recover the direction and intensity of light source from images. We present a novel method for light source calibration by using a planar mirror with a chessboard pattern and a diffuse region. The light direction can be accurately estimated from one mirror orientation by recovering the normal direction of the mirror plane. The location and intensity of light source can be further estimated if two mirror orientations are used. Experimental results show that the calibration accuracy of the proposed method is much higher than traditional sphere-based techniques and can offer improved three-dimensional reconstruction in photometric stereo.*
© 2011 SPIE and IS&T. [DOI: 10.1117/1.3533326]

1 Introduction

Acquisition of light source information is an important issue in computer vision and computer graphics. For example, in the fields of shape from shading[1,2] and photometric stereo,[3–5] light direction is directly involved in the mathematical reconstruction of three-dimensional (3D) surface shapes. If the information of light sources is known, it can be further utilized in manipulating shadow, shading, and highlights, or in seamlessly synthesizing virtual objects into real scenes.[6–8] Because of this, light source calibration has attracted much interest in recent years. As spheres have wide distribution of normal directions, they are frequently used as calibration objects.[9,10] Alternatively, the light direction can also be recovered from scene cues such as highlights[11] or silhouettes.[4] Although the scene cue-based methods are feasible in some circumstances, the methods with calibration objects generally produce more accurate estimations.

This paper proposes a novel method to estimate the direction and intensity of light source for photometric stereo, by using a planar mirror attached with a chessboard pattern and a diffuse reflective patch. To our knowledge, this is the first work that employs a planar mirror for light source calibration. The mirror plane is modeled by perspective projection; its normal is computed by a procedure similar to camera calibration. The direction of light source can be determined from the image with only one mirror orientation. The location and intensity of light source can be further estimated when two orientations are used. The proposed method is evaluated in terms of direction and distance error metrics, by using light sources located at different positions. The accuracy of the proposed method is also validated by 3D surface reconstruction in photometric stereo.

2 Related Work

Spheres, with either diffuse or specular reflection properties, have been widely adopted in light source calibration. Zhou and Kambhamettu[10,12] used a pair of stereo images of a sphere and separated the image into diffuse and specular reflection parts. According to the characteristics of these two reflection components, the light direction is determined from highlight locations and the light intensity is acquired from pixels with Lambertian reflections. This technique was employed to estimate light direction in a dense photometric stereo system.[13] Powell et al.[9] calibrated light sources by using a custom-made calibration object that consists of three spheres with known relative positions. The two specularly reflective spheres are used to produce highlights for triangulating the light position, and the distant diffuse sphere is used to estimate the focal length. It is also possible to calibrate light source by using spheres with only Lambertian reflection, by exploiting the geometric relationship between illumination direction and critical points[8,14] or by intensity differencing.[15]

By using scene cues, light direction can be estimated from object images without utilizing calibration objects. For example, by assuming that the 3D model of an object is known, Lagger and Fua[11] recovered light direction from the extracted specular pixels, while Xu and Wallace[16] estimated object reflectance and lighting parameters by using an additional stereo image pair. Hernandez et al.[4] constructed the visual hull from object silhouettes and used the surface normals and intensities of the visual hull points to estimate the light knowledge based on a voting scheme. Wang and Samaras[17] estimated illuminant direction from a single image based on the shading and shadow cues after specularity removal.

When compared with the scene-based methods, the sphere-based methods are generally more reliable as the explicit knowledge (the radius, and sometimes also the location) of the sphere is available in the calibration procedure. However, the best estimation of light direction is in the range of 2.0 to 3.0 deg.[9,10] This accuracy might be insufficient to some applications such as 3D reconstruction in

Paper 10157R received Sep. 16, 2010; revised manuscript received Nov. 22, 2010; accepted for publication Nov. 23, 2010; published online Jan. 25, 2011.

1017-9909/2011/20(1)/013002/6/$25.00

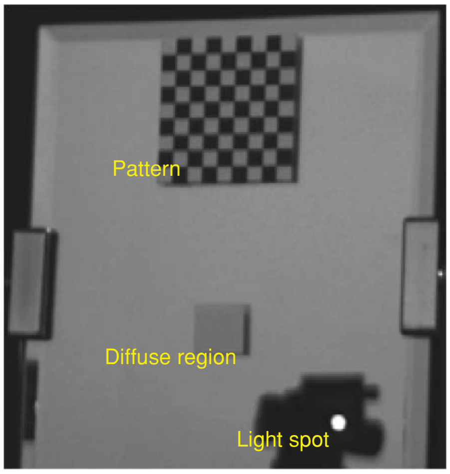

Fig. 1 A captured image of the planar mirror with chessboard pattern and squared diffuse region.

photometric stereo. Motivated by this, we present a novel method for light source calibration by using a planar mirror, instead of the most frequently adopted spheres. Although mirror has been previously adopted in capturing stereo images[18] and camera calibration,[19] the usage is quite different to the purpose of light source calibration in this paper.

3 Proposed Method

As in most previous work,[4,9,10,13] this paper deals with point light sources, which are widely adopted in photometric stereo. A planar mirror, attached with a chessboard pattern and a diffuse reflective area, acts as a calibration object. The mirror is ideal for detecting the specular spots of light sources. The chessboard pattern is used to determine the orientation of the mirror plane, using a procedure similar to camera calibration.[20] The diffuse region, which is formed by a Lambertian surface paper, is used for estimating light intensity. It is assumed that an image is formed by perspective projection in light source calibration. As shown in Fig. 1, the light source fixed on a tripod is clearly visible as a specular spot in the image.

As a calibration object, the fundamental difference between a planar mirror and a sphere is that the former has only one normal direction. Hence, the first step is to accurately determine the orientation of the mirror plane with respect to the camera. Under perspective projection, the orientation is specified by rotation and translation. The calibration of light source can be carried out using either one orientation or two orientations of the planar mirror. More light parameters can be obtained in the two-orientation case. The procedure of light calibration is elaborated in the following.

3.1 *Projection Model of the Mirror Plane*

We use $\mathbf{M} = [X, Y, Z]$ to denote a 3D scene point and $\mathbf{m} = [u, v]$ to represent the projected two-dimensional (2D) image point. $\mathbf{M}$ refers to the corner points of the chessboard pattern. In this paper, all corner points are used to recover the orientation of the planar mirror. For easy notation, we use $\widetilde{\mathbf{M}}$ and $\widetilde{\mathbf{m}}$ to denote the homogeneous coordinate vectors of $\mathbf{M}$ and $\mathbf{m}$, respectively. When the image of the planar mirror is modeled by perspective projection, a 3D scene point $\mathbf{M}$ and its projected 2D point $\mathbf{m}$ are related by[20]

$$\lambda\widetilde{\mathbf{m}} = \mathbf{A}[\mathbf{R}\,\mathbf{t}]\widetilde{\mathbf{M}}, \tag{1}$$

where λ is an arbitrary scale factor, $\mathbf{R} = [\mathbf{r}_1\,\mathbf{r}_2\,\mathbf{r}_3]$ and $\mathbf{t}$ are the rotation matrix and translation vector that relate the world coordinate system to the camera coordinate system. $\mathbf{R}$, together with $\mathbf{t}$, are the extrinsic parameters of the plane. $\mathbf{A}$ is the camera intrinsic matrix with the form

$$\mathbf{A} = \begin{bmatrix} \alpha_u & \gamma & u_0 \\ 0 & \alpha_v & v_0 \\ 0 & 0 & 1 \end{bmatrix}, \tag{2}$$

where α_u and α_v are scale factors of the u and v axes in the image, γ describes the skewness of the two image axes, and (u_0, v_0) is the coordinate of the principal point. For a common camera, it is reasonable to assume that $\gamma = 0$. As the size of the pixel is of square and usually known, α_u and α_v are equal. In this paper we assume f is known; otherwise, it can be obtained by camera calibration. In this way, all the variables in matrix $\mathbf{A}$ are known *a priori*.

Without loss of generality, we assume that the mirror is on a plane with $Z = 0$ of the world coordinate system. Then Eq. (1) becomes

$$\lambda\widetilde{\mathbf{m}} = \mathbf{A}[\mathbf{r}_1\,\mathbf{r}_2\,\mathbf{t}]\widetilde{\mathbf{M}} = \mathbf{H}\widetilde{\mathbf{M}}, \tag{3}$$

where $\widetilde{\mathbf{M}} = [X, Y, 1]^{\mathsf{T}}$ and $\mathbf{r}_1$ and $\mathbf{r}_2$ are the first two column vectors of the rotation matrix $\mathbf{R}$. The two-plane homography $\mathbf{H} = \mathbf{A}[\mathbf{r}_1\,\mathbf{r}_2\,\mathbf{t}]$, which relates to the scene point $\mathbf{M}$ and the corresponding image point $\mathbf{m}$, can be computed by camera calibration.[21] As $\mathbf{A}$ is known, the rotation and translation of the mirror plane can be obtained from $\mathbf{H}$.

3.2 *Calibration Using One Orientation*

Figure 2 illustrates the light calibration scheme when using one orientation of a planar mirror. According to the law of mirror reflection, at the specular spot P, the incoming angle from the light source position S is equal to the outgoing angle to the optical center C of the camera. The normal vector $\mathbf{n}$ of the mirror is on the plane determined by lines $\overline{PS}$ and $\overline{PC}$, and bisects their intersection angle θ.

We can obtain the world coordinate $\mathbf{P}_{\mathrm{w}}$ of the specular spot from the two-plane homography $\mathbf{H}$. Then the specular spot under the camera coordinate system is computed as

$$\mathbf{P} = \mathbf{R}\mathbf{P}_{\mathrm{w}} + \mathbf{t}. \tag{4}$$

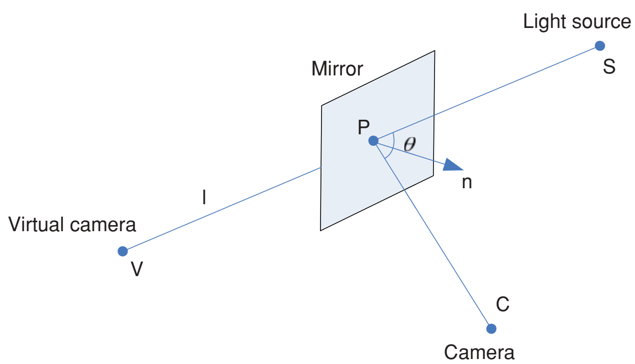

Fig. 2 Light calibration under one mirror orientation.

In the world coordinate system, the normal direction of the planar mirror $\mathbf{n}_w = [0, 0, 1]^T$. In the camera coordinate system it becomes

$$\mathbf{n} = \mathbf{R}\mathbf{n}_w = \mathbf{r}_1 \times \mathbf{r}_2. \tag{5}$$

Then the direction of line $\overline{PS}$ can be easily determined by the mirror normal $\mathbf{n}$ and the coordinate of P according to the reflection law, as shown in the previous sphere-based methods.[9,10] In this paper, in order to unify the light calibration in the one-orientation and two-orientation cases, we propose an alternative solution which is described as follows.

We use the concept of "virtual camera," which is the virtual image (denoted by point V) of the actual camera in the mirror (see Fig. 2). According to the imaging principle, the three points, i.e., V, P, and S, are on the same line l. The positions of the virtual and actual cameras are symmetric with respect to the mirror plane. More specifically, in the world coordinate system, the X and Y coordinates of points V and C keep the same, while the Z coordinates are opposite. In the camera coordinate system, the coordinate of V is

$$\mathbf{V} = -\mathbf{R}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix}\mathbf{R}^{-1}\mathbf{t} + \mathbf{t}, \tag{6}$$

and then the normalized light direction $\mathbf{l}$ can be computed by the coordinate of points P and V

$$\mathbf{l} = \frac{\mathbf{P} - \mathbf{V}}{\|\mathbf{P} - \mathbf{V}\|}. \tag{7}$$

It is clear from Fig. 2 that, in the one-orientation case, the light source position S is on line l, but the exact location cannot be determined.

In this paper, the accuracy of light source direction is evaluated by the intersection angle θ between lines $\overline{PS}$ and $\overline{PC}$. We define L_{PC} as the distance between points P and C and L_{PS} and L_{SC} in a similar manner. When these distances are manually measured, the ground truth of θ is

$$\theta = \cos^{-1}\left(\frac{L_{PC}^2 + L_{PS}^2 - L_{SC}^2}{2\,L_{PC}L_{PS}}\right). \tag{8}$$

Based on the recovered $\mathbf{n}$ in Eq. (5) and $\mathbf{l}$ in Eq. (7), the estimate of θ is

$$\hat{\theta} = 2\cos^{-1}(\mathbf{l}^T\mathbf{n}). \tag{9}$$

The direction error of the estimated light source can then be evaluated in terms of angle difference as

$$\Delta\theta = |\,\hat{\theta} - \theta\,|\,. \tag{10}$$

3.3 *Calibration Using Two Orientations*

When the planar mirror is placed in two different positions, we can recover the light source position by two virtual cameras and estimate the light source intensity by the Lambertian model. Figure 3 shows the light calibration scheme when using two orientations. For each orientation, there is a corresponding virtual camera position. The light source position S is determined by the intersection point of lines l_1 and l_2, as

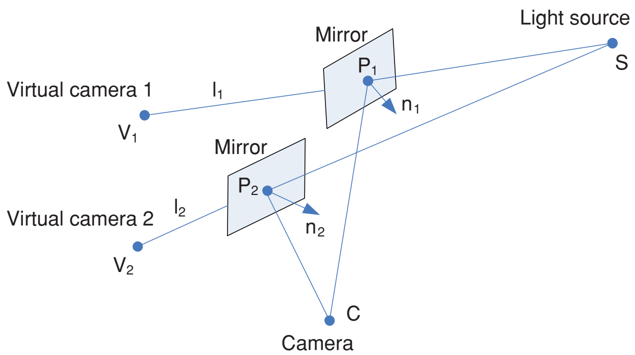

Fig. 3 Light calibration under two mirror orientations.

will be detailed in the following. Without loss of generality, we take orientation 1 as a reference. Based-on the estimated point position S, the angle is calculated based on distances L_{P_1C}, L_{P_1S}, and L_{SC} as

$$\hat{\theta}_1 = \cos^{-1}\left(\frac{L_{P_1C}^2 + L_{P_1S}^2 - L_{SC}^2}{2\,L_{P_1C}L_{P_1S}}\right). \tag{11}$$

Let $\mathbf{P}_d$ denote the coordinate vector of a point P_d in the diffuse region on the mirror plane and i_d denotes the image brightness at P_d. The light intensity can be calculated according to the Lambertian model as

$$l_d = i_d/\left(\mathbf{l}_d^T\mathbf{n}\right), \tag{12}$$

where $\mathbf{l}_d = (\mathbf{P}_d - \mathbf{S})/\|\mathbf{P}_d - \mathbf{S}\|$ is the direction of line $\overline{P_dS}$.

It is noted that the estimated intensity l_d is not the exact irradiation power strength of the light source. Rather, it is a relative measurement that includes factors such as surface albedo, camera response, and light source distance. This relative intensity measurement suffices in many applications.

The calculation of light source position S is an important issue. Because errors may exist in the recovery of homography $\mathbf{H}$ and the localization of specular spots, the lines l_1 and l_2 usually do not actually intersect. In a similar case of 3D reconstruction in multiple stereo, this problem is usually solved by nonlinear least-square techniques.[22] In this paper, we present a simple solution. The fundamental idea is to find the two points (each on one line) with minimum distance and then regard the optimal line intersection as the geometric center of these two points. The details are as follows.

The coordinate vector of every point on line l_1 can be denoted by a parameter ξ_1, together with a starting point and the line direction

$$\mathbf{X}_1(\xi_1) = \mathbf{V}_1 + \xi_1\mathbf{l}_1, \tag{13}$$

where $\mathbf{V}_1$ is the coordinate vector of camera position 1 and $\mathbf{l}_1$ denotes the direction of line l_1. Equation (13) is the parameter equation of line l_1. Similarly, the parameter equation of line l_2 is

$$\mathbf{X}_2(\xi_2) = \mathbf{V}_2 + \xi_2\mathbf{l}_2. \tag{14}$$

The calculation of points with minimum distance is treated as an optimization problem. The cost function is defined as the squared distance between $\mathbf{X}_1$ and $\mathbf{X}_2$

$$E = \|\mathbf{X}_1 - \mathbf{X}_2\|^2. \tag{15}$$

It is clear that the cost function E in Eq. (15) is quadratic. By setting $\partial E/\partial \xi_1 = 0$ and $\partial E/\partial \xi_2 = 0$, we obtain

$$\begin{cases} \mathbf{l}_1^{\mathsf{T}}(\mathbf{V}_1 + \xi_1 \mathbf{l}_1 - \mathbf{V}_2 - \xi_2 \mathbf{l}_2) = 0 \\ \mathbf{l}_2^{\mathsf{T}}(\mathbf{V}_2 + \xi_2 \mathbf{l}_2 - \mathbf{V}_1 - \xi_1 \mathbf{l}_1) = 0. \end{cases} \tag{16}$$

From these two linear equations, the parameters $\hat{\xi}_1$ and $\hat{\xi}_2$ corresponding to the two points with minimum distance can be easily solved. Consequently, the coordinate of the optimal intersection point S is

$$\mathbf{S} = \frac{1}{2}\left(\mathbf{X}_1(\hat{\xi}_1) + \mathbf{X}_2(\hat{\xi}_2)\right). \tag{17}$$

Possibly, the accuracy of light source calibration can be improved by using more than two orientations. In that case, the procedure for determining an intersection point can be straight forwardly extended by defining the cost function as the sum of squared distance between each point pair

$$E = \sum_{1 \le i < j \le n} \|\mathbf{X}_i - \mathbf{X}_j\|^2, \tag{18}$$

where n is the number of mirror orientations. The optimal intersection can also be calculated in a similar manner.

As mentioned above, compared with the one-orientation case, the most important advantage of the two-orientation case is the estimation of light position S. This should be quite beneficial as the inverse-square law of lighting intensity can be considered in the piecewise 3D reconstruction of large objects in photometric stereo.[5]

4 Experiment

The experiment was conducted in a dark room. The surrounding surfaces were covered by black cloth to eliminate the influence of stray light. We used a digital camera model SONY XCD-SX90CR with image resolution 1024×768 pixels in the experiment. The physical size of a pixel on the CCD chip is 0.00375×0.00375 mm^2. The focal length of the lens is f = 8.3 mm. Hence, the parameters in the intrinsic matrix $\mathbf{A}$ are $\alpha_u = \alpha_v = 2213.3$, $u_0 = 512$, and $v_0 = 384$. The images used in the experiment were of grayscale. We located the mirror reflection of light source by image thresholding and then regarded the centroid of the detected pixels as the specular spot. We evaluated the direction errors of the proposed method in the one- and two-orientation cases and the distance error in the two-orientation case. In addition, we used photometric stereo as an example to compare the performance of the proposed method with the traditional sphere-based method.[10]

4.1 *Accuracy Evaluation*

In the experiment, a LED light source was placed in 29 different positions. The distances from the planar mirror to the light sources ranged from 0.6 to 1.3 meters; the intersection angles θ (see Fig. 2) were in the range from 25 to 95 deg. To obtain the ground truths of the intersection angles and the distances, the exact locations of the light sources with respect to the camera and the planar mirror were manually measured.

Figure 4 shows the direction errors in the one- and two-orientation cases with respect to different light source locations. The distribution of direction error agrees quite well in these two cases. The direction error does not have clear correlation with the light source position. The maximum direction error is below 0.6 deg, and the average error is 0.23 deg. The distribution of distance error with respect to light source position is plotted in Fig. 5. Although fluctuation is obvious, the approximate trend is that the distance error increases when the light source is far to the scene. The error is mainly due to the determination of the intersection point of two lines, which is affected by two factors: light source distance and mirror orientations. Generally, the distance error is low when the light source is close to the camera. For a certain light source location, the distance error would be comparatively lower when the rotation difference of the two mirror orientations is larger. For these 29 different light source locations, the maximum distance error is 29.6 mm. The average absolute and relative distance errors are 8.6 mm and 0.7% respectively. In comparison, Powell et al.[9] reported that their average direction error is 2.7 deg, and their average distance

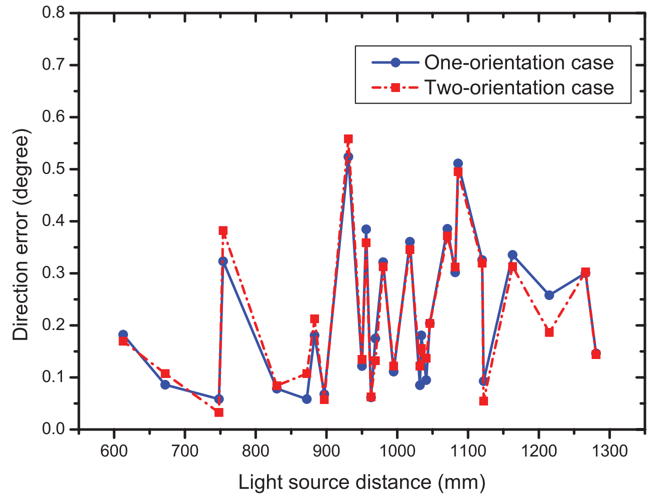

Fig. 4 Direction estimation errors with respect to light source positions in the one-orientation and two-orientation cases.

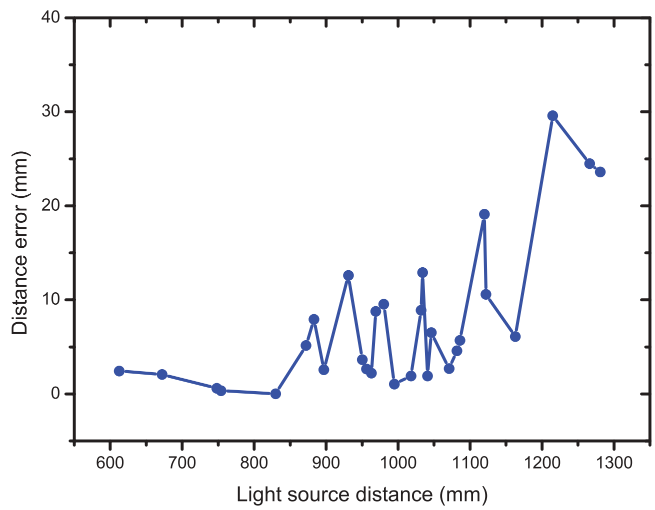

Fig. 5 Distance estimation errors with respect to light source positions in the two-orientation case.

Table 1 Direction errors (in degree) of the five light sources in the photometric stereo system.

Light No.	Sphere (Ref. 10)	Mirror (1-orient. case)	Mirror (2-orient. case)
1	2.19	0.43	0.47
2	4.06	0.25	0.18
3	1.23	0.47	0.45
4	2.73	0.10	0.04
5	1.33	0.43	0.32

Table 2 Estimated intensities of the five light sources in the photometric stereo system.

Light No.	Sphere (Ref. 10)	Mirror (2-orient. case)
1	1.00	1.00
2	0.96	0.97
3	0.98	0.94
4	0.99	0.93
5	1.00	0.87

error is 130 mm under the absolute metric and 9% under the relative metric. This clearly indicates the superiority of the proposed method over their three-sphere based method.

4.2 *An Example of Photometric Stereo*

To further validate the planar mirror-based method, we set up a photometric stereo system with five LED light sources and reconstructed the 3D shape of a ball with only diffuse reflection. Although three light sources are the minimum requirement in traditional photometric stereo, we used five lights to obtain robust 3D reconstruction. The distances from the light sources to the object were in the range of 700–800 mm, and the θ angles (see Fig. 2) were all around 30 deg. For a fair comparison, we implemented the sphere-based light source calibration method introduced in Ref. 10.

Table 1 shows the direction errors of the sphere-based method and the two cases of the proposed method. The average direction error of the sphere-based method is 2.3 deg, which is consistent with the results reported in Ref. 10. The average errors of proposed method in the one- and two-orientation cases are 0.34 and 0.29 deg, respectively.

It was almost impossible to accurately measure the absolute radiometric intensities of the light sources due to the limited space in the imaging system. Instead, we used different Lambertian surfaces and a number of mirror orientations to measure the relative intensities and found that the results were very similar. Table 2 shows the estimated relative intensities normalized with respect to the first light source. For the sphere-based method, the estimated intensities are very close; for the two-orientation planar mirror based method, the intensity of the fifth light source is relatively lower. As the ground truths are unavailable, we cannot directly judge which method is more robust in intensity estimation from Table 2. Nevertheless, the accuracy could be validated by the 3D reconstruction of the ball.

The imaging distance of the camera was 640 mm, which was more than 20 times larger than the radius of the ball. For each light source, the lighting direction $\mathbf{l}$ was assumed identical for every point on the ball surface. The inverse-square law of lighting intensity was not considered. These assumptions are in accordance with the standard photometric stereo technique.[3,13] The normal of each pixel is calculated from image intensity and light source parameters under the least-square criterion.[3] The height of each pixel position is reconstructed using the Poisson solver.[2] The cross-sections of the reconstructed surfaces by the mirror-based and sphere-based methods are shown in Fig. 6. It is observed that the reconstructed height of the mirror-based method almost

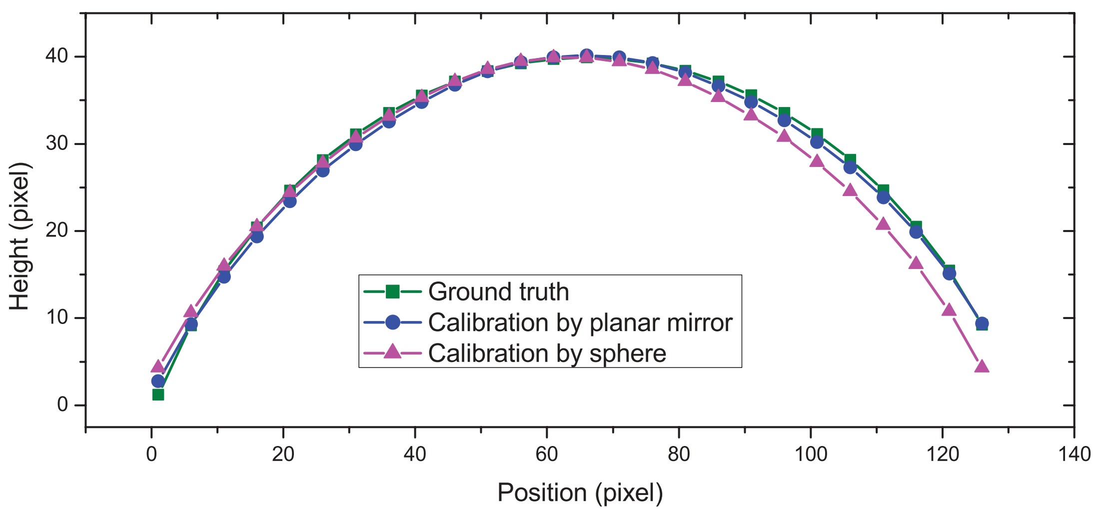

Fig. 6 Reconstructed ball height by photometric stereo. The five light sources were calibrated by planar mirror (two-orientation case) and sphere, respectively.

coincides with the actual one, while that of the sphere-based method deviates obviously. Quantitatively, the actual radius of the ball is 73.5 pixels; the fitting radius of the proposed and the sphere-based methods are 73.40 ± 0.20 pixels and 71.20 ± 0.25 pixels, respectively. These results clearly indicate that the light source calibration complemented by the planar mirror produces more accurate 3D reconstruction in photometric stereo.

5 Conclusions

This paper presents a novel method for light source calibration by using a planar mirror. When the normal of the mirror plane is recovered, the direction of light source can be acquired by using either one or two orientations. In the two-orientation case, the position and intensity of light source can be further estimated. The average direction error and relative distance error are around 0.3 deg and 0.7%, respectively. The 3D reconstruction of a simple object also verifies the superiority of the proposed method.

It is noted that, compared with the sphere-based method, the proposed method cannot simultaneously estimate all lights in the scene as the planar mirror has only one normal direction. The advantage of the proposed method lies in the much improved calibration accuracy, which is vital to many computer vision applications including photometric stereo.

Acknowledgments

This work was supported by the National Basic Research Program of China (973 Program) under Grant No. 2009CB320801 and the National Natural Science Foundation of China (NSFC) under Grant No. 60778050.

References

1. R. Zhang, P. Tsai, J. Cryer, and M. Shah, "Shape from shading: a survey," *IEEE Trans. Pattern Anal. Mach. Intell.* **21**, 690–706 (1999).
2. A. Agrawal, R. Raskar, and R. Chellappa, "What is the range of surface reconstruction from a gradient field?" in *Proc. European Conf. Computer Vision*, pp. 578–591, Graz, Austria (2006).
3. R. Woodham, "Photometrc method for determining surface orientation from multiple images," *Opt. Eng.* **19**, 139–144 (1980).
4. C. Hernandez, G. Vogiatzis, and R. Cipolla, "Multiview photometric stereo," *IEEE Trans. Pattern Anal. Mach. Intell.* **30**, 548–554 (2008).
5. H. Rushmeier and F. Bernardini, "Computing consistent normals and colors from photometric data," in *Prof. 2nd International Conf. 3D Digital Imaging and Modeling*, pp. 99–108, Ottawa, Canada (1999).
6. X. Cao and M. Shah, "Camera calibration and light source estimation from images with shadows," in *Proc. IEEE Conf. Computer Vision and Pattern Recognition*, pp. 918–923, San Diego, California (2005).
7. F. Xie, L. Tao, G. Xu, and H. Di, "Estimating illumination parameters in real space with application to image relighting," in *Proc. Asian Conf. Computer Vision*, pp. 490–499, Hyderabad, India (2006).
8. Y. Zhang and Y. Yang, "Multiple illuminant direction with application to image synthesis," *IEEE Trans. Pattern Anal. Mach. Intell.* **23**, 915–920 (2001).
9. M. Powell, S. Sarkar, and D. Goldgof, "A simple strategy for calibrating the geometry of light sources," *IEEE Trans. Pattern Anal. Mach. Intell.* **23**, 1022–1027 (2001).
10. W. Zhou and C. Kambhamettu, "Estimation of illuminant direction and intensity of multiple light sources," in *Proc. 7th European Conf. Computer Vision*, Vol. IV, pp. 206–220, Copenhagen, Denmark (2002).
11. P. Lagger and P. Fua, "Retriving multiple light sources in the presence of specular reflections and texture," *Comput. Vis. Image Underst.* **111**, 207–218 (2008).
12. W. Zhou and C. Kambhamettu, "A unified framework for scene illuminant estimation," *Image Vis. Comput.* **26**, 415–429 (2008).
13. T. Wu and C. Tang, "Dense photometric stereo using a mirror sphere and graph cut," in *Prof. IEEE Conf. Computer Vision and Pattern Recognition*, pp. 140–147, San Diego, California (2005).
14. C. Bouganis and M. Brookes, "Multiple light source detection," *IEEE Trans. Pattern Anal. Mach. Intell.* **26**, 509–514 (2004).
15. T. Takai, K. Niinuma, A. Maki, and T. Matsuyama, "Difference sphere: an approach to near light source estimation," in *Prof. IEEE Conf. Computer Vision and Pattern Recognition*, pp. 98–105, Washington, DC (2004).
16. S. Xu and A. Wallace, "Recovering surface reflectance and multiple light locations and intensities from image data," *Pattern Recogn. Lett.* **29**, 1639–1647 (2008).
17. Y. Wang and D. Samaras, "Estimation of multiple directional illuminants from a single image," *Image Vis. Comput.* **26**, 1179–1195 (2008).
18. R. R. J. Davis, D. Nehab, and S. Rusinkiewicz, "Spacetime stereo: a unifying framework for depth from triangulation," *IEEE Trans. Pattern Anal. Mach. Intell.* **27**, 296–302 (2005).
19. R. K. Kumar, A. Ilie, J. M. Frahm, and M. Pollefeys, "Simple calibration of non-overlapping cameras with a mirror," in *Proc. IEEE Conf. Computer Vision and Pattern Recognition*, Anchorage, Alaska (2008).
20. Z. Zhang, "A flexible new technique for camera calibration," *IEEE Trans. Pattern Anal. Mach. Intell.* **22**, 1330–1334 (2000).
21. J. Bouguet, "Camera calibration toolbox for matlab," http://www.vision.caltech.edu/bouguetj/calib_doc/index.html.
22. D. Forsyth and J. Ponce, *Computer Vision: A modern Approach*, Prentice Hall, Upper Saddle River, NJ (2003).

Hui-Liang Shen received his PhD degree in electronic engineering from Zhejiang University, China, in 2002. He has been a research associate and post-doctorial fellow in The Hong Kong Polytechnic University, from 2001 to 2005. He joined the Department of Information and Electronic Engineering, Zhejiang University, in 2005, and is currently a professor. His research interests are image processing, computer vision, and color imaging.

Yue Cheng received his BE degree in electronic engineering from Zhejiang University, China, in 2008. He is currently pursuing his PhD degree. His research interest is computer vision, especially in photometric and binocular stereo vision.