

Joint optimisation model for light source position based on a combined target

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Abstract. Photometric stereo vision, as a non-contact three-dimensional imaging technology, can achieve fast and high-precision reconstruction of normal vectors and three-dimensional morphology of object surfaces by resolving the intensity changes under different angles of illumination. However, the existing near-field photometric stereo vision system is limited by the complexity of the light source calibration process and the error accumulation, which seriously restricts the expansion of the application of this technology. This paper addresses the problem of accurately determining the centre of a spherical mirror target combined with a planar calibration board. We proposed a joint optimization model that simultaneously estimates both the light source positions and the sphere centre coordinates. The model defines a unified objective function to guide the optimization. The calibration is implemented using the Ceres Solver, based on near-field photometric stereo principles. Compared with the pre-optimization results, the error in the estimated sphere centre is reduced from 0.541 mm to 0.228 mm.

1 Introduction

Since photometric stereo introduction, it has undergone extensive research and development over the years. It has achieved significant progress in recovering surface normals and reconstructing 3D shape [1]. Researchers have continuously improved reflectance models, refined normal estimation methods, and enhanced the accuracy of light source calibration. Among these factors, accurate calibration of light source positions has become a critical component for achieving high-precision 3D reconstruction. To address this challenge, various scholars have proposed a range of novel calibration methods. Xie et al. [2] used multiple specular spheres to calibrate the spatial position of the light source, which is unique in that multiple incident lines of light can be acquired in a single shot, and then the principle of light intersection is used to determine the position of the light source; Takai et al. [3] used a pair of reference spheres to determine the geometric position of the light source. They focused on analysing the grey scale curves on the spheres, and through the careful study of these curves, information related to the position of the light source was extracted from them to determine the position of the light source. This approach relies on the precise interpretation of the grey scale variations on the sphere and provides another effective way for light source calibration; Santo et al. [4] used a large pinhole pin as a calibrator and studied in depth the shadow formation process of the pinhole pin under the light source. After using beam levelling, they were able to simultaneously recover the position of the calibrator and the direction or

position of the light source. This method comprehensively considered the interrelationship between the calibrator and the light source, and achieved the accurate acquisition of the position information of both through an optimisation algorithm; The core of the self-calibrating photometric stereo technique [5-7] lies in the use of information from the image itself to infer parameters such as the light source, camera response, etc., without the need for an additional calibration process. It is based on the basic principle of photometric stereo, i.e. recovering surface normals and shapes by analysing image grey scale changes of an object under different lighting conditions.

In the method of using the standard ball calibration, the accuracy of the estimated sphere centre directly affects the precision of light source calibration. However, directly fitting the outer contour of the sphere often introduces errors. Combining the standard sphere with a planar calibration target can improve the estimation of the sphere centre's coordinates in the target coordinate system. This improvement relies on a critical assumption: the spatial relationship between the sphere centre and the calibration plane must be known with high accuracy. In our previous work [8], we obtained the ball centre coordinates by beam levelling and using multiple angle shooting. However, the established optimisation model still needs further improvement. To address the above issue, this paper proposes treating both the sphere centre coordinates and the light source positions as jointly estimated parameters. By doing so, we construct a unified optimization model that avoids the errors introduced by solving for the

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sphere centre independently. This approach provides a reliable calibration method for light source position estimation based on a combined calibration target.

2 Method

2.1 Light source positions calibration based on a combined target

The traditional specular sphere light source calibration method is based on the principle of specular reflection, which determines the spatial position of the light source by analysing the intersection point of the light direction in the highlight region on the surface of the specular sphere under different attitudes. However, this method has significant limitations in practical applications: the non-uniform illumination of a single light source will lead to an unavoidable shadow effect on the surface of the sphere, and the weak contrast between the sphere contour and the background will easily lead to the edge extraction bias, which all these factors together result in the systematic error in the positioning accuracy of the light source. In order to solve the above problems, the combination of specular sphere and planar target is used for calibration, and the sphere centre coordinates are directly reprojected onto the imaging surface through spatial transformation, which has a higher accuracy than the sphere contour centre extraction, and thus ensures the spatial position solution of the near-field point light source.

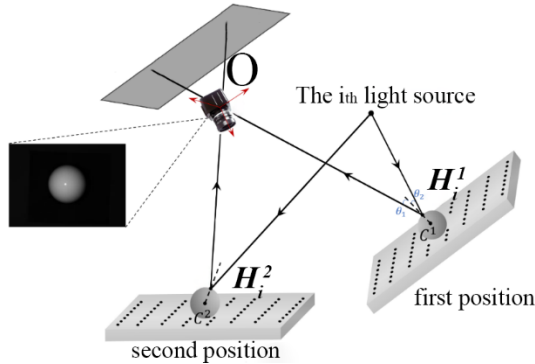


Fig. 1. Schematic diagram of combined target calibration.

Figure 1 shows the combination of target calibration process, in the light source position calibration requires two steps. Firstly, the position of the specular sphere relative to the plane target needs to be determined, and then it is necessary to collect the photographs of the highlights $H^j(x_i^j, y_i^j, z_i^j)$ irradiated by the light source on the specular sphere in this position, and the spatial position $C^j(x_c^j, y_c^j, z_c^j)$ of the light source can be solved according to the geometric relationship based on the light reflection model. In order to obtain the relative position relationship between the specular sphere and the plane target, the beam levelling method can be used to optimize the parameters of the combined target. In the previous work, using the minimum reprojection error as the optimisation objective, there is still a certain error in the model, so this paper further proposes a joint optimisation method, i.e., to optimise the sphere centre coordinates and the light source position jointly.

2.2 Combined optimisation model

In the use of the combination of target calibration of the light source position, the camera will be used to collect in different light source irradiation mirror standard ball reflection of the formation of the high light point, it can be seen that the formation of the high light point at the same time by the light source, the ball, the camera, i.e., the position of the location of the high light point and the light source position, the centre of the ball position and the camera position of the formation of a one-to-one correspondence of the mapping. When the spatial position coordinates of the light source, sphere, and camera are determined, the spatial position coordinates of the highlight point can be uniquely determined, and vice versa, so there is no need for more operations and redundant analyses, and no additional system structure is added. The combined target co-optimization model proposed in this paper will use the highlight point captured in the reflectance calibration as the intermediate value between the target parameter determination and the calibration of the reflectance model, and at the same time, the specular standard sphere Spherical centre coordinates and light source position are optimised for the calibration results, and the specific steps and principles of the optimisation are described in detail below.

(1) Get initial value

The position of the light source is calibrated using the combined target in accordance with the normal process, and the intermediate parameters obtained during the calibration process will be used as the initial values for the joint optimisation, including the coordinates of the position of the light source $L_i(x_{li}, y_{li}, z_{li})$, the coordinates of the centre of the sphere $C^j(x_c^j, y_c^j, z_c^j)$, and the spatial position of the highlight point of the i th light source at the L th combined target position $H^j(x_i^j, y_i^j, z_i^j)$.

(2) Solve the expression for a reflected ray

From the reflection model and the geometrical relationship, it can be expressed that under the condition that the incident light and normal vector are determined, the vector expression of the reflected light ray can be calculated by the reflection formula as:

$$\begin{pmatrix} 2 \frac{(x_i^j - x_c^j)^2}{d_n^2} - 1 & 2 \frac{(x_i^j - x_c^j)(y_i^j - y_c^j)}{d_n^2} & 2 \frac{(x_i^j - x_c^j)(z_i^j - z_c^j)}{d_n^2} \\ 2 \frac{(x_i^j - x_c^j)(y_i^j - y_c^j)}{d_n^2} & 2 \frac{(y_i^j - y_c^j)^2}{d_n^2} - 1 & 2 \frac{(y_i^j - y_c^j)(z_i^j - z_c^j)}{d_n^2} \\ 2 \frac{(x_i^j - x_c^j)(z_i^j - z_c^j)}{d_n^2} & 2 \frac{(y_i^j - y_c^j)(z_i^j - z_c^j)}{d_n^2} & 2 \frac{(z_i^j - z_c^j)^2}{d_n^2} - 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \frac{x_i^j - x_{li}}{d_l} \\ \frac{y_i^j - y_{li}}{d_l} \\ \frac{z_i^j - z_{li}}{d_l} \end{pmatrix} \quad (1)$$

$$d_l = \sqrt{(x_i^j - x_{li})^2 + (y_i^j - y_{li})^2 + (z_i^j - z_{li})^2} \quad (2)$$

$$d_n = \sqrt{(x_i^j - x_c^j)^2 + (y_i^j - y_c^j)^2 + (z_i^j - z_c^j)^2}$$

Where d_l and d_n represent the modulus of the incident light vector and normal vector, respectively.

(3) Calculate the residuals

The difference between the reflected light and the true value of the reflection vector obtained by numerical computation from the input initial value condition is used as the residual, in this system the true value is the shooting highlight point pixel coordinates converted to

the image point coordinates $P_i^j(x_i^j, y_i^j, z_i^j)$ to the centre of light vector, then the residual expression is:

$$\begin{cases} x_{residual} = x - x_i^j \\ y_{residual} = y - y_i^j \\ z_{residual} = z - z_i^j \end{cases} \quad (3)$$

(4) Iterative optimization

To ensure the global optimality of the optimisation estimation results, the optimisation objective function can be determined as:

$$\min \sum_{j=1}^N \sum_{i=1}^M \left\| f_i^j(p_i^j; L_i, C^j, H_i^j) - P_i^j \right\|^2 \quad (4)$$

2.3 Parameter solving based on ceres

Ceres is a widely used open-source library for efficient least squares problem solving, its flexibility and power make it ideal for complex optimisation problems, solving large-scale nonlinear least squares problems.

First, define the parameter block and residual block, from the parameter block can be calculated to get the residual block, the residual block represents the reprojection error of the reflected light, and the residual value returned after calculating the error value will be used as the value of the objective function; the next step is to construct the optimisation cost function, name AddResidualBlock to add parameter block and residual block to it step by step, and together with the cost function deduced in the previous section, we listed global Optimisation cost function, where $f_{ij}()$ is the residual function, where the parameters are the parameters to be optimised, and $\rho_{ij}()$ is the loss function, the optional Huber loss optimisation can make the optimisation robust and suppress the influence of outliers; finally, configure the solver, using the built-in Auto Diff function of Ceres, the numeric difference numeric function (numeric Diff), or the user can provide the solver to Ceres. The user provides the analytical formulas to Ceres' gradient optimisation derivation method.

$$\min \frac{1}{2} \sum_i \sum_j \rho_{ij} \left(\left\| f_{ij}(L_i(x_i, y_i, z_i), C^j(x_c^j, y_c^j, z_c^j)) \right\|^2 \right) \quad (5)$$

3 Experimental results and analysis

In order to precise the calibration accuracy before and after the optimisation, the combination target used in this experiment is calibrated precisely by Shenzhen Institute of Metrology and Quality Inspection using optical three coordinate integrated measuring machine and coordinate measuring machine, the ceramic mirror ball is fixed on the combination target, and the diameter of the mirror ball is 20.0016 mm, and the planar target pattern consists of 4 large circle datums and 74 small circle datums, with the small circle centre spacing of 5 mm. The precise parameters in the calibrated combination target are shown in Fig. 2.

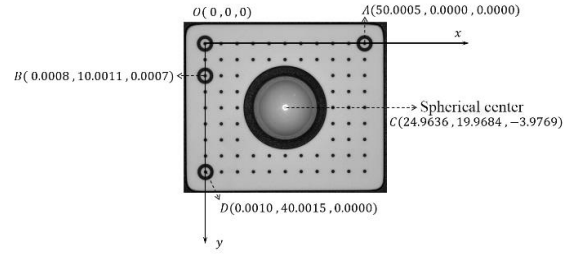


Fig. 2. Schematic diagram of key datum parameters for calibrating combined targets

As shown in Table 1, the average deviation of the spherical centre coordinates from the true value is reduced by 0.313 mm after optimisation, while indices such as the standard deviation and error span are improved, indicating that the optimised model enhances the parameter stability while improving the calibration accuracy. In terms of light source position accuracy verification, for the industrial-grade integrated LED lighting system used in the experiment, the adjacent distance error [9] is used to effectively determine the authenticity of the light source distribution, and quantitative analysis is performed by comparing the Euclidean distance of the diagonal light source before and after the optimisation. As shown in Table 2 and Fig 3, the average relative error between the diagonal light source spacing and the theoretical value is reduced to within 0.5% after optimisation, an improvement of about 94.6%, which is significantly better than the error level before optimisation.

Finally, the reflection model optimisation is verified by light vector parallelism. As shown on in Fig. 4, by calculating the average value of the angle between the reflected light and the actual light in 8 positions, the average value of the angle between the reflected light and the actual highlight-centre vector is reduced to 3.15° after the optimisation of the reflection model, which is 4.8° deviation from that before the optimisation, and fully verifies the validity of the optimisation scheme of the reflection model in realising the theoretical aspects.

Table 1. Spherical coordinate distance residuals before and after optimisation.

Pose	Before optimization (mm)			After optimization (mm)		
	X	Y	Z	X	Y	Z
1	0.355	-0.213	0.346	-0.060	-0.032	0.227
2	0.321	-0.188	0.312	-0.084	-0.033	0.243
3	0.388	-0.246	0.321	-0.015	0.003	0.257
4	0.368	-0.223	0.335	-0.043	-0.084	0.206
5	0.312	-0.199	0.301	-0.032	-0.034	0.252
6	0.346	-0.210	0.357	-0.036	-0.049	0.223
7	0.379	-0.235	0.368	-0.073	-0.005	0.152
8	0.390	-0.257	0.379	-0.047	-0.040	0.180
Average distance (mm)	0.541			0.228		
Discrete standard deviation	0.042			0.033		
Span of distribution (mm)	0.124			0.091		

Table 2. Comparison of diagonal Euclidean distances of light sources before and after optimisation.

Compare parameters	Before optimization	After optimization
Average value (mm)	107.673	106.090
MAE(mm)	3.328	1.148
RMSE(mm)	3.679	1.529

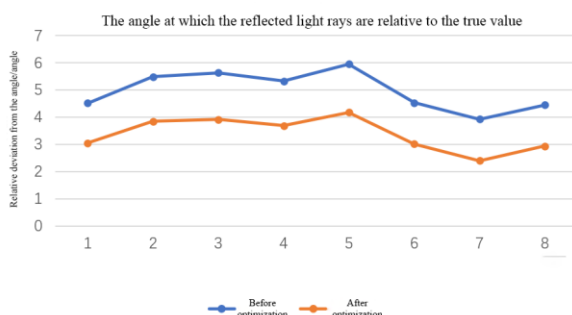


Fig. 3. Comparison before and after the optimization of the angle between the reflected light and the ground truth

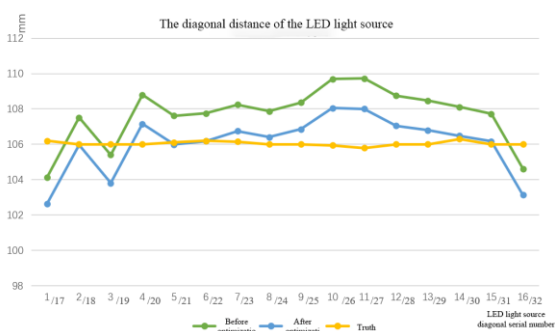


Fig. 4. Before and after the optimization of the diagonal distance of the LED light source

4 Conclusion

To reduce the systematic error present in traditional mirror-sphere-based light source calibration methods, this paper proposes a joint geometric calibration and optimization framework based on a combined calibration target. By integrating multi-view geometric constraints with nonlinear optimization techniques, the method achieves high-precision joint calibration of light source pose, mirror sphere centre, and reflection paths. Experimental results demonstrate that the proposed framework effectively addresses the error accumulation caused by the separation of sphere centre localization and reflection path computation in conventional methods. The proposed method improves the spatial localization accuracy of light sources and reduces systematic errors compared to existing approaches. These results validate both the theoretical advantages and practical applicability of the proposed calibration model.

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