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Calibration Methods of Projector-Camera Structured Light System: A Comparative Analysis

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***Abstract*—Calibration is a critical issue in the development of projector-camera-based structured light systems. In this paper, underlying calibration principle and research progress are briefly reviewed firstly. Then, three representative calibration methods, i.e. the *ProcamCalib*, *SLSCalib* and *3DCalib* methods are introduced in details. To compare the performance of various calibration approaches, a prototype of projector-camera system is constructed and calibrated by three calibration methods respectively. To evaluate the calibration accuracy, three metric error terms are used based on a reference plane with printed markers. By the analysis of experimental results, some conductive conclusions are obtained which can provide guidance for the researchers in structured light research domain.**

Keywords-structured light system; projector-camera calibration; 3D reconstruction

I. INTRODUCTION

Projector-camera-based structured light system (SLS) has been an important 3D scanning technology, which has gained widely applications like robot navigation, industrial inspection, medical surgery, reverse engineering, historic preservation, and so on [1]. A typical SLS consists of one projection device and one camera. The pattern images are projected on the target surface and then captured by the camera synchronously. With the decoding procedure, dense correspondences between camera and projector can be established and reconstructed via triangulation.

Calibration is usually the first step to construct a projector-camera SLS, which has great influence to the final 3D reconstruction accuracy. The camera and projector calibration is the process of finding the intrinsic and extrinsic parameters of two devices, which describes the relationship between captured images and the scenes that they depict [2]. The intrinsic parameters include parameters related to the device itself such as focal length and distortion. The extrinsic parameters indicate the pose of the camera with respect to the projector coordinate system. The calibration is usually performed by taking pictures of a calibration object. This object has a known pattern with known distances between recognizable markers. The parameters are calculated by locating and comparing those points across multiple images to calculate the intrinsic parameters. Since the projector cannot capture the markers like the camera, the projector is usually treated as an inverse camera since it cannot capture the calibration targets like the camera [3]. Usual means for the calibration of projector-camera SLS is to calibrate the camera first, and then use the calibrated camera for the calibration of projector device.

In this paper, state-of-art of existing projector-camera SLS are briefly reviewed, and three major calibration methods are implemented and compared with respect to the calibration precision and reconstruction precision. These calibration methods including: 1) *ProcamCalib*: which calibrates the projector by projecting a checkerboard to a 2D calibration plate [4]; 2) *SLSCalib*: which calibrates the projector by projecting a sequence of phase shifting patterns onto the 2D calibration plane [5]; and 3) *3DCalib*: which calibrates the projector by projecting a sequence of phase shifting patterns onto a 3D right angle plate [6]. The experimental results can provide guidance and useful information for the researchers in SLS domain.

Rest of the paper is organized as follows. State-of-the-art of major calibration means for projector-camera SLS are introduced in Section 2. The proposed evaluation framework and calibration accuracy comparison results are provided in Section 3. The discussion and conclusion are presented in Section 4.

II. UNDERLYING PRINCIPLE AND STATE-OF-THE-ART FOR THE SLS CALIBRATION

Basic motivation of the SLS research is to solve the difficult corresponding problem that involved in stereo vision methods. By projecting some features that embedded coding information, and extract that from the captured images, dense correspondences can be established between camera and projector. The calibration of camera or stereo vision systems have been very mature like the methods proposed in [7-8]. However, for the calibration of projector-camera-based SLS, major difficulty comes from the calibration of projector device, since the project cannot see the calibration targets. Existing SLS calibration methods usually follow the same calibration manner, i.e. to use the calibrated camera for the calibration of projector. However, such calibration scheme usually causes the calibration error propagation from the camera to projector.

A basic geometrical model of projector-camera SLS is as shown by Fig. 1. The structured light patterns are projected onto the object by a projector, a camera is used to capture the distorted images. The surface point $P(X_W, Y_W, Z_W)$ on object surface in the world coordinate is mapped to the point (u_p, v_p) and (u_c, v_c) in the projector and camera image plane respectively. In order to improve the accuracy of the system, the accurate calibration of the camera and projector is necessary. The intrinsic parameters includes the focal f_p and f_c, the coordinate origin of image plane in the pixel coordinate (u_{p0}, v_{p0}), (u_{c0}, v_{c0}), and distortion coefficients. The extrinsic parameter refers to matrix M which describes the rotation and translation vectors between camera and projector. By treating the projector as an inverse camera, the perspective pinhole model can be used to depict both camera and projector as:

$$Z_c \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = K \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} M \begin{bmatrix} X_W \\ Y_W \\ Z_W \\ 1 \end{bmatrix}, \tag{1}$$

where (X_W, Y_W, Z_W) is the 3D location of a scene point P and its projection in an image is (u, v). Z_C is a scale factor, K is known as the intrinsic matrix and M is the extrinsic matrix. When the problem comes to high precision measurement, the tangent and radial distortion coefficients $\{k_1, k_2, p_1, p_2, k_3\}$ are usually considered and the undistorted image coordinates can be computed as [9]:

$$\begin{cases} x_r = x(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) \\ y_r = y(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) \end{cases}, \tag{2}$$

$$\begin{cases} x_t = x + [2p_1 xy + p_2(r^2 + 2x^2)] \\ y_t = y + [p_1(r^2 + 2y^2) + 2p_2 xy] \end{cases}, \tag{3}$$

where $r^2 = x^2 + y^2$; Dist is the distortion coefficients; the parameters $\{k_1, k_2, p_1, p_2, k_3\}$ are used to express the lens distortion of two devices; (x_r, y_r) and (x_t, y_t) stand for the undistorted image coordinates; (x, y) are the realistic image coordinates with distortion. Difference among various calibration methods mainly comes from the calibration procedure, i.e. how to determine the calibration markers from the calibration rig and to map the markers from image coordinate to projector sensor plane, and three representative calibration means are introduced as follows.

A. *ProcamCalib* Calibration Method

ProcamCalib is a popular SLS calibration tool [4], which makes the calibration of a projector the same as that of a camera because the projector is considered as an inverse camera. In this method, a planar checkerboard is used to minimize calibration complexity. The checkerboard pattern is first imaged by camera. Keeping the checkerboard static, another checkerboard pattern will be projected from the projector and then imaged by the camera again. By changing the position and pose of checkerboard pattern, and repeating above procedures, a group of calibration images can be obtained by the camera and projector respectively. The physical checkerboard pattern images are used for the calibration of camera. Therefore, 3D coordinate of each checkerboard pattern can be determined w.r.t the camera frame. By extracting the projected pattern features, their 3D coordinates on the calibration plane can be calculated. As a result, Eqn. (1) can be solved for the projector device. This calibration means requires only one planar checkerboard and single projection of the projector, which is easily to operate and the calibration procedure is more efficient.

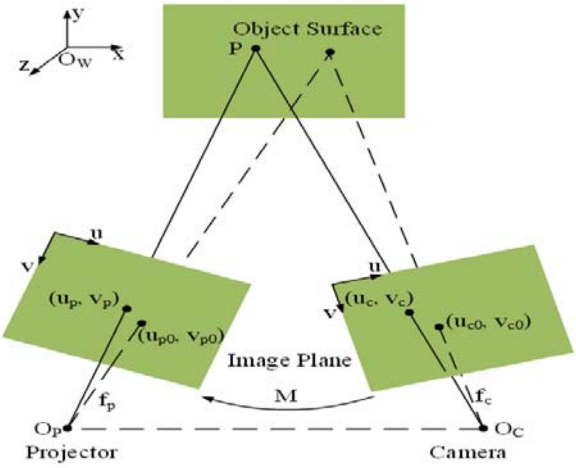


Figure 1. Geometrical illustration of a projector-camera system.

B. *SLSCalib* Calibration Method

SLSCalib is another popularly used calibration tool for projector-camera SLS [5]. The 2D planar checkerboard is used for the system calibration. Keeping the calibration board static, one image is captured by the camera firstly. And then, a set of orthogonal Gray code patterns are projected onto the checkerboard plate [10-12]. Via the decoding procedure, dense correspondence between the calibration plane and projector pixels can be established. In [5], the local homographies are applied to improve the feature localization precision. A dense set of projector row and column correspondences that acquired by decoding the Gray code patterns according to robust pixel classification is used to compute a group of local homographies that can find the projection of points in the calibration plate onto the projector image plane. Then, the projector can be calibrated as a normal camera. This calibration method utilizes structured light coding principle, which can obtain dense correspondences. But it usually takes a long time for the pattern projection and image processing.

C. *3DCalib* Calibration Method

3DCalib is another usual calibration means [6]. Different with the *ProcamCalib* and *SLSCalib*, *3DCalib* utilizes a 3D object, which can be a right angle calibration plate on which some circular markers instead of printed checkerboard [13]. This calibration object is obtained from the 3DScanner Product proposed by Hewlett-Packard Corporation. It needs not to change the pose of calibration plate because of the determinate z axis, the director of the right angle plate, in the world coordinate system. Thus, only one image is captured, a camera can be calibrated using Tsai's method [7]. And only one pose of a set of encoded pattern sequence images is obtained to calculate the parameters of a projector. Before calibration, the target should be placed in the common field of view, that is to say, the calibration target should be seen by both devices [14]. Then the major problem is the correspondences between the pixel coordinates of the circular markers in the projected images and the physical coordinates of these markers. In this method, the Gray code and phase shift pattern projection is also adopted. This calibration method is efficient and simple to operate. But it needs a specific 3D target with high manufacturing precision.

III. Evaluation of Three Calibration Methods

To evaluate calibration precision of three calibration methods, an experimental projector-camera SLS is established in our laboratory. The system consists of a FLIR BFS-U3-13Y3C camera with the resolution of 1280×1024 pixels, and a DLP LightCrafter 4500 projector with the resolution of 1280×800 pixels as shown by Fig. 2. A high quality laser engraving checkerboard pattern as shown by Fig. 3a is used for the calibration by *ProcamClib* and *SLSCalib*. Fig. 3b shows the 3D calibration rig, which used by the 3DCalib method.

To make the comparison more fairly, for each calibration method, the calibration procedure is repeated 3 times. Specifically, for the calibration methods of *ProcamClib* and *SLSCalib*, 30 groups of images are collected to accomplish one calibration procedure. With three independent operations, we can obtain three calibration results for each method. Since only one pose was required to complete a calibration by the *3DCalib* method, we changed the position and pose of the 3D rig 3 times and obtain 3 calibration results.

To evaluate the calibration accuracy by various calibration methods, a simple experimental rig is designed as shown by Fig. 4, where a 3×3 point array was engraved by laser on a flat glass surface. Distance between each point is precisely set to 100 mm. The structured light method in [15] was used for the 3D scanning, and three metric terms are used for the measurement error evaluation, i.e. the distance error, angular error and the planarity error.

A. Distance Error

Based on the 3D reconstruction results of the reference plane with markers, distances between four points A, B, C and D are measured. Absolute mean error, max error, min error and std. values of the distance measurement results are listed in Table I. Mean, max, min, std stand for the average, maximum, minimum, standard deviation values of these errors. Best measurement results in each group are highlighted. In comparison, results by the *ProcamCalib* can outperform, and result by the *3DCalib* is the worst.

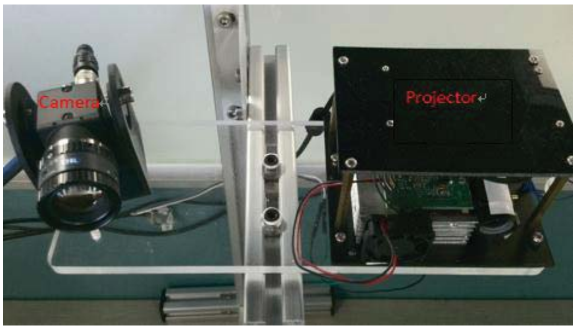
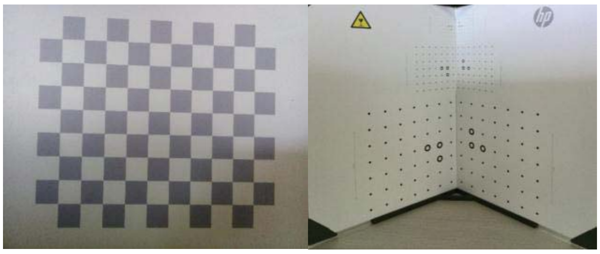


Figure 2. Experimental projector-camera SLS is established for the evaluation of three calibration methods.



a) b)

Figure 3. a) A printed checkerboard pattern that used in the calibration method *ProcamClib* and *SLSCalib*; b) A 3D calibration rig used by the *3DCalib* method.

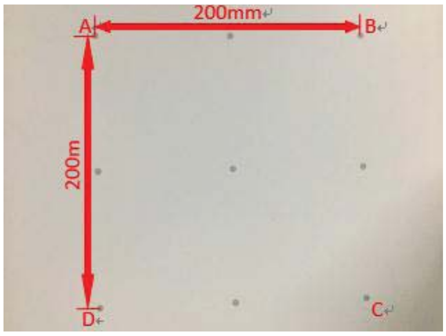


Figure 4. A planar surface with markers is used to evaluate calibration errors.

TABLE I. Distance Errors by Three Calibration Mehtods

Method		Distance Error (mm)			
		mean	***max***	***min***	***std***
ProcamCalib	1	0.1411	0.2106	0.0099	0.0778
	2	0.2914	0.4271	0.0996	0.1252
	3	**0.1098**	**0.2148**	**0.0354**	**0.0713**
SLSCalib	1	0.1414	0.2490	0.0357	0.0947
	2	**0.1356**	**0.2625**	**0.0168**	**0.1168**
	3	0.1479	0.2384	0.0848	0.0631
3DCalib	1	0.5254	0.5403	0.4984	0.0165
	2	0.5093	0.7046	0.3055	0.1475
	3	**0.4814**	**0.8604**	**0.3197**	**0.2199**

B. *Angular Error*

Angles between adjacent lines composed by points A, B, C and D are computed to evaluate the angular error by various calibration methods. The results are listed in Table II. Results show that, best accuracy also output by the calibration result of *ProcamCalib*, and the *3DCalib* calibration result performs worst.

TABLE II. ANGULAR ERRORS BY THREE CALIBRATION MEHTODS

Method		Angular Error (°)			
		mean	***max***	***min***	***std***
ProcamCalib	1	0.0554	0.0904	0.0202	0.0318
	2	0.0386	0.0635	0.0011	0.0256
	3	**0.0135**	**0.0292**	**0.0012**	**0.0118**
SLSCalib	1	0.0697	0.0771	0.0624	0.0052
	2	**0.0682**	**0.0719**	**0.0647**	**0.0030**
	3	0.0711	0.0813	0.0610	0.0091
3DCalib	1	**0.0686**	**0.0763**	**0.0610**	**0.0059**
	2	0.0705	0.1412	0.0075	0.0551
	3	0.0773	0.1522	0.0026	0.0727

C. *Planarity Error*

Based the reconstructed point clouds by the 3 calibration results, all the points inside marker region are planar fitted via least square means. The results are listed in Table III. Results show that, *SLSCalib* performs the minimum planarity error among three methods. That is to say, the minimal distortion of the reconstructed plane is unfolding in *SLSCalib* because of the application of local homography.

TABLE III. PLANARITY ERRORS BY THREE CALIBRATION MEHTODS

Method		Planarity Error (mm)			
		mean	***max***	***min***	***std***
ProcamCalib	1	0.0264	1.5616	0.3847	0.4425
	2	0.1430	8.6227	0.5987	1.0396
	3	**0.0131**	**2.2451**	**0.4662**	**0.5873**
SLSCalib	1	0.0121	1.5690	0.3817	0.4338
	2	**0.0022**	**1.5932**	**0.3879**	**0.4350**
	3	0.0034	1.5791	0.3892	0.4338
3DCalib	1	0.1503	4.3992	0.4618	0.7583
	2	0.1333	8.4826	0.4190	0.7122
	3	**0.0527**	**3.7958**	**0.4599**	**0.6186**

From the measurement results, it is easily to analyze that the *ProcamCalib* method performs best for the minimum distance and angular error. And the *SLSCalib* method can outperform in the planarity error test according to the Table IV and Fig. 5. In additions, the *3DCalib* method underperforms the other two calibration methods in all the error tests. In fact, only one image is required to calibrate the camera for the right angle plate in *3DCalib*. However, dozens of images are used to calibrate the camera both in *ProcamCalib* and *SLSCalib*. Thus, the inaccurate camera calibration has a negative effect to the projector calibration.

TABLE IV. BEST RESULTS BY THREE CALIBRATION MEHTODS.

Errors		ProcamCalib	SLSCalib	3DCalib
Distance Error	*mean*	**0.1098**	0.1356	0.4814
	max	**0.2148**	0.2625	0.8604
	min	**0.0354**	0.0168	0.3197
	std	**0.0713**	0.1168	0.2199
Angular Error	*mean*	**0.0135**	0.0682	0.0773
	max	**0.0292**	0.0719	0.1522
	min	**0.0012**	0.0647	0.0026
	std	**0.0118**	0.0030	0.0727
Planarity Error	*mean*	0.0131	**0.0022**	0.0527
	max	2.2451	**1.5932**	3.7958
	min	0.4662	**0.3879**	0.4599
	std	0.5873	**0.4350**	0.6186

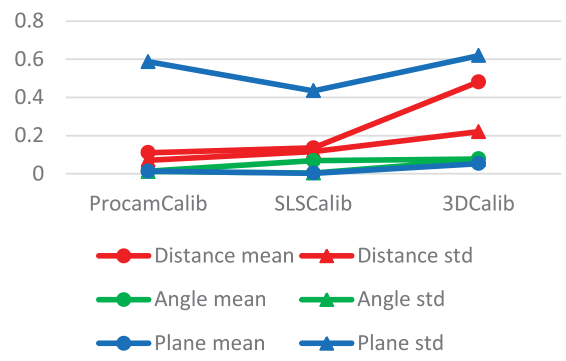


Figure 5. Comparison of three errors by three calibration methods.

IV. DISCUSSION AND CONCLUSION

With above experimental results and comparisons, it is understandable that the reconstruction error of *3DCalib* was slightly larger than that of *ProcamCalib* and *SLSCalib*. But the *3DCalib* method is simplicity of operation and less time consuming for the approximate calibration accuracy, which makes this method worth considering in the situations that high speed and simple operation are required. Then the selection of *ProcamCalib* and *SLSCalib* depends on the specific application scenarios. All the three calibration methods have been widely used in the SLS for depth information acquisition. A trade-off is required to choose a suitable method under different circumstances according to the purpose. The *ProcamCalib* and *SLSCalib* need more human intervention and perform better in reconstruction error. *ProcamCalib* can provide better measurement precision, the *SLSCalib* method can provide better lens distortion estimations, and the *3DCalib* method can provide more efficient calibration procedure.

In this paper, the accuracy and usability of three usual SLS calibration methods are evaluated with respect to several metric errors. The experimental results can provide guidance and helpful information for the users to judge which calibration method is best suited to their needs, and help them make better decisions regarding their choice of calibration. Each method may have their advantages under some circumstances.

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