Flexible Projector Calibration in the Structured Light 3D Measurement System

Haitao Wu, Biao Li, Jiancheng Zhang, Jie Yang, and Yanjun Fu(✉)

Key Laboratory of Nondestructive Testing (Ministry of Education),
Nanchang Hangkong University, Nanchang 330063, China
fyjpkh@sina.com.cn

Abstract. In the structured light 3D shape measurement system, the projector plays an essential part for 3D shape reconstruction. As the projector calibration accuracy affects the 3D shape measurement accuracy, a flexible projector calibration approach in the structured light system is proposed. Key to the proposed method is to establish the relationship between the projector coordinate and the world coordinate using the pre-calibrated camera. The process of the system calibration can be divided into three steps. First, a black-and-white (B/W) checkerboard is pasted on the white board plane for camera calibration. Second, the pre-calibrated camera is used to obtain the 3D world coordinates of the checkerboard corners. Here, instead of using complicated process with spatial color illuminations or phase-unwrapping method for the pixel mapping, a projected B/W checkerboard is used for the projector calibration. Unlike some other methods, the non-wide-angle camera can be used to capture the images of both pasted and projected checkerboards. Also the calibration process is not vulnerable to the environment. Finally, the results of the camera and projector calibration are used to reconstruct 3D shape. Experiments show that the reprojection errors for both camera and projector are within ±1 pixel, and the RMS error of 3D reconstruction is 0.25 mm.

Keywords: Structured light system · Camera · Projector · Calibration

1 Introduction

The structured light 3D measurement system has been widely used in industry for on-line inspection, quality control, solid modeling and dimensional analysis [1]. Fringe projection profilometry (FFP) has received significant attention for 3D shape measurement because of non-contact operation, full-field acquisition, and fast data processing [2]. The projector plays an important part for 3D shape reconstruction in the structured light. Also the projector calibration accuracy affects the 3D shape measurement accuracy. The key to accurate reconstruction of the 3D shape is the accurate calibration of each element used in the structure light system, including the camera and the projector.

To calibrate the structured light 3D measurement system, the internal and external parameters of the camera and the projector need to be got, as well as the relationship

T. Tan et al. (Eds.): IGTA 2015, CCIS 525, pp. 158–166, 2015.
DOI: 10.1007/978-3-662-47791-5_19

between the camera and the projector in the world coordinate. The camera calibration has been relatively mature, many researchers have carried out relevant research about it, and there are several effective methods, such as direct linear transformation (DLT), two-steps, nonlinear parameters optimization, self-calibration and Zhang's method [3, 4]. As the projector can not capture images itself, the process of the projector calibration is complicate. At present, many researchers have studied the projector calibration methods, as well as the improvement of the calibration accuracy [5]. Several methods use a pre-calibrated camera to find world coordinates in some calibration artifact, which in turn to map projector correspondences [6, 7]. A different approach is adopted in [8, 9] where, neither a calibrated camera, nor a printed pattern is required. Instead, they ask the user to move the projector to several locations so that the calibration pattern-projected onto a fix plane changes its shape. Wang uses the error surface compensation method to calibrate the projector of the structured light system. In this method, the calibration points in the camera image plane can be mapped to the projector according the homography of the planar projection [10]. Peng et al. developed the calibration methods using bundle adjustment. Although satisfactory calibration results can be got, they usually involve complicated procedures and the complete steps are time-consuming [11]. Zhou proposed a planar method, in which the intersection points of the light stripe and grids on the target are obtained as the control points [12]. Zhang and Huang proposed a novel method that enabled a projector to "capture" images likes a camera, thus making the calibration of a projector the same as that of a camera [13, 14, 15]. But both white light and red light illuminations are necessary in this method, which increased the complexity and hardware cost. Zhang introduced a calibration method by using a checkerboard and a white plate having discrete markers with know separation. The checkerboard determines the internal parameters of a CCD camera. The plate gives phase and depth data of each pixel to establish their relationship [16]. According to the researchers, the methods can be divided into two categories: the pre-calibrated camera and the phase mapping. In the first category, the object world coordinates of projection points are calculated by the calibrated camera or other approaches, and then the projection points are used to calibrate the projector. In the second category, the phase mapping or active adjustment method is used to obtain the image coordinate of the calibration points in the projector from the camera image, and then the projector can be calibrated in the same way as the camera by using the calibration points and their corresponding projector image points. The first category is simple and convenient, but the calibration accuracy of the projector relies on that of camera. On the contrary, the second category depends less on camera calibration and can achieve higher accuracy, yet its process is complicated because it need to project multiple phase images each time, and phase unwrapping or identification is vulnerable to environment.

In this paper, a flexible projector calibration in the structured light 3D measurement system is proposed. Here, a planar B/W checkerboard is used for both the camera and the projector calibration. For the projector calibration, it dose not require any spatial color illuminations, but requires a pre-calibrated camera. Instead of using the phase-unwrapping method to map the pixels between the camera and the projector, the checkerboard projected on the thin white paper is used to establish the homography between the projector coordinate and the 3D world coordinate. At the same time, the checkerboard pasted on the white board plane is used for the camera calibration. The proposed method can use the non-wide-angle camera to capture the images, which is not vulnerable to the environment. The projector calibration method is easy and active to realize, also accurate in the laboratory environment.

2 Projector Model

A projector can be regarded as the inverse of a camera, because it projects images instead of capturing them. Here, the projector model can be explained with pinhole model and the distortion model.

2.1 Projector Pinhole Model

Same as the camera, the pinhole model of the projector can be seen in Fig. 1, where q is an arbitrary point with coordinates (x^W, y^W, w^W) and (x^P, y^P, z^P) in the world coordinate system $\{o^W; x^W, y^W, z^W\}$ and projector coordinate system $\{o^P; x^P, y^P, z^P\}$, respectively. $\{o; u, v\}$ is the image coordinate system of the projector. Projecting a point p with coordinate (u, v) in the projector image plane into the 3D object's point q, then the relationship between them can be described as follows based on the projector pinhole model:

$$sI = HX^W \tag{1}$$

Where s is a scale factor, $I = [u, v, 1]^T$ is the homogeneous coordinate of the image point p in the image coordinate system of the projector, $X^W = [x^W, y^W, z^W, 1]^T$ is the world coordinate of the point q in the world coordinate system. H is the homography, which can be replaced by $H = A[R, T]$. Here, R, T is the rotation and translation matrix between the world coordinate system and the projector coordinate system, respectively. And $[R, T]$ represent the extrinsic parameters matrix of the projector. A is the projector intrinsic parameters matrix and can be expressed as

$$A = \begin{bmatrix} f_x & 0 & u_0 \\ 0 & f_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Here, f_x, f_y represents the focal length along u and v axes of the image plane, respectively. (u_0, v_0) is the coordinate of principle point.

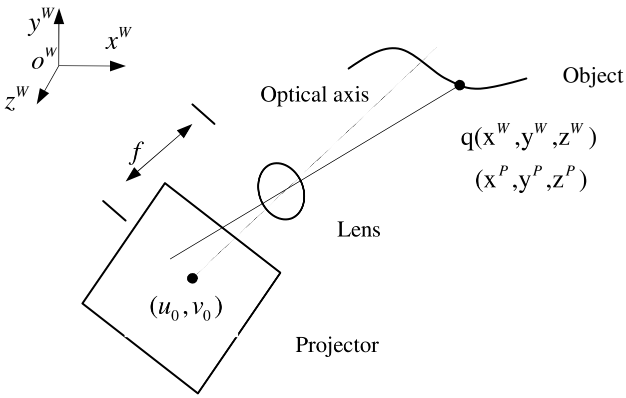


Fig. 1. Projector pinhole model

Replace R with $R = \begin{bmatrix} r_1 & r_2 & r_3 \\ r_4 & r_5 & r_6 \\ r_7 & r_8 & r_9 \end{bmatrix}$, and replace T with $T = \begin{bmatrix} t_1 \\ t_2 \\ t_3 \end{bmatrix}$. Then with Eq. (1) and (2), the projector pinhole model can be expressed as

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = H\begin{bmatrix} x^W \\ y^W \\ z^W \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & 0 & u_0 & 0 \\ 0 & f_y & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}\begin{bmatrix} R & T \\ 0^T & 1 \end{bmatrix}\begin{bmatrix} x^W \\ y^W \\ z^W \\ 1 \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \end{bmatrix}\begin{bmatrix} x^W \\ y^W \\ z^W \\ 1 \end{bmatrix} \quad (3)$$

This equation can be used to describe the ideal projecting model without the distortion of the lens. But, the distortions of the projector need to be taken into consideration for high-accuracy measurements of 3D shape.

2.2 Distortion Model of the Projector

The projector distortion model is established based on the pinhole model. When the lens designed and machined, the nonlinear distortions of the projector exist. And the distortions should be taken into consideration for high-accuracy measurements of 3D shape. Here, mainly considering the radial, tangential and the thin prism distortion, because the measurement accuracy may be less affected by other distortions.

The radial distortion model with the first and second order can be expressed as

$$\begin{cases} \delta_{xr} = x(k_1 r^2 + k_2 r^4) \\ \delta_{yr} = y(k_1 r^2 + k_2 r^4) \end{cases} \tag{4}$$

Where, $r = \sqrt{x^2 + y^2}$, k_1, k_2 are the radial distortion factors.

The tangential distortion model with the first and second order can be expressed as

$$\begin{cases} \delta_{xd} = p_1\left(3x^2 + y^2\right) + 2p_2xy \\ \delta_{yd} = 2p_1xy + p_2\left(x^2 + 3y^2\right) \end{cases} \tag{5}$$

Where, p_1, p_2 are the tangential distortion factors.

The thin prism distortion model with the first and second order can be expressed as

$$\begin{cases} \delta_{xp} = s_1\left(x^2 + y^2\right) \\ \delta_{yp} = s_2\left(x^2 + y^2\right) \end{cases} \tag{6}$$

Where, s_1, s_2 are the thin prism distortion factors.

Considering all the distortion models above, the projector distortion model can be expressed as

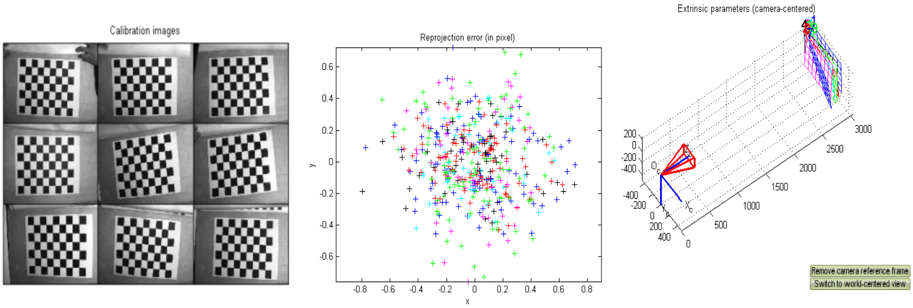
$$\begin{cases} \delta_x(x, y) = k_1x\left(x^2 + y^2\right) + k_2x\left(x^2 + y^2\right)^2 + p_1\left(3x^2 + y^2\right) + 2p_2xy + s_1\left(x^2 + y^2\right) \\ \delta_y(x, y) = k_1y\left(x^2 + y^2\right) + k_2y\left(x^2 + y^2\right)^2 + 2p_1xy + p_2\left(x^2 + 3y^2\right) + s_2\left(x^2 + y^2\right) \end{cases} \tag{7}$$

So, Eq. (7) is the projector distortion model. And the distortion model should be considered for the projector calibration, so that the measurement accuracy can be improved.

3 Experiments

3.1 Camera Calibration

The camera is calibrated using Zhang's method [4]. Paste the planar B/W checkerboard on the white board plane, and change the position of the white board plane, so that the images of the pasted checkerboard can be captured by CCD from different orientations. Then the camera can be calibrated using Camera Calibration Toolbox for Matlab. Fig. 2 show the process of the camera calibration. Table 1 is the camera calibration result.



(a) (b) (c)

Fig. 2. Camera calibration: (a) images of the pasted checkerboard; (b) reprojection error in pixel; (c) 3D schematic diagram of the extrinsic parameters

Table 1. Camera calibration result

Intrinsic parameters	Focal length ($fc = [f_x, f_y]$)	Principal point ($cc = [u_0, v_0]$)	Distortion ($kc = [k_1, k_2, p_1, p_2, s_1, s_2]$)	Pixel error ($err = [x, y]$)
	[2481.16824, 2484.11014]	[674.08180, 387.37752]	[-0.17914,-4.72010, -0.00316,-0.00320,0,0]	[0.26468, 0.24437]
Extrinsic parameters	Translation vector ($Tc = [T_1; T_2; T_3]$)	Rotation vector ($omc = [o_1; o_2; o_3]$)	Rotation matrix ($Rc = \begin{bmatrix} R_1 & R_2 & R_3 \\ R_4 & R_5 & R_6 \\ R_7 & R_8 & R_9 \end{bmatrix}$)	Pixel error ($err = [x, y]$)
	[-134.24865; -50.40282; 904.33855]	[-2.14704; -2.22992; -0.02394]	[-0.03737,0.99905,-0.02238; 0.99834,0.03830,0.04301; 0.04382,-0.02074,-0.99882]	[0.26547, 0.21332]

3.2 Projector Calibration

Homography matrix between the projector image coordinate and the 3D world coordinate is the key factor for projector calibration. With the camera calibration results and the images of the projected B/W checkerboard which captured by the calibrated camera, the 3D world coordinates of the projected checkerboard can be got. Then the homography between the 2D pixel coordinates of the projected checkerboard in the projector image plane and its 3D world coordinates can be got using iteration algorithm, and finally the projector calibration can be completed. The experiment process can be divided into the following steps:

(1) Paste the checkerboard on the white board plane, fix the positions of the camera and the projector to meet the triangulation method. Then capture the image of it by CCD camera.
(2) Cover the checkerboard with a thin white paper, project the B/W checkerboard grid on the paper, and then capture it by CCD camera.
(3) Change the position of the board, and repeat (1) and (2). So that CCD camera can capture the images of both pasted and projected checkerboard orderly at 9 different orientations.
(4) Complete the camera calibration and projector calibration using the images of the pasted and projected checkerboard, respectively.

Fig. 3 show the projector calibration process. Table 2 is the projector calibration result.

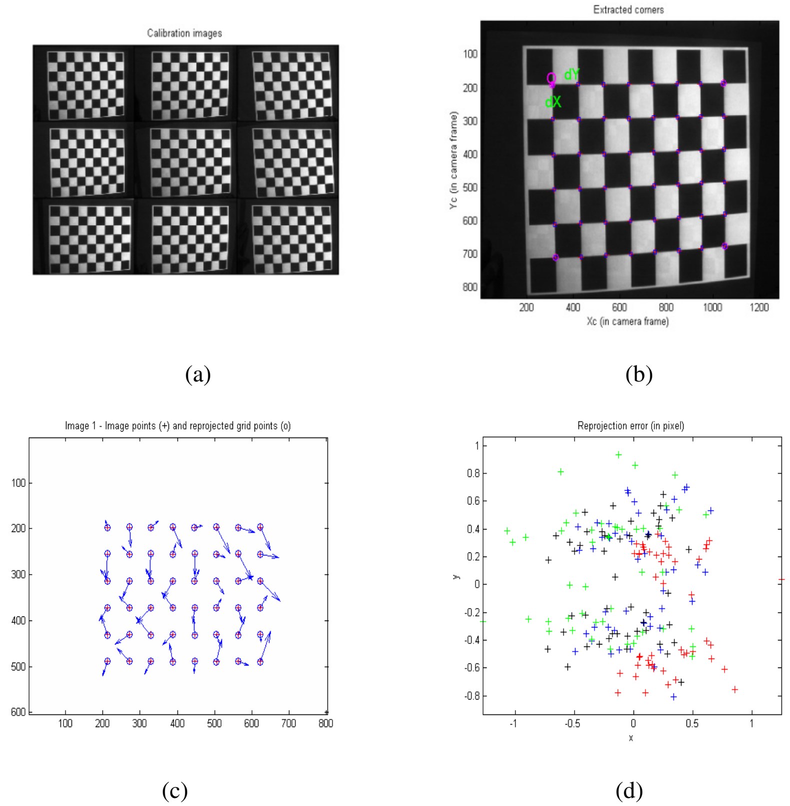


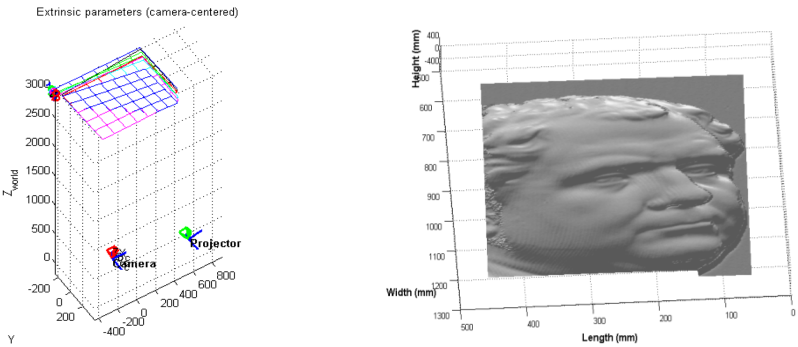
Fig. 3. Projector calibration: (a) images of the projected checkerboard; (b) extracted corners; (c) reprojection of the first image; (d) reprojection error in pixel

Table 2. Projector calibration result

Intrinsic parameters	Focal length ($fc=[f_x,f_y]$)	Principal point ($cc=[u_0,v_0]$)	Distortion ($kc=[k_1,k_2,p_1,p_2,s_1,s_2]$)	Pixel error ($err=[x,y]$)
	[1648.23236, 1671.79350]	[394.14848, 432.54224]	[0.57980,-2.19221, 0.08297,-0.00406,0,0]	[0.39041, 0.42263]
Extrinsic parameters	Translation vector ($Tc=[T_1;T_2;T_3]$)	Rotation vector ($omc=[o_1;o_2;o_3]$)	Rotation matrix ($Rc=\begin{bmatrix} R_1 & R_2 & R_3 \\ R_4 & R_5 & R_6 \\ R_7 & R_8 & R_9 \end{bmatrix}$)	Pixel error ($err=[x,y]$)
	[-717.34750 ; -112.63249 ; 557.27455]	[0.05536 ; 0.25931 ; 0.03274]	[0.96605,-0.02522,0.25713; 0.03949,0.99794,-0.05048; -0.25533,0.05892,0.96506]	[0.39041, 0.42263]

3.3 3D Reconstruction

After the calibration of the camera and the projector, the structured light measurement system can be calibrated. With the help of stereo vision measurement model, the relationship in 3D world coordinate system between the camera and projector can be expressed in Fig. 4 (a). Fig. 4 (b) shows the 3D reconstruction result of a plaster statue (length, width and height are about 45cm*30cm*65cm).



(a) (b)

Fig. 4. (a) 3D schematic diagram of the structured light system; (b) 3D reconstruction

Experiments show that both the camera and the projector calibration error are within ±1 pixel. And the RMS error of 3D reconstruction is 0.25mm. The proposed method can do well for the projector calibration. Also, the accuracy of it can be guaranteed.

4 Conclusions

This paper proposed a flexible projector calibration in the structured light 3D measurement system based on planar homography. The method has the following merits:

(1) Instead of using the phase-unwrapping method to map the pixels between the camera and the projector, the projected B/W checkerboard grid is used to establish the homography between the projector coordinate and the 3D world coordinate; (2) This method dose not require any spatial color illuminations, but requires a pre-calibrated camera; (3) The non-wide-angle camera can be used to capture the images of both pasted and projected checkerboard; (4) This method is not vulnerable to the environment, it is easy to realize high accuracy in the laboratory environment.

Acknowledgments. This project was supported by the National Natural Science Foundation of China (Grant Nos. 51365045, 61462063) and the Aviation Science Fund (Grant Nos. 2013ZE56013, 20135756010).

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