Calibration of components in an optical measurement system for obtaining 3D data of complex parts

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Abstract. In this paper, we study calibration of all components in optical measurement system, which is a fundamental issue in optical measurement. For physical components we use Zhang's method to calibrate the binocular cameras. And we utilize Zhang's method in fringe projection profilometry to calibrate the projector, in which detailed calibration steps are given. For virtual components, three vital coordinate systems need to calibrate in our measurement system. We use cloud registration and epipolar rectification algorithm to locate their position and orientation. The results show that accuracy of physical components' calibration parameters is enough and calibration algorithm for virtual components is feasible.

1. Introduction

With the development of the manufacturing industry, three-dimensional (3D) profile measurement of complex parts has received considerable attention. Reconstruction the 3D data of complex parts using optical measurement system is a significant challenge in 3D measurement because inter-reflections and strong reflections often occur in measurement process. Fringe projection profilometry (FPP) is one of the most widely used techniques in practical 3D shape measurements, because of it's high-accuracy and speed, especially it's dense reconstruction cloud which can reflect the surface profile.[1]

Using FPP to obtain 3D data of complex parts easily leads to phase calculation error because of inter-reflections and strong reflections. For strong reflections, the intensity of some pixels on images captured by cameras is easily saturated. Many methods have been proposed to address this issue. [2, 3] For inter-reflections, surfaces adjacent to each other are likely from mixed fringe. Using polarization to separate mixed fringe is one approach to measure 3D cloud of this type complex parts. [4]

Calibration is a fundamental issue on optical measurement system. In our paper, for measuring 3D surface profile of complex parts, there are two groups component to be calibrated. One group is physical components including intrinsic and extrinsic parameter of cameras and projector. Another group is virtual components including posture of pre-input model cloud in system and transformation of measured cloud after rectification of stereo pairs in cloud reconstruction procedure. [5] Paper in the following we state the principle of calibration method first and then show the experiment results, draw a conclusion finally.

2. Principle

2.1 Calibration of physical components principle

Our optical measurement system consists of binocular cameras and a projector. The projector projects sinusoidal fringe pattern on parts and then FPP is used for reconstruction 3D cloud. Therefore, determining the camera and projector's intrinsic parameters and their extrinsic parameters before measurement is needed.

Binocular cameras are calibrated by Zhang's method. [6] In our system, a planar pattern with circular points at several different orientations is showed to the camera. Pixel coordinates extracting from the center of circular point are data sources for calibration. Camera's intrinsic parameters include two focal lengths, two optical centers and four lens distortion parameters. We set left camera as the origin of world coordinate system, thus the extrinsic parameters of binocular cameras mean that right camera's position and orientation reference to left camera. Once intrinsic parameters are known, the extrinsic parameters for each image are readily computed.

By treating the projector as a camera, we can calibrate it's intrinsic parameters (focal length, optical center and lens distortion) and extrinsic parameters (position and orientation reference to left camera) using Zhang's method. [8] The remaining issue is the calibration data sources. For FPP method which we use in our measurement system, it is easy to establish mapping relationship between image point of camera and image point of projector using phase value.

Assuming that a point on left camera is $m_L(\mathrm{x}_1, \mathrm{y}_1)^{\mathrm{T}}$, mapping it to the image coordinate system of the projector is given by:

$$\begin{cases} x_p = \varphi \times \lambda / 2\pi \\ y_p = \phi \times \lambda / 2\pi \end{cases} \tag{1}$$

Where φ and ϕ are vertical and horizontal absolute unwrapped phase values. λ is the pitch of the projected sinusoidal fringe patterns.

So we can obtain point $m_L(\mathrm{x}_1, \mathrm{y}_1)^{\mathrm{T}}$ mapping to image point of projector as $m_P(\mathrm{x}_p, \mathrm{y}_p)^{\mathrm{T}}$. Fig1 is the flow chart of projector's calibration, detailed steps as follows:

1) Placing the planar pattern on the range of measurement system's working distance;
2) Projecting vertical and horizontal sinusoidal fringe on planar pattern, the left and right cameras capture synchronously;
3) Extracting pixel coordinates of the circular point center;
4) Using four-step phase shifting and three-frequency phase unwrapping algorithm to calculate vertical and horizontal phase value;
5) For points of the circular point center, calculating their mapping point on image

of projector using formula 1;
6) Changing to a new position of pattern ,then repeat above steps 2-5;
7) Gathering calibration data and using Zhang's method to calibrate intrinsic and extrinsic parameters.

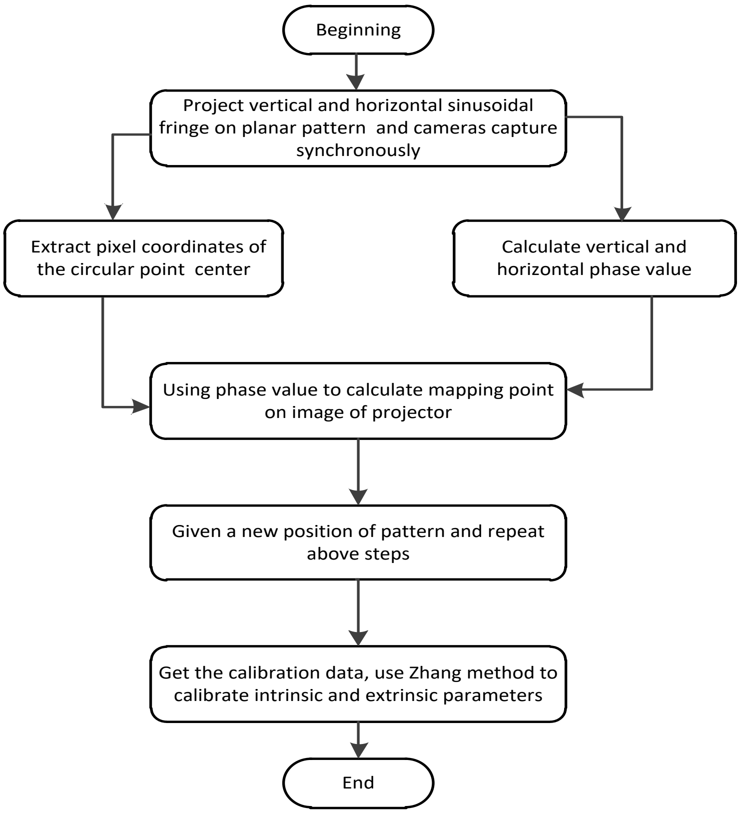


Fig. 1 Flow chart of projector's calibration

2.2 Calibration of virtual components principle

To obtain 3D cloud data of complex parts, optical measurement system often pre-inputs model cloud to hackle with the issue of inter-reflections. [7] This cloud model ought to transform to coordinate system of parts placed. And in FPP, rectification of stereo pairs is applied to accelerate phase matching speed. Therefore, 3D cloud reconstructed locates epipolar standard geometry and also transforming it to coordinate system of parts placement is necessary. These three coordinate systems are virtual components needed to calibrate in our measurement system.

Fig2 illustrates transformation of these three coordinate systems. $O_m - X_m Y_m Z_m$ is coordinate system of parts placed, which sets optical center of left camera as origin of world coordinate system. $O_s - X_s Y_s Z_s$ is coordinate system after rectification of stereo pairs. $O_c - X_c Y_c Z_c$ is coordinate system where cloud model locates in. Transforming cloud model from $O_c - X_c Y_c Z_c$ to $O_m - X_m Y_m Z_m$ includes two steps.

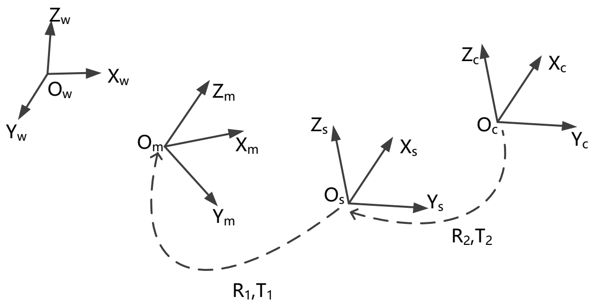


Fig. 2 Transformation of three coordinate systems

Firstly, cloud model coordinate system translates to epipolar rectification coordinate system, which can be finished by cloud registration. In our method, cloud registration is a coarse registration first and then fine registration scheme. After registration of cloud model and the first measured cloud, we get transformation matrix $[R_2, T_2]$ between them.

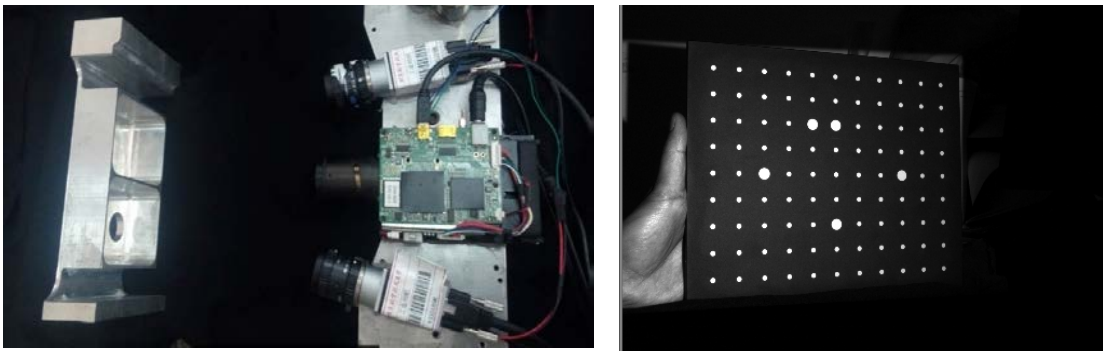
Secondly, epipolar rectification coordinate system translates to world coordinate system. Assuming transformation matrix between them is $[R_1, T_1]$, which is finished by rectification of stereo pairs algorithm. Thus transforming cloud model from $O_c - X_cY_cZ_c$ to $O_m - X_mY_mZ_m$ is:

$$H = \begin{pmatrix} R_2 & T_2 \\ 0^T & 1 \end{pmatrix} \times \begin{pmatrix} R_1 & T_1 \\ 0^T & 1 \end{pmatrix} \tag{2}$$

3. Experiments and results

3.1 Experimental setup

The Experimental system is showing in Fig3 (a). It includes two Basler cameras and a DLP projector. Fig3 (b) is the planar pattern used for calibration. The first experiment calibrates intrinsic parameters of cameras and projector and gives the position and orientation of these three components. This system measures 3D cloud data of a complex parts, showing in Fig3 (a). The second experiment is about registering model cloud and initial measured cloud.



(a) (b)

Fig. 3 Experimental system setup

3.2 Experimental results

The lenses of two cameras we used with focal length fixed at 8mm and the the pixel size of the cameras is 4.5 mm×4.5 mm. The focal length of our projector's lens is adjustable, thus we don't know it's nominal value. Table 1 shows the calibration results of our system's intrinsic parameters.

Table1 the intrinsic parameters of left camera and right camera

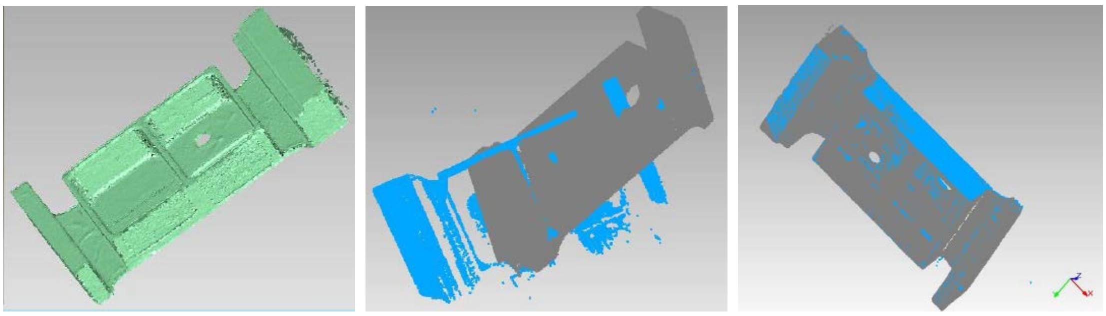
Component	(a_x, a_y)(pixel)	(u_0, v_0)(pixel)	k_1	k_2	k_3	k_4
Left Camera	(1859.12, 1858.99)	(741.60, 579.87)	-0.09	0.18	0.0008	0
Right Camera	(1868.96, 1868.91)	(756.67,574.49)	-0.09	0.197	0.0003	0
Projector	(1756.78, 1755.80)	(597.70, 371.86)	-0.061	-0.009	0.0012	0

The distance between two cameras is about 140mm, distance between left camera and the projector is about 70mm. Table 2 shows the calibration results of our system's extrinsic parameters.

Table2 the extrinsic parameters of right camera and projector

Component	Rotation Vector	Translation Vector (mm)
Right Camera	(0.014, 0.424, 0.022)	(-138.43, -3.25, 30.81)
Projector	(-0.012, 0.238, 0.006)	(-67.92, 6.66, -2.57)

Fig4 shows the calibration results of three coordinate systems introduced above. Fig4 (a) is the cloud model map. At beginning, cloud model and initial cloud is not in the same place, which is showing in Fig4 (b). After two steps transformation of coordinate system, the two pieces of cloud aligns. The result is showed in Fig4 (c).



(a) (b) (c)

Fig. 4 Registration of cloud model and initial cloud

4. Summary

This paper presents the full components calibration in optical measurement system for obtaining complex parts' 3D cloud data. We use Zhang's method to calibrate intrinsic and extrinsic parameters of cameras. By treating the projector as a camera with taking advantage of mapping relationship between image point of camera and image point of projector in FPP method, we calibrate parameters of projector successfully and give the detailed calibration steps. The results show that accuracy of calibration parameters is enough.

Also in this paper, we use cloud registration algorithm to determine position and orientation of three vital coordinate systems in the optical measurement system. The results show that these coordinate systems are located correctly.

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