# A Practical Means for the Calibration of a Binocular Structured Light System

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*Abstract* – **This paper presents a practical means for the calibration of a binocular structured light system (SLS). Considering the characteristics of binocular SLS, 3D coordinates of space points are indicated by the average values of two cameras and then used to calibrate the projector. According to the idea of bundle adjustment, an error function is constructed to minimize the whole calibration errors. And a non-linear least squares function is applied to find the minimum to the sum of squares of the function. The experimental results show that, with the optimized calibration results, less calibration errors and better alignment of 3D scanning data can be obtained.**

***Index Terms* – *Binocular structured light, projector calibration, 3D alignment.***

## I. INTRODUCTION

Structured Light System (SLS) is an important 3D scanning technology. It has been widely applied in industrial measurement, inspection and medicals etc. [1-2]. Current SLSs usually adopt two cameras and one projector. The two cameras are calibrated to form a stereo vision setup [3-4]. And the projector illuminates some coding lights to the target surface so as to solve the corresponding problem. However, due to the underlying principle of SLS, it is practical to use only one projector and camera. By calibrating the single camera and projector respectively, a traditional SLS can be decomposed into two independent SLSs. And thus more 3D information from two various viewpoints can be obtained [5-7]. Such a SLS configuration can be name as the binocular SLS. And the major concern involved is how to utilize the two groups of calibration information so as to realize the automatic 3D registration of two groups of 3D point clouds.

In the binocular structured light system, each camera and the projector can be treated as a SLS which can be calibrated individually. Since the two SLSs are shared same projector, the two groups of scanning data can be registered directly with respect to the projector reference frame theoretically. However, subject to the calibration errors, the direct registration based on calibration data are usually not practically. In [8], it utilized one camera's calibration parameters to calibrate the projector. And then, an improved iterative closest points (ICP) algorithm was used to register the two scanning data. In [9], the direct linear transformation algorithm is introduced to establish the mapping relationship between two cameras. Generally, extrinsic parameters between two individual SLSs in the binocular SLS are subject to the calibration errors of both camera and projector as well as the systematic errors in the measurement system.

In order to overcome the above problem, this paper presents a new calibration method of a binocular SLS. In the algorithm, three-dimensional coordinates of space points indicated by average value are used to calibrate the projector. And then, according to the idea of bundle adjustment, a global optimization is introduced to optimize the system parameters. Finally, the extrinsic calibration parameters are used for the alignment of two individual SLS. The rest of the paper is organized as follows. Section II introduces the proposed camera, projector, and system calibration method. Experimental results with accuracy evaluation are provided in Section III. Conclusion is offered in Section IV.

## II. THE OPTIMIZED CALIBRATION OF A BINOCULAR STRUCTURED LIGHT SYSTEM

### A. *Camera Calibration*

The diagram of a binocular structured light system is as shown by Fig. 1. Calibrations of the two cameras based on Zhang's method [10]. The relationships between the object point $Q_W$ ($X_W$, $Y_W$, $Z_W$) in the world coordinate and its corresponding image points ($u_{cu}$, $v_{cu}$) and ($u_{cd}$, $v_{cd}$) in the image coordinates of up and down cameras can be formulated as:

$$K_{cu/cd}[R_{cu/cd} \quad T_{cu/cd}]\begin{bmatrix} X_W \\ Y_W \\ Z_W \\ 1 \end{bmatrix} = \rho_{cu/cd}\begin{bmatrix} u_{cu/cd} \\ v_{cu/cd} \\ 1 \end{bmatrix} \tag{1}$$

where $\rho_{cu}$ and $\rho_{cd}$ are the scale factor of up and down cameras, $K_{cu}$ and $K_{cd}$ are the intrinsic parameter matrix respectively. $R_{cu}$, $R_{cd}$, $T_{cu}$, and $T_{cd}$ are the rotation and translation matrices between the world coordinate system and the up and down

This work was supported in part by the National Natural Science Foundation of China (NSFC, grant no. 61002040, 61375041), the Introduced Innovative R&D Team of Guangdong Province-Robot and Intelligent Information Technology R&D Team(grant no. 201001D0104648280), and the Shenzhen Key Lab for Computer Vision and Pattern Recognition (grant no. CXB201104220032A).

**978-1-4799-4808-6 /14/$31.00 ©2014 IEEE**

camera coordinate systems respectively. Via an external checker board like pattern, two cameras can be calibrated via Zhang's calibration method individually.

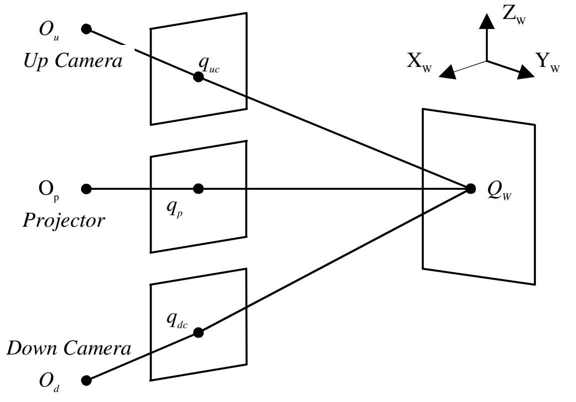


Fig. 1. Diagram of a binocular SLS and the two cameras can be calibrated via Zhang's method individually.

### *B. Projector Calibration*

The optical model of a projector can be regarded as the inverse process of a camera. So the projector can be modeled mathematically as a camera [11]. The relationship between the world coordinate and the related image coordinate of the projector can be described as:

$$K_p[R_p \quad T_p]\begin{bmatrix} X_W \\ Y_W \\ Z_W \\ 1 \end{bmatrix} = \rho_p \begin{bmatrix} u_p \\ v_p \\ 1 \end{bmatrix} \tag{2}$$

where $\rho_p$ is a scale factor and $K_p$ is the projector intrinsic parameter, $R_p$ and $T_p$ are the projector extrinsic parameter matrices which are the rotation and translation matrices between the world coordinate system and the projector coordinate system respectively.

Similar to the calibration of cameras, a checker boarder like pattern is generated by the computer and is projected onto the calibration board of camera. The world coordinates of these checker board corners can be determined with the calibrated camera. As described in [12], with $Z_W = 0$, we have:

$$\rho_p = \frac{R_c(:,3)\cdot T_c}{R_c(:,3)\cdot U_{cp}} \tag{3}$$

where, $U_{cp} = (u_{cp}, v_{cp}, 1)^T$ is the coordinates in the image domain, $R_c$ and $T_c$ are the rotation and translation matrices between the world coordinate system and the camera coordinate system. Thus, we have

$$\begin{bmatrix} X_W \\ Y_W \\ 0 \end{bmatrix} = \rho_p R_c^T\left(U_{cp} - T_c\right) \tag{4}$$

With above equations, intrinsic and extrinsic parameters of the projector can be calibrated.

In the calibration procedure, the checker board pattern is projected onto the camera calibration board. So the world coordinates of the projected chessboard corners should be the same with respect to the two cameras coordinates. Theoretically, it should be identical to use either the up camera's calibration parameters or the down camera's calibration parameters to calculate the world coordinates. But in fact, the calibration results are usually not stable subject to the cameras calibration and systematic errors. Consequently, the projector calibration parameters are usually different. To improve the robustness of the projector calibration result, the average values of two sets of the projected checker board corners are used as:

$$\begin{bmatrix} X_W \\ Y_W \\ 0 \end{bmatrix} = \frac{1}{2}\left(\begin{bmatrix} X_{uW} \\ Y_{uW} \\ 0 \end{bmatrix} + \begin{bmatrix} X_{dW} \\ Y_{dW} \\ 0 \end{bmatrix}\right) \tag{5}$$

where $[X_{uW}, Y_{uW}, 0]$ are the results using the up camera parameters, and $[X_{dW}, Y_{dW}, 0]$ are the results using the down camera parameters respectively.

### *C. System Calibration and Global Optimization*

Based on the camera calibration toolbox of Matlab, we can calculate the rotation and translation matrices $R_c$ and $T_c$ between the world coordinate system and the camera coordinate system and the rotation, and translation matrices $R_p$ and $T_p$ between the world coordinate system and the projector coordinate system. So we can calculate the rotation and translation matrices $R$ and $T$ between the camera coordinate system and the projector coordinate system by:

$$R = R_c \times R_p^{-1}, T = T_c - R \times T_p \tag{6}$$

For the up camera and the projector as an example, we can obtain a group of extrinsic camera parameters $r_{cui}$ and $t_{cui}$ and a group of extrinsic projector parameters $r_{pui}$ and $t_{pui}$ at each calibration position. Thus, the rotation and translation parameters $r_{ui}$ and $t_{ui}$ between the up camera coordinate system and the projector coordinate system can be expressed as:

$$r_{ui} = r_{cui} \times r_{pui}, t_{ui} = t_{cui} - r_{ui} \times t_{pui} \tag{7}$$

Consider the calibration errors and statistical noise, if there are $n$ calibration images, the rotation and translation matrices $R_u$ and $T_u$ of the up-camera-projector system can be computed as:

$$R_u = \frac{\Sigma r_{ui}}{n}, T_u = \frac{\Sigma t_{ui}}{n} \tag{8}$$

Similarly, the rotation and translation matrices $R_d$ and $T_d$ of the down-camera-projector system can be computed as:

$$R_d = \frac{\Sigma r_{di}}{n}, T_d = \frac{\Sigma t_{di}}{n} \quad (9)$$

In above, the binocular SLS is calibrated as two individual SLS. But with the experiments, the two sets of 3D point cloud data cannot match well. So the calibration parameters need optimizations. In the view of bundle adjustment, we can consider the binocular SLS as a single system. And a global optimization is applied to improve the non-linear least squares function to achieve accurate intrinsic and extrinsic parameters of the two cameras and the projector.

Based on Zhang's calibration method, with $Z_W = 0$, world coordinates of the checker board corners can be expressed with respect to the projector reference frame as:

$$\begin{bmatrix} X_W \\ Y_W \\ 0 \end{bmatrix} = \rho_p R_p^T \left(U_p - T_p\right) \quad (10)$$

where $U_p = (u_p, v_p, 1)$ are the image coordinates of the projected patterns, and we set $X = (X_W, Y_W, Z_W)$. From Eqn. (1-3), we can get following equation:

$$\begin{bmatrix} H_{u00} & H_{u01} & H_{u02} & -u_{cu} & 0 & 0 \\ H_{u10} & H_{u11} & H_{u12} & -v_{cu} & 0 & 0 \\ H_{u20} & H_{u22} & H_{u23} & -1 & 0 & 0 \\ H_{d00} & H_{d01} & H_{d02} & 0 & -u_{cd} & 0 \\ H_{d10} & H_{d12} & H_{d13} & 0 & -v_{cd} & 0 \\ H_{d20} & H_{d21} & H_{d22} & 0 & -1 & 0 \\ H_{p00} & H_{p01} & H_{p02} & 0 & 0 & -u_p \\ H_{p10} & H_{p11} & H_{p12} & 0 & 0 & -v_p \\ H_{p20} & H_{p21} & H_{p22} & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} X_W \\ Y_W \\ Z_W \\ \rho_{cu} \\ \rho_{cd} \\ \rho_p \end{bmatrix} = \begin{bmatrix} -H_{u03} \\ -H_{u13} \\ -H_{u23} \\ -H_{d03} \\ -H_{d13} \\ -H_{d23} \\ -H_{p03} \\ -H_{p13} \\ -H_{p23} \end{bmatrix} \quad (11)$$

Since $K_{cu}$, $R_{cu}$, $T_{cu}$, $K_{cd}$, $R_{cd}$, $T_{cd}$, $K_p$, $R_{up}$, $T_{up}$, $R_{dp}$ and $T_{dp}$ are known, $H_u$, $H_d$ and $H_p$ can be calculate. Assume an error function as $E_r = X - X'$, Eqn. (10) can be solved for $\boldsymbol{X'} = [\boldsymbol{X}_W\ \boldsymbol{Y}_W\ \boldsymbol{Z}_W]^{\mathrm{T}}$. With the initial calibration results, a non-linear least squares function can be applied to find the minimum of the function $E_r$. Then we acquire the intrinsic and extrinsic parameters of the two cameras and the projector, as well as the system rotation and translation matrix $R_u$, $T_u$ and $R_d$, $T_d$.

## III. EXPERIMENTAL RESULTS

The experimental setup is as shown by Fig. 2, which consists of two IEEE 1394 cameras with the resolution of 1280×960 pixels, and one DLP projector with the resolution of 1024×768 pixels. The focal length of the both cameras is 10 mm. The object is placed at a distance of about 1560 mm away from the cameras. A black-and-white chessboard with grids of 8×9 is used for the calibrations. During calibration, the chessboard is placed at 25 different positions in front of the cameras. The calibration algorithm is as described in [13]. For the 3D scanning process, a temporal approach as reported in [14] is implemented.

Fig. 2. The experimental binocular SLS which is consists of two cameras and one projector.

Performance of the proposed calibration method is evaluated by the terms of camera calibration errors and system measurement errors. Camera calibration errors are represented by the re-projection error, of which are to sum the squared differences between the re-projected coordinates and the real coordinates on checker board patterns as:

$$error = \frac{1}{n} \sum_{i=1}^{n} \left(x_i' - x_i\right)^2 + \left(y_i' - y_i\right)^2 + \left(z_i' - z_i\right)^2 \quad (12)$$

where $(x', y', z')$ is the measured results with calibration parameters, $(x, y, z)$ is the real coordinates, and $n$ is the total number of corners taken by two cameras. System measurement errors are expressed by the sum of the squared differences between reconstructed 3D coordinates by the up and down cameras and the projector respectively. The statistical results are as shown in Table I. Error distribution curves of each corner point are also plot by Fig. 3. Fig. 3 (a) shows the number of corners with respect to different camera calibration errors. Fig. 3 (b) shows the number of corners with respect to different system measurement errors.

From the results, we can see that, the camera calibration error is reduced by two orders of magnitude, and the system measurement precision is raised by one order of magnitude. It shows the calibration accuracy can be greatly improved. With the calibration results as registration matrix, some objects are scanned and aligned directly as shown by Fig. 4. Fig. 4 (a), (c), (e) show the 3D registration results via conventional calibration method, and Fig. 4 (b), (d), (f) show the 3D registration results by the proposed method. We can see that, although the two groups of the scanning data cannot be perfectly aligned with the proposed method. But the alignment errors can be greatly reduced. And that can provide a better initial estimation for the incoming precise registration algorithms like ICP.

Table I
COMPARISON OF CALIBRATION ERRORS

| Error | Conventional method | Improved method |
|---|---|---|
| Camera (pixel) | 632.448575 | 3.295546 |

| | | |
|---|---|---|
| Measurement (pixel) | 51.952092 | 7.253256 |

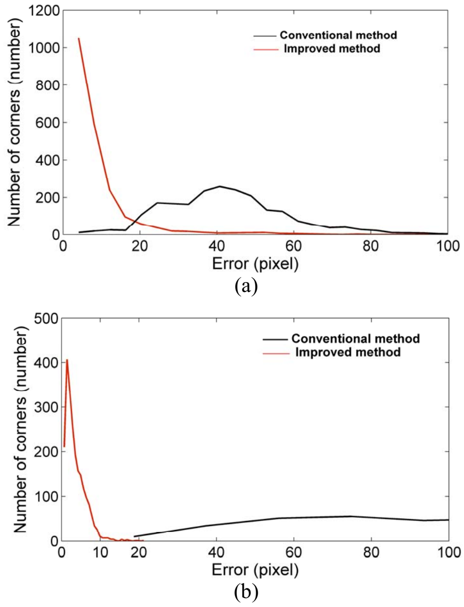


Fig. 3. (a) Camera calibration errors; (b) System measurement errors.

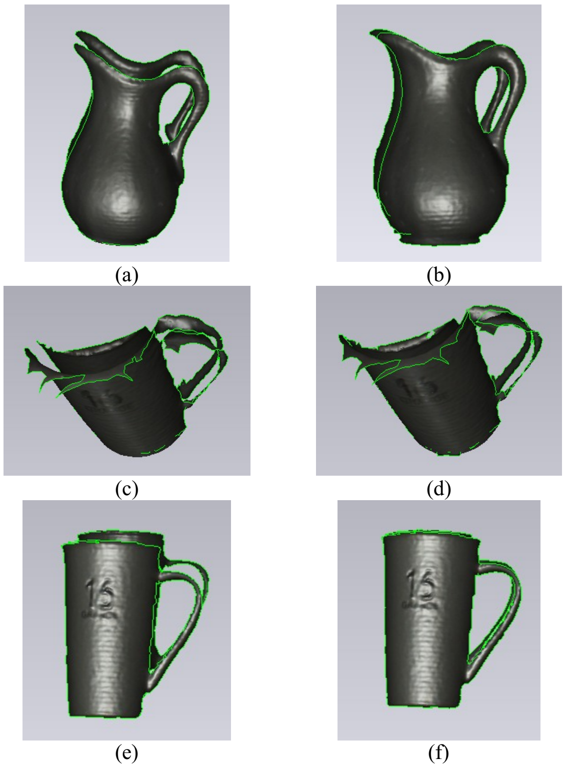


Fig. 4. 3D alignment of the scanning results via the conventional and the proposed calibration methods.

## IV. Conclusion and Future Work

This paper presents an improved calibration method for a binocular SLS. To calibrate the projector, world coordinates with respect to two camera calibration results are averaged to improve its calibration robustness. And then, according to the idea of bundle adjustment, a global optimization is introduced to optimize the system parameters. Finally, the extrinsic calibration parameters are used for the alignment of two individual SLS. In the experiments, the calibration errors are evaluated from the aspects of re-projection and measurement errors. And the primary registration results are also provided and compared with the conventional calibration method to shows its improvements in calibration accuracy. Future work can address how the utilization of a 3D object can be used for the fast estimation of the inter-extrinsic parameters within the binocular SLS so as to further improve its calibration accuracy.

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