Calibration Algorithm for Structured Light 3D Vision Measuring System

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Abstract
A novel procedure is proposed to calibrate a structured light 3D vision measuring system. Firstly, robust subpixel and substripe calibration methods are proposed for the camera and the projector. Secondly, a novel approach is introduced to solve the nature restriction of the structure light system: the calibration of the camera and the projector is restricted with the locations of them. Thirdly, the systemic calibration procedure based on rigidity constraint to system architecture is developed according to the stereo vision, the L-M optimization algorithm is used to adjust the internal and external parameters of each respective component in this system. Finally, this system calibration algorithm is proved to be robustness and effectiveness by reconstructing a 3-D standard cylinder. The experiment results show that the precision of single view is about 0.06mm over a measurement volume of 250mm×200mm×250mm. It roughly meets the need of the industry.

1. Introduction
Since the early 1980s, with the development of some vision theory frameworks including the famous Marr vision theory (also called three-dimensional reconstruction), as well as the model-based vision theory and the active vision theory, the measurement methods based on optical calibration have been a broad and deep development. At present, the non-contact optical measurement method has been widely applied in the industrial testing, rapid prototyping, mold, heritage, etc [1-2]. The key of the reconstruction of the accurate 3-D measurement is the proper calibration of the structured light system (SLS). Many approaches of the calibration structured light system can be found in the literature, such as techniques based on neural networks, genetic algorithm, etc. All of the methods are mostly designed to calibrate two components separately. They do not consider the effect of the system architecture to the accuracy of the system [3].

2. Model of the structured light system
Structured light measurement system is a non-contact optical measurement method based on active triangulation method. A projector projects high robustness time-space coding light model, the object space is divided into numerous measurements region with unique code. The object’s coordinates can be computed using the triangular geometric relation [2]. The Specific schematic is shown in Fig. 1.

In this system, camera model is the same used in photogrammetry, which is a combination of the pinhole model and lens distortions [4 5].

In the mathematical model, a 3-D point \( p_w = (x_w, y_w, z_w) \) is transformed into pixel coordinate \( p_f = (x_s, y_s) \) through the following formulas according to the principle of photogrammetry.

\[
p_f = T(p_w, \Theta_{cc}, \Theta_c)
\]  

Where \( \Theta_c \) and \( \Theta_{cc} \) are the camera’s extrinsic and internal parameters need to calibrate.

The model of the projector is similar to the camera as the projector can conceptually be regarded as a camera with a 1-D image, acting in reverse. Lathuilière [7] has confirmed that the projector model can be used in structured light system as pinhole model using some experimentation. However, there is a little difference from the camera, as the projector project stripes, which are a 1-D, coordinate \( x_s \).

The transformation from 3-D point in the world coordinate \( p_w \) to the image pixel point \( x_s \) can be expressed as:
\[x_i = T(P_w, \Theta_{dmd}, \Theta_p)\]  
(2)

Where \(\Theta_p\) and \(\Theta_{dmd}\) are the projector’s extrinsic and internal parameters need to calibrate.

**Fig.1. Structured light measurement system model**

### 3. Procedure of calibration

The calibration procedure of the whole system includes the following three parts. (1) Camera component is calibrated separately. (2) Projector component is calibrated separately. (3) The entire system is calibrated.

#### 3.1. Calibration of the camera

There are many camera calibration algorithms in literatures, such as famous “two steps”[4-5], “four-step method”[8], implicit method [9], etc. An improved algorithm based on the Tsai’s multi-plane calibration method is proposed in this paper.

First, we acquire the subpixel coordinates of the calibration circle by the moment method [6]. Some points nearing the principle point which are distortion minimum data points are used to estimate the initial value of the system parameters [5]. Then, distortion factors, which are radial and decentering distortions, are introduced. The nonlinear optimization L-M algorithm [10] is used for the overall system because there are a number of local extreme points using the objective optimization function in the Tsai’s methods [11]. Moreover, the penalty function is used and made up Tsai’s method’s defect which is that the rotation vector of the external parameters are not satisfied with the orthogonal characters [12]. Finally, the desired results are achieved. Detailed data are shown in the table 1.

The system accuracy is expressed to use the following method that is called reprojection error. The accuracy of camera calibration is assessed by comparing the difference between the acquired 2D coordinates \(p(x_i, y_i)\) of the test points using the moment method and the coordinates \(p'(x_i, y_i)\) computed. The symbols of “err”, “stddev”, “max”, “sse” in the below table meaning average error, standard deviation, max error and mean-square error of all the test points. All kind of type errors are the average result of 10 times measurement experiments.

<table>
<thead>
<tr>
<th>(f) (mm)</th>
<th>(C_x) pixel</th>
<th>(C_y) pixel</th>
<th>(k_1) 1/mm(^2)</th>
<th>(p_1) 1/mm(^2)</th>
<th>(S_x)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.069</td>
<td>664.315</td>
<td>520.839</td>
<td>5.841×10^{-4}</td>
<td>2.233×10^{-5}</td>
<td>1.008</td>
</tr>
</tbody>
</table>

**Table.1a. camera’s internal parameters**

<table>
<thead>
<tr>
<th>(\sum) error (pixel)</th>
<th>err (pixel)</th>
<th>max (pixel)</th>
<th>stddev (pixel)</th>
<th>sse (pixel(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.23275</td>
<td>0.85039</td>
<td>0.11569</td>
<td>8.77841</td>
<td></td>
</tr>
</tbody>
</table>

#### 3.2. Calibration of the projector

**1) Restrictive conditions of the projector calibration**

In structured light system, the projector is not able to capture the image as the camera, so the projector’s image coordinates are acquired through the stripes images which are captured by the camera. The image point \((u_i, v_i)\) in the camera and the projector are corresponded through the strips code \((u_i, v_i, code_i)\) [2]. It is showed in Fig 2a.

**Fig.2. Code stripe image used for projector calibration. (a. Traditional affected stripes map; b. Stripes image no affected in this article)**

It is clear that the stripes image in the Fig 2a captured by the camera does not have enough contrast in the areas of the white circles. This confusion phenomenon in the image could seriously affect the accuracy of the projector calibration. This paper describes a novel method to solve this problem according to Zhang’s method [13].

When we calibrate the camera, the blue and red calibration plate in Fig 3a is illuminated with red light,
a good contrast gray image are acquired in Fig 3b. Then when we calibrate the projector, the calibration plate is illuminated by white light, and the stripes image no affected is acquired as Fig 2b.

![Fig.3. Calibration image for the camera (a. Calibration plate image; b. Black white image with red light illumination)](image)

(2) Calibration process

As shown in Fig 4, a set of target points (circles points or rectangular boxes) with known coordinates (\(U_{dmd}, V_{dmd}\)) are projected onto the reference plate, in which the plate can be shifted to different preset locations along the object known Z-axis, to form a non-planar measurement space. The camera acquires the target points image coordinates (\(U_{id}, V_{id}\)) in the CCD, which are the image coordinates of the corresponding target points of the object coordinates which is located in \(z_i\) position can be derived form \(\Theta_o\), which is the parameter model established by the above camera calibration model. Two arrays (\(x_i, y_i, z_i\)) and (\(U_{dmd}, V_{dmd}\)) are the input data to calibrate the projector. The projector parameter model \(\Theta_p\) is acquired as the camera calibration. Specific parameters are as follows Table 2. All kind of type errors are the average result of 10 times measurement experiments.

![Fig.4. Calibration model of the projector](image)

Table 2a. Projector’s Internal parameters

<table>
<thead>
<tr>
<th></th>
<th>(f_{(mm)})</th>
<th>(c_x) pixel</th>
<th>(c_y) pixel</th>
<th>(K_1) 1/mm²</th>
<th>(P_1) 1/mm²</th>
<th>(s_x)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.931</td>
<td>478.843</td>
<td>637.036</td>
<td>(3.313 \times 10^{-4})</td>
<td>(6.645 \times 10^{-5})</td>
<td>1.079</td>
<td></td>
</tr>
</tbody>
</table>

![Table 2b. Reprojection error of the projector calibration](image)

<table>
<thead>
<tr>
<th>error (unit)</th>
<th>err pixel</th>
<th>max pixel</th>
<th>stddev pixel</th>
<th>sse pixel²/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sum_i^l)</td>
<td>0.39452</td>
<td>1.11753</td>
<td>0.23906</td>
<td>10.47349</td>
</tr>
</tbody>
</table>

3.3. Calibration of the system

In the system, the camera captures the calibration point’s images in the camera and the projector. As shown in Fig 5. Therefore, it is possible to use a unique device (camera and projector) coordinate system, and to apply only one transformation from the object coordinate system to the device coordinate system to calibrate the system. The complete sequence of transformation for the system is defined as:

\[
p_i = T(p_{(i,j)}) \rightarrow g(p_i, \Theta_{cd})
\]

Where \(\Theta_i\) is the external parameters vector of the camera, \(\Theta_o\) is the vector that characterizes the rigid displacement camera to projector. \(\Theta_{cd}\) is defined as

\[
(u_{dmd}, v_{dmd}) = \Theta_s(u_{id}, v_{id})
\]

![Fig.5. Strict relation of camera and projector](image)

As can be seen in these equations, this displacement acts as a rigidity constraint in a simple way, and this is extensively used a bound in the estimation of parameters for classical stereo system [2]. In this paper, substripe estimation is used to calibrate the projector [14], then, an objective function to be minimized is the mean-square discrepancy between the observed stripes coordinates and their inferred image projections computed with the estimated parameters \(\Theta_s\).

Let \(P_{(i,j)}\) and \(P'_{(i,j)}\) be the corresponding pixel coordinate of \(P_{(i,j)}\) in the camera and the projector respectively, where \(i\) is the position number of the calibration plate. The objective function to be minimized is showed as following.
E(\(\varphi\)) = \sum_i \sum_j \left\{ \left\| p_j(i, j) - T(p_c, \Theta_{ccd}) \right\|^2 + \left\| p_j(i, j) - T(p', \Theta_{dmd}) \right\|^2 \right\}, \quad (4)

Where \(\varphi = [\Theta_{ccd}, \Theta_{dmd}, \Theta_1, \Theta_2, \ldots, \Theta_N]\) is the vector to be minimized using \(N\) positions of the calibration plate and \(M\) number of target marks in the calibration plate. The above problem is solved by the common method of Levenberg-Marquardt optimization algorithm [10] or Gaussian-Newton. System calibration results are as follows Table 3.

Table 3a. Camera’s internal parameters after system calibration

<table>
<thead>
<tr>
<th>(f) (mm)</th>
<th>(C_x) pixel</th>
<th>(C_y) pixel</th>
<th>(k_1) 1/mm^2</th>
<th>(p_1) 1/mm^2</th>
<th>(s_x)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.969</td>
<td>626.353</td>
<td>537.950</td>
<td>3.313 (\times) 10^-4</td>
<td>4.283 (\times) 10^-5</td>
<td>0.996</td>
</tr>
</tbody>
</table>

Table 3b. Camera’s Reprojection error after system calibration

<table>
<thead>
<tr>
<th>Error (unit)</th>
<th>err pixel</th>
<th>max pixel</th>
<th>stddev pixel</th>
<th>sse pixel^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\bar{\Sigma}_{error}) /10</td>
<td>0.1691</td>
<td>0.5886</td>
<td>0.0894</td>
<td>4.8613</td>
</tr>
</tbody>
</table>

Table 3c. Projector’s internal parameters after system calibration

<table>
<thead>
<tr>
<th>(f) (mm)</th>
<th>(C_x) pixel</th>
<th>(k_1) 1/mm^2</th>
<th>(p_1) 1/mm^2</th>
<th>(p_2) 1/mm^2</th>
<th>(s_x)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.4932</td>
<td>487.4358</td>
<td>4.651 (\times) 10^-4</td>
<td>5.445 (\times) 10^-5</td>
<td>4.542 (\times) 10^-5</td>
<td>1.0062</td>
</tr>
</tbody>
</table>

Table 3d. Projector’s Reprojection error after system calibration

<table>
<thead>
<tr>
<th>Error (unit)</th>
<th>err pixel</th>
<th>max pixel</th>
<th>stddev pixel</th>
<th>sse pixel^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\bar{\Sigma}_{error}) /10</td>
<td>0.2243</td>
<td>0.6390</td>
<td>0.1541</td>
<td>5.9830</td>
</tr>
</tbody>
</table>

It is shown that the accuracy is improved largely after system calibration. The errors of the camera and projector drop 27% and 43% respectively. The reason is that system calibrations improve the stripes accuracy largely. Moreover, Zhang [3] and Trobina [15] analyses the error of the structured light system and present an error model of between the geometric structure and the system accuracy.

4. Experimental results and accuracy estimation

According to the above principles, a measuring device is set up. This measure device contains a projector (NEC NP 50+), a microview CMOS camera, JANPAN computer MP-1214 lens, and a high-speed computer. Two machining cylinders are measured and the measurement point clouds are fitted using reverse soft Imageware. The standard radiuses of machining cylinder are 10 \(\pm\) 0.002mm and 30 \(\pm\) 0.002mm, our measurement result are 10.0475 and 30.0601mm, The precision of single view is about 0.06mm over a measurement volume of 250mm \(\times\) 200mm \(\times\) 250mm.

Fig.6. Standard cylinder used to test the accuracy of the calibration and the fitting point cloud data use Imageware. (a. Standard cylinder image; b. The fitting point cloud data of 30mm radius cylinder; c. The fitting point cloud data of 10 mm radius cylinder)

5. Conclusion and future work

This paper proposes a structured light overall system calibration method. The camera calibration algorithm is a improved method based on Tsai’s multiplane method, it eliminate the local convergence of the method, and overcome the external parameters of rotation matrix no orthogonal. A substripe calibration method is proposed to the projector and a good result is achieved. Take into account the system architecture affection to the system accuracy, system calibration is described. Experiment results show the system’s robust and accuracy.

References


