DIRECT SENSOR-ORIENTED CALIBRATION OF THE PROJECTOR IN CODED STRUCTURED LIGHT SYSTEM

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ABSTRACT:

Today, close range photogrammetry is known as an accurate and automatic 3D geometric measurement method especially for 3D point features (targets), but unfortunately it needs human supervision for 3D surface measurement due to nature of image matching problem. Therefore, in the last decade, coded structured light technique surpasses as one of the main complementary automatic and precise 3D surface measurement methods in different industrial and medical applications. Regardless of hardware considerations, the accuracy of structured light method highly depends on system calibration issue. Calibration of the projector, which is one of the major components of the structured light system, is a very difficult, time-consuming and expensive process. In this paper, the close range photogrammetry method is utilized for direct calibration of a projector. The experiments demonstrate the proposed method not only is a low-cost and high-speed process but also is capable to calibrate the projector with precision as 20 times of projector resolution. With this level of potential, we could achieve the relative accuracy of 1:13000 for 3D surface measurement.
Keywords: Close range photogrammetry, structured light, projector calibration, geometric distortion.

1 INTRODUCTION

Nowadays, 3D surface measurement is one of the important subjects in computer vision due to variety of its applications in industry (such as quality control and reverse engineering), cultural heritage (such as 3D documentations and visualizations) and medicine (such as body growing). Therefore, many investigations in surface reconstruction and 3D information extraction have been accomplished under topic of "shape from X" that X is stereo images, structured light, texture, focus, shading, reflection and silhouette (Salvi and et al, 2004).

Close range photogrammetry is one of the conventional methods for indirect 3D surface measurement but it is not generally an efficient method due to both reasons: (a) the fully automatic image matching has not been completely solved yet so it requires human supervision [Paar and et al, 2001] (b) it is unavoidable to put targets on the object surface especially in high precision applications. To prevent from these problems, it is possible to utilize the complementary methods such as structured light method that is proper for measurement of a small and simple surface. To measure a large and/or complex surface, one of the best solutions could be fusion of close range photogrammetry and structured light methods.

The coded structured light method measures a 3D surface based on imaging of multiple regular optical pattern projected on the surface (Salvi and et al, 2004) (Figure 1). The patterns encode and segment the surface to several small sub-regions as automatic correspondence problem for image matching is solved completely [Rocchini, 2001]. It is noted that the projector is actually an inverse camera that project a pattern into a surface instead of imaging it from the surface. Therefore, an image of a camera and a pattern of a projector are pseudo stereo images that need interior and exterior sensor orientation or calibration before image ray corresponding and intersection for 3D measurement. Since the calibration of camera and projector has critical effects on 3D surface measurement accuracy; and camera calibration is more known for users, this paper only studies the projector calibration issue.

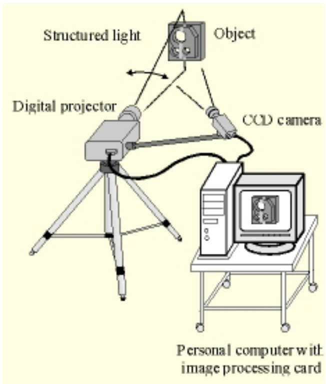

Figure 1. the system configuration of the structured light used in the study (picture from [Tzung-Sz and et al, 2000])

There are two methods for projector calibration including surface-related and sensor-related calibration methods. In the surface-related projector calibration, a known surface such as a flat plane is posed in different known distances and/or orientations from projector. Then, the projector is calibrated based on projected pattern changes on the surface [Rocchini and et al, 2001; Tzung-Sz and et al, 2000; Sinlapeecheewa and et al, 2002]. This is entirely a laboratory method and requires a known surface and precise equipments of distance and orientation measurements while its computations are low cost.

The sensor-oriented projector calibration method could be implemented with both indirect and direct techniques. In indirect implementation technique, a test field including a regular 3D grid of points with known coordinates is used for indirect 3D coordinates measurement of projected patterns first. Then they are projected up into image space and compared with 2D coordinates of corresponding pattern's points to detect the geometric distortion of the projector [Alan and et al, 1995; Salvimas, 2001; Guhring and et al, 2000]. Building of the test field is expensive and indirect measuring of 3D coordinates of projected pattern is inaccurate due to interpolation error. In the direct implementation technique of the sensor-oriented calibration method, patterns are projected on unknown surfaces first. Then the 3D projected patterns are directly measured by close range photogrammetry (Zang and et al, 2006). This method is a quick and precise solution so we selected it for projector calibration in our experiments.

As it is mentioned, it is possible to simply consider the projector as an inverse camera but it has some differences to camera so that it causes to be more difficult its calibration. The first and most important difficulty is that for camera calibration, 2D image coordinates are measured from known 3D object coordinates whilst it is vice versa for projector calibration. It means we have to accurately measure the 3D projected pattern that is a time-consuming and expensive task. In camera calibration for different camera placements, object points are static to each others in the imaging period but they are displaced by projector movement. In addition, the stability of lens system and body of the projector is not as good as camera so that it has to be recalibrated in shorter periods. Also, interior distortion size of the projector is larger than the camera so it needs more complex distortion model with more additional parameters. Further these facts, the projector calibration is so difficult because there is only a single pseudo image (pattern) in our hand!

In this paper, in attention to above difficulties, we use our effort to calibrate a projector rapidly and accurately by a direct sensor-oriented method. In other words, we utilize existing close range photogrammetry facilities for projector calibration. Next, the details of direct sensor-oriented projector calibration are described first to make a background for reader to better understand our experiments.

2 DIRECT SENSOR-ORIENTED PROJECTOR CALIBRATION

The basic steps of our proposed calibration solution are as follows:

1. At First, a 2D regular grid of similar binary circular targets is drawn using CAD software to be used as a pattern slide for projector. The size of circles should be at minimum ten pixels on acquired images and the grid cell size should be more that two times of the circle size. It is noted that the grid must cover the whole area of the slide in order to be capable to accurately estimate the distortion model parameters of the projector.

2. The pattern slide is projected on the center of a 3D wall corner with three pairs of right planes. The reason to select a 3D corner as projection surface is to make 3D projected targets in different depths. It causes to not only more imaging network strength that leads to more accurate 3D measurement of the projected targets, but also the projector is optimally calibrated for 3D measurement of surfaces within predefined depth variations. The best direction of the projector optical axis is 3D bisector of corner angle because the ellipse-shaped projected targets on right plans have minimal elongations. It causes they could be measured with higher accuracy by close range photogrammetry method in the next step.

3. Several convergent images are acquired from the projected targets by a single digital camera under some considerations that is known in close range photogrammetry (Atkinson, 1998): (1) The camera stations should make four to eight rays distributed around each 3D projected targets. (2) In some camera stations, two or more images should be acquired with 90 degree of roll angles in order to reduce the dependency between interior and exterior camera orientation parameters. (3) The 2D image points should cover whole frame of more images to validate the estimated distortion parameters. (4) To acquire semi-binary images from the optical targets, imaging should be done under low light of workspace, high lens aperture, and a fix zoom and focus. Besides, the camera stations also are placed so that they don't obstacle the projection pyramid.

4. The image coordinates of targets are measured for all images. Then, the camera is calibrated through bundle adjustment and self-calibration process which is based on the geometric mathematical model between image and object points coordinates. The outputs of network adjustment are estimation value and covariance matrices of the camera calibration parameters, exterior orientation parameters of all images, and 3D coordinates of the projected targets. For more information about bundle adjustment and self-calibration, please refer to basic books of close range photogrammetry such as (Atkinson, 1998).

5. In the final step, the projector is directly calibrated based on the known 3D coordinates of projected targets. As for projector calibration, we used an existing software of close range photogrammetry, named Australis (Fraser and et al, 2000), and in the software it is not possible to work with a single image (slide of projector), both camera and projector are simultaneously introduced to the software, the former with all images and latter with a single pseudo image. The camera parameters and 3D targets coordinates are set to fix known variables. Then a second multiple camera bundle adjustment and self-calibration is accomplished. The outputs are projector calibration parameters and exterior orientation of the projector and all camera images.

It is noted that, since the projector has only one image in bundle adjustment, for more reliability of calibration and more accuracy of 3D coordinates of targets, the camera and projector calibration has been done in two separate phases. Since the projector is a reverse camera, in proposed solution we consider its calibration model as conventional model for digital camera in close range photogrammetry known as collinearity condition equations (Atkinson, 1998):

$$x_{ij} - x_{oj} + \Delta x_j = \frac{-c_j[r_{j,11}(X_{Oj} - X_i) + r_{j,12}(Y_{Oj} - Y_i) + r_{j,13}(Z_{Oj} - Z_i)]}{[r_{j,31}(X_{Oj} - X_i) + r_{j,32}(Y_{Oj} - Y_i) + r_{j,33}(Z_{Oj} - Z_i)]}$$

$$y_{ij} - y_{oj} + \Delta y_j = \frac{-c_j[r_{j,21}(X_{Oj} - X_i) + r_{j,22}(Y_{Oj} - Y_i) + r_{j,23}(Z_{Oj} - Z_i)]}{[r_{j,31}(X_{Oj} - X_i) + r_{j,32}(Y_{Oj} - Y_i) + r_{j,33}(Z_{Oj} - Z_i)]} \quad (1)$$

in which $[X_{oj}, Y_{oj}, Z_{oj}]$ are coordinates of projection center of jth camera station, $r_j=\{r_{3x3}\}_j$ is rotation matrix of jth camera station, $[X_i, Y_i, Z_i]$ are object coordinates of ith projected target, c_j principal distance of jth image, $[x_{oj}, y_{oj}]$ are principal point coordinates of jth image, $[x_{ij}, y_{ij}]$ are image coordinates of ith projected target in jth image, and $[\Delta x_{ij}, \Delta y_{ij}]$ are distortion corrections for i[th] projected target in j[th] image. The geometric distortion correction model is as follows (Atkinson, 1998):

$$\Delta x_{ij} = (x_{ij} - x_{oj}) r_{ij}^{-1} (K_{1j} r_{ij}^3 + K_{2j} r_{ij}^5 + K_{3j} r_{ij}^7) + P_{1j} [r_{ij}^2 + 2(x_{ij} - x_{oj})^2] + 2P_{2j}(x_{ij} - x_{oj})(y_{ij} - y_{oj}) + B_{1j} x + B_{2j} y$$
$$\Delta y_{ij} = (y_{ij} - y_{oj}) r_{ij}^{-1} (K_{1j} r_{ij}^3 + K_{2j} r_{ij}^5 + K_{3j} r_{ij}^7) + P_{2j} [r_{ij}^2 + 2(y_{ij} - y_{oj})^2] + 2P_{1j}(x_{ij} - x_{oj})(y_{ij} - y_{oj}) + B_{2j} x \qquad (2)$$
in which $r_{ij}^2 = (x_{ij} - x_{oj})^2 + (y_{ij} - y_{oj})^2$

in which K_{1j}, K_{2j}, K_{3j} are radial lens distortion parameters, P_{1j}, P_{2j} are decentering lens distortion parameters, B_{1j}, B_{2j} are image affinity parameters in j[th] image. In our proposed solution, parameters of all images are sensor invariant.

3 EXPERIMENTS

In our experiments, we calibrated a DLP video-projector from Infocus model X2 with brightness of 1500 lumens, resolution of SVGA 800x600 by a consumer-grade digital camera from Canon model Powershot G3 with 4 Mega Pixels image quality (2272x1704 pixels with 3µm CCD pixel size), 4x zoom, and widest focal length of 35mm (Figure 2).

Figure 2. digital camera and video projector used in our experiments

To calibrate the projector, it set out in three meters back distance of a wall corner in size of 1.5x1.5x1.5 cubic meters with the axis along its bisector (Figure 3). Then, zoom and focus of the projector are set so that the targets sharply project into the whole corner space. Therefore, the proportion of object size to object-projector distance is approximately 0.5 that is a rough proportion of pattern slide size to projector principal distance. Since the virtual size of the pattern slide is measured on the monitor about 25 mm, virtual principal distance of projector is approximately 50 mm.

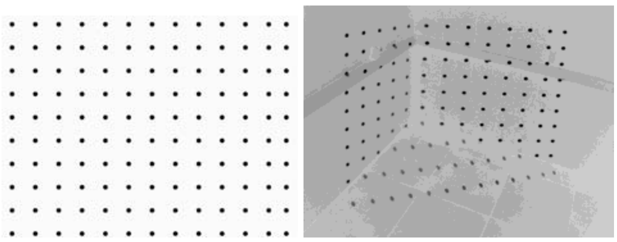

Figure 3. the pattern slide designed for making optical targets (left) and the projected targets on the wall corner (right)

The designed pattern is a grid of circular targets with diameters of 0.4 mm and distance of 2 mm on the monitor with virtual size of 25 mm. So it contains 13x10 = 130 optical targets (Figure 3).

3.1 Camera and Test-Field Calibration

Before calibration of the projector, the distortion parameters of the camera and 3D coordinates of projected targets in test filed should be estimated through the first bundle adjustment and self-calibration process. The next step is second bundle adjustment and self-calibration that is done for projector calibration.

To do so, a network of 32 convergent images under considerations mentioned in the previous section is acquired. Figure 4 illustrates a general view of the photogrammetric network. The self-calibration and free bundle adjustment of the network with 6374 image observations, 568 unknown parameters, 11 constraints (5817 degree of freedom) was done by Australis software.

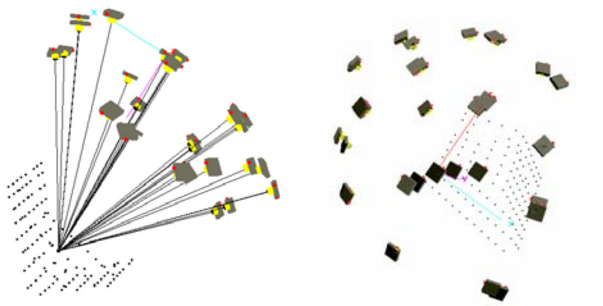

Figure 4. side view (right) and top view (left) of the photogrammetric network

As the authors had calibrated the camera in their last investigations, we knew the camera stability and its significant calibration parameters, so K_2, K_3, P_1, P_2 parameters were removed from model then camera and test field were calibrated. Table 1 shows the estimated value and precision of camera calibration parameters, Table 2 shows average precision of estimated coordinates of 130 projected targets in test field, and Figure 5 illustrates their standard ellipsoid errors. To calibrate the projector, these estimated values will be introduced to the second bundle adjustment as known values.

As it is seen from Figure 5, the ellipsoid errors are relatively spherical shape and similar size. This fact means the network is strong and results are reliable.

Parameters	Evaluated Value	Standard Deviation
c	7.0866	8.22E-04(mm)
x_o	0.065	5.00E-04(mm)
y_o	-0.0414	5.14E-04(mm)
K_1	3.25E-03	8.77E-06
B_1	6.76E-05	2.15E-05
B_2	1.73E-04	2.11E-05

Table 1. Evaluated calibration parameters of the camera

RMS_X	RMS_Y	RMS_Z	RMS_{XYZ}
0.046	0.080	0.042	0.101

Table 2. The RMS of standard deviations of 3D target coordinates in the test filed (mm)

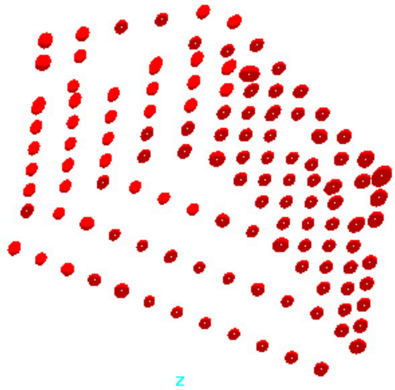

Figure 5. Standard ellipsoid errors of targets in test filed (with exaggeration)

Case	**A**		**B**		**C**		**D**	
RMS of Image Residuals (μm)	19.44		3.11		3.07		1.67	
Unit Weight Variance	25.007		3.913		3.865		1.046	
	X	σ_x	**X**	σ_x	**x**	σ_x	**x**	σ_x
c	48.9254	2.47E-01	52.4927	4.14E-02	51.9045	6.19E-02	52.1147	4.42E-02
x_o	-	-	0.1333	1.67E-02	0.2506	1.97E-02	0.4644	5.34E-02
y_o	-	-	-10.6501	2.27E-02	-11.2788	6.14E-02	-11.7825	5.28E-02
K_1	-	-	-	-	1.34E-05	1.10E-06	4.76E-05	1.74E-06
K_2	-	-	-	-	-	-	9.19E-08	4.84E-09
K_3	-	-	-	-	-	-	8.01E-11	5.19E-12
P_1	-	-	-	-	-	-	2.72E-05	7.96E-06
P_2	-	-	-	-	-	-	3.88E-05	1.04E-05
B_1	-	-	-	-	2.52E-04	1.65E-04	1.28E-03	2.12E-04
B_2	-	-	-	-	1.96E-04	1.24E-04	5.25E-04	

Table 3. The result of four projector self-calibration processes

3.2 Projector Distortion Model Determination

As it is mentioned in section 2, the general calibration model of the projector is based on relation 2. In this model, there are 10 parameters. For the projector under calibration, the statistically insignificant and dependent parameters should be removed form the model first to derive the optimal calibration model for that specific projector.

To do so, four bundle adjustment and self-calibration processes were accomplished with predefined different significant parameters:

a) Only one parameters for projector calibration model (c).
b) Three parameters for projector calibration model (c, x_o, y_o).
c) Six parameters for projector calibration model (c, x_o, y_o, K_1, B_1, B_2).
d) All ten parameters for projector calibration model (c, x_o, y_o, K_1, K_2, K_3, P_1, P_2, B_1, B_2).

In all computations, all previous known 3D projected targets are considered as control points and camera calibration parameters set to fix known variables. Then the projector are considered as second sensor with approximate principal distance of 50 mm, virtual pixel size of 30 μm and sensor size of 800x600 pixels (virtual size of 24x18 mm^2).

As you can see in Figure 6, the residual vectors have a high level of systematic pattern in case A (magnification 32).

Therefore, a single parameter c for projector calibration is not enough. In cases of B and C, also there is systematic error in residuals but with less level (magnification 512). In case D, the residuals are random vectors without detectable systematic error pattern. Therefore, the general mathematical model with ten parameters seems to be optimal for projector calibration.

The similar result could be proved from Table 3 using unit weight variance of adjustment. As it is known, if systematic error remains in observations (or residuals), then unit weight variance of adjustment will be rejected in related statistical tests. Therefore, in Table 3, unit weight variance from case A to case D is sequentially reduced from 25 to unit. It proved there is not systematic error in observations in case D. Our final result is that all ten parameters are significant. The column D of Table 3 shows the estimated values and their standard deviations of calibration parameters.

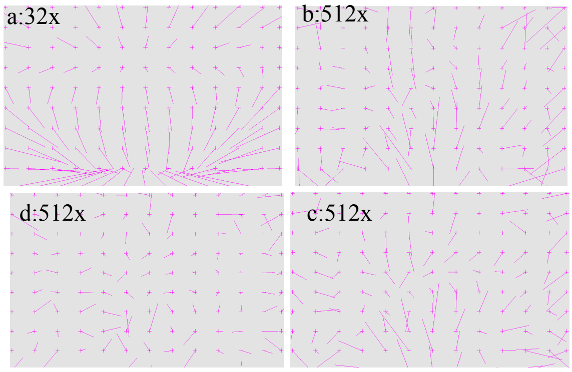

Figure 6: the image residuals in projectors for four distortion models

3.3 Accuracy Evaluation of the Proposed Calibration

To study the accuracy of projector calibration with ten mentioned parameters, we divided 130 targets into two homogeneous and complementary groups: 75 control points and 75 check points. The control points were used for calibration of the projector while the check points were used for accuracy evaluation of the calibration result. Table 4 shows the calibration parameters estimated by the control points.

Parameters	Evaluated value	Standard deviation
C	52.1149	4.069e-002 (mm)
x_o	0.4120	4.394e-002 (mm)
y_o	-11.7416	5.537e-002 (mm)
K_1	4.35E-05	1.67E-06
K_2	8.74E-08	4.59E-09
K_3	7.20E-11	4.86E-12
P_1	2.45E-05	6.59E-06
P_2	7.42E-05	1.01E-05
B_1	1.94E-03	1.95E-04
B_2	6.40E-04	1.32E-04

Table 4: the value of calibration parameters estimated by 75 control points

		Control Points		Check Points			
				with blunders		without blunders	
		Mean	RMS	Mean	RMS	Mean	RMS
Object Space (mm)	d_X	-0.000	0.083	0.040	0.129	-0.022	0.085
	d_Y	-0.019	0.203	0.073	0.601	0.000	0.182
	d_Z	0.027	0.101	0.019	0.182	0.002	0.096
	d_{XYZ}	0.015	0.241	0.044	0.641	0.008	**0.223**
Image Space (μm)	d_x	-0.021	1.183	0.318	2.306	-0.017	1.073
	d_y	0.307	0.815	-0.274	2.937	-0.383	0.920
	d_{xy}	0.164	1.436	0.296	3.734	0.200	**1.414**

Table 5: accuracy of image and object coordinates on control and check points

Then the parameters of the calibrated projector was fixed and camera/projector bundle adjustment was repeated with all control and check point observations. Table 5 shows the result of coordinates comparison in image and object space for both control and check points. It is noted that the level of object space errors showed in Table 5 is derived in case that projector-object distance is three meters. In other words, the object relative accuracy of 3D surface measurement is 0.223 mm for 3 m about 1:13000. Also, the level of image space error showd in Table 5 is derived in case that the virtual pixel size of projector is 30 µm. It means the image relative accuracy of projector calibration is 1.414 µm for 30 µm about 20 times of projector resolution.

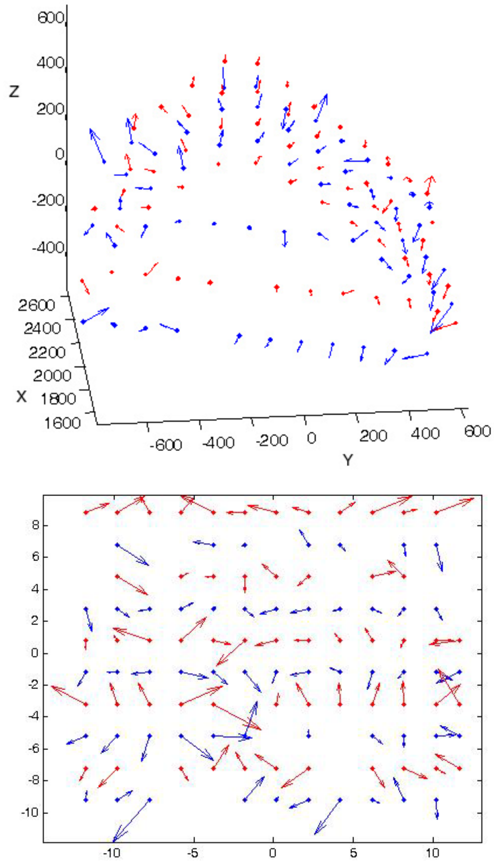

Figure 7: (down) residual vectors of check points (blue) and control points (red) in image space and (up) object space after blunder removal (mag. factor: 1000)

Parameters	Evaluated value	Standard deviation
c	52.1461	2.61E-02(mm)
x_o	0.4546	3.08E-02(mm)
y_o	-11.7882	3.15E-02(mm)
K_1	4.17E-05	1.09E-06
K_2	-8.02E-08	2.96E-09
K_3	6.38E-11	3.15E-12
P_1	-3.00E-05	4.54E-06
P_2	7.62E-05	6.33E-06
B_1	1.95E-03	1.26E-04
B_2	7.38E-04	8.72E-05

Table 6: the final estimated value of projector calibration parameters with all targets

Figure 7 illustrates the residual vectors of control/check points in image/object spaces after blunder removal. As it can be seen, some blunder vectors have been detected and removed. The blunders are unavoidable for optical targets because the surface of projection for some targets may be have small geometric irregularities that make local errors for these targets. For more precise calibration of projector and 3D surface measurements, these projected targets have been detected and eliminated from observations.

To evaluate the final value of calibration parameters, all 130 optical targets are considered as control points and participate in bundle adjustment and projector self-calibration. To have more precise and robust estimation, the large image residuals automatically detected and eliminated in Australis software. Table 6 shows the final projection calibration result that has small differences to Table 3-column D and Table 4.

4 CONCLUSION AND FUTURE WORKS

One of the most important points to achieve a high accuracy for 3D surface measurement using a structured light system is precise calibration of the system. It includes interior calibration of camera and projector and their relative calibration. In this regard, interior calibration of projector is more difficult that camera and takes more time and cost. In this paper, the close range photogrammetry method is used to calibrate the projector rapidly and accurately. At first, selection of a proper calibration model with ten parameters to model distortions of projector was studied through four experiments. Then, the projector was calibrated with mentioned distortion model rapidly. The time of imaging (33 images) and computations (about 6400 observations and 600 unknowns) with Australis software was in range of ten minutes. The result of our experiments demonstrates projector can be calibrated in accuracy of 20 times of its resolution by close range photogrammetry. This calibrated projector also can measure 3D surfaces in accuracy of 1:13000 of projector-object distance.

In our proposed calibration process, we expected if a more geometrically robust projector with higher resolution and depth of focus is utilized and if the projector is installed in a fixed position, it may be to get more precise results under higher measurement speed. Therefore, our future research is to build a structured light system with higher quality of hardware and especial automatic processing software. The fusion of close range photogrammetry and structure light methods is another topic for our future research to be able to measure 3D surface of large and/or complex objects.

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