THE ACCURACY INFLUENCE OF DIFFERENT CAMERA CALIBRATION CONDITIONS TO BUNDLE ADJSUTMENT OF CLOSERANGE IMAGES

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KEY WORDS: Close Range Photogrammetry, Camera Calibration, Bundle Adjustment, Additional Parameter;

ABSTRACT: Nowadays, close range photogrammetry is gradually applied in numerous fields. While using for mapping, the accuracy is a critical problem that we care. Generally speaking, the non-metric camera would be used in close-range photogrammetry. Therefore, the camera should be calibrated carefully before the bundle adjustment is performed on the determination of precise position and orientation of close-range images. However, different camera calibration conditions will affect the accuracy of bundle adjustment. In this study, the Canon EOS 5D, a SLR-type digital camera, will be used and different camera parameters will be calibrated by iWitnessPRO, a close-range photogrammetry software product. The different camera parameters with different camera calibration data sets from different distances will be used to discuss the accuracy influence of bundle adjustment. The bundle adjustment with additional parameters will be used to overcome several imaging systematic errors which are remained from imperfect calibration under operational conditions as part of solution to increase the accuracy of close range photogrammetry. Meanwhile, the results of bundle adjustment with additional parameters will be compared with the results of bundle adjustment. And both of them are performed by using different camera parameters calibrated with different distances. From the test results, the suggestions will be made for the mapping by using close-range images.

1. INTRODUCTION

The history of close-range photogrammetry can be traced back to the late 1840s (Ahmed and Hass, 2009).It's a method for recording and monitoring architecture originally. After World War II conservators spare no effort to precise and accurate recording of buildings conservation and restoration (Desmond, 1994). Now, close-range photogrammetry has been already applied in numerous fields and the accuracy is still important problem that we care.

The accuracy of close-range photogrammetry can be affected by lots of factors, e.g. shooting distance, the distribution of control points, and the camera calibration, etc. For promoting the accuracy of bundle adjustment, some studies were conducted. Habib et al. (2000) present tie/control line for close-range photogrammetry. As the same as the function of tie/control point does, tie/control line can be used to increase redundancy and improve the geometric strength of bundle adjustment. Additionally, some studies suggest prompting the accuracy of bundle adjustment with self-calibration (Hsieh, 2011).

The main purpose of this study is to investigate the accuracy of bundle adjustment of close-range images with different camera parameters calibrated from different calibration distances. Therefore, section 2 will describe the relevant theory. Experiment design, relevant tests, and test results will be described in section 3. Finally, the conclusion will be drawn in the last section.

2. RELEVANT THEORY

2.1 Bundle adjustment for close-range photogrammetry

Bundle adjustment is a method to calculate the object coordinates and the elements of exterior orientation with overlapped and unlimited numbers of images. It comes from the principle of analytical photogrammetry which uses the least squares method to solve huge and complex redundant observation equations. With the development of close-range photogrammetry, bundle adjustment is utilized to cope with the tilted and infinite number of images.

Analytical photogrammetry is based on the collinearity condition, which assumed the exposure station, an object point, and its image point all lie in a straight line in three-dimensional space. As shown in Figure 1, where 'L', 'A', and 'a' lie along a straight line. Two equations can express the collinearity condition as the following equations (1):

$$
\begin{cases}
x_a = x_0 - f\left[\dfrac{m_{11}(X_A - X_L) + m_{12}(Y_A - Y_L) + m_{13}(Z_A - Z_L)}{m_{31}(X_A - X_L) + m_{32}(Y_A - Y_L) + m_{33}(Z_A - Z_L)}\right] \\
y_a = y_0 - f\left[\dfrac{m_{21}(X_A - X_L) + m_{22}(Y_A - Y_L) + m_{23}(Z_A - Z_L)}{m_{31}(X_A - X_L) + m_{32}(Y_A - Y_L) + m_{33}(Z_A - Z_L)}\right]
\end{cases}
\qquad (1)
$$

In the equation,
x_a, y_a: the photo coordinates of image point a;
x_0, y_0: the photo coordinates of the principal point;
X_A, Y_A, and Z_A: the object space coordinates of point A;
X_L, Y_L, and Z_L : the object space coordinates of the exposure station;
f: the camera focal length;
m_{ij}: functions of three rotation angles.

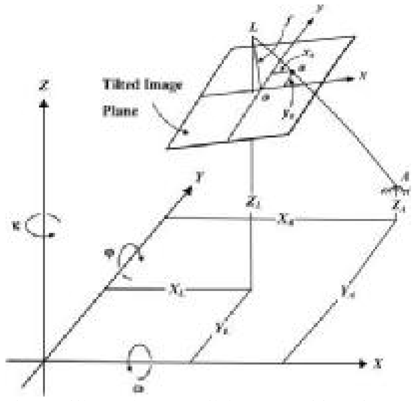


Figure 1. The collinearity condition (Wolf and Dewitt, 2000)

The concept of the bundle adjustment for close-range photogrammetry is similar to aerial photogrammetry. It can be illustrated as Figure 2.

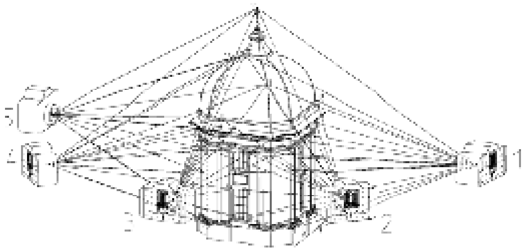


Figure 2. Illustration of bundle adjustment for close range photogrammetry (PHOCAD, 2005)

The mathematical model of the bundle adjustment is non-linear, so the approximate values for the unknowns are required (PHOCAD, 2005). All the approximate values are usually calculated through the sequence by relative orientation, absolute orientation as well as space resection.

2.1.1 Relative orientation

Relative orientation is aim to reconstruct the relative angular attitude and positional displacement of the photos to the moment when the photos were taken. The results only express the relative relation, not the actual values that existed when the photos were exposed. The minimum number of tie points per image pair is five, yet for a well result there should generally use at least seven to eight tie points. Each two images establish a model. As shown in Figure 3, the exterior orientation parameters of left photo are fixed. X_{L_2}, indicates the X coordinate of the exposure of right photo, is set equal to the photo base line. Therefore there are only 5 unknown left. Then the relative orientation can be calculated by the least squares method. As result, the three-dimensional models coordinates, in a model system, of each model can be obtained. The same concept can be used in close-range photogrammetry, as Figure 4 shown below.

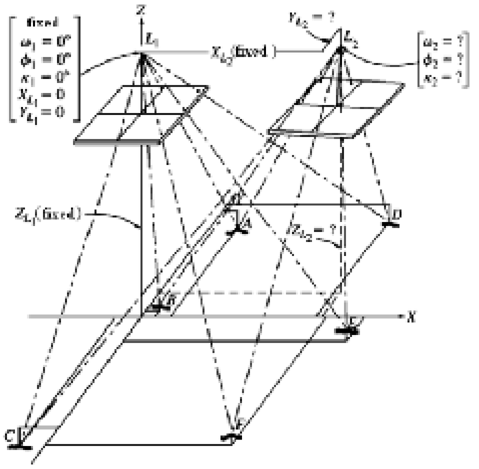


Figure 3. Relative Orientation in aerial photogrammetry (Wolf and Dewitt, 2000)

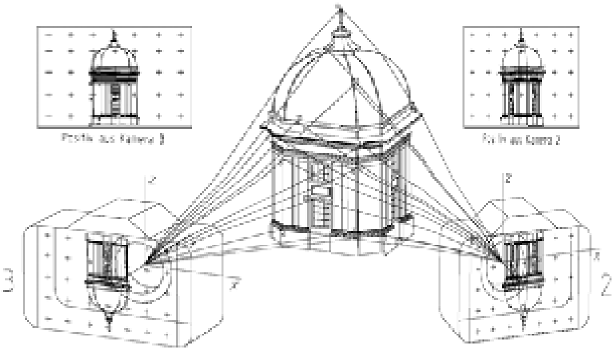
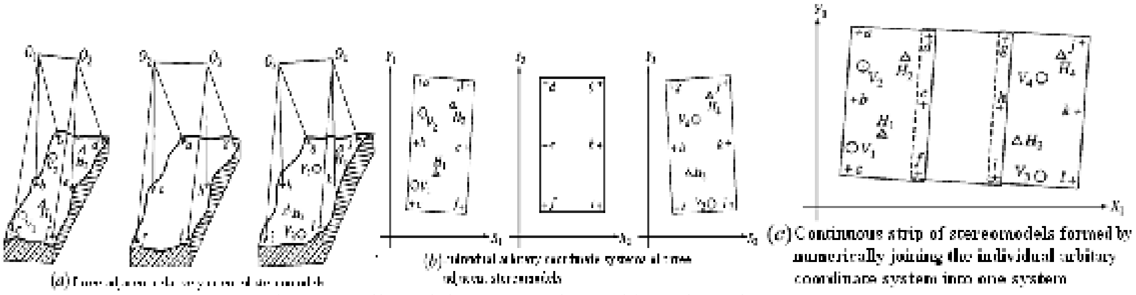


Figure 4. Relative orientation in close range photogrammetry (PHOCAD, 2005)

2.1.2 Absolute orientation

Absolute orientation is utilized to transform models from the model system to the control system, which can be performed by using a three-dimensional conformal coordinate transformation. There are two respects using in the absolute orientation. Firstly, a suitable reference model is chosen, so the models generated in relative orientation can all be transformed to the reference system. As shown in Figure5, all models are transformed to the reference system. Generally speaking, the transformation from models to reference model needs at least 3 tie points in each case. After the finish of models transform to reference system, the models in the reference system are transformed, if the control points exist, to the control system then, as shown in Figure 6. In the end, the approximate values of the tie points in three-dimensional system (in this study called new points) can be received (PHOCAD, 2005).



(a) Three adjacent relatively oriented stereomodels

(b) Individual arbitrary coordinate systems of three adjacent stereomodels

(c) Continuous strip of stereomodels formed by numerically joining the individual arbitrary coordinate system into one system

Figure 5 All models are transformed into the reference system
(Wolf and Dewitt, 2000)

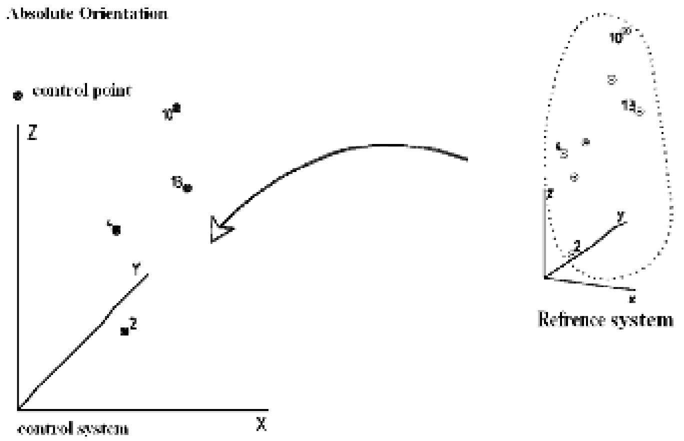


Figure 6 Absolute orientation-model system transforms to the control system (PHOCAD, 2005)

2.1.3 Space Resection

The last step to determine the approximate values is space resection. As shown in Figure 7 below, space resection is uses to determine the coordinate values of the control points and the new points, to determine the 6 exterior orientation parameters by least squares. The minimum number of points for space resection is 3, however for acceptable precision the number of points are the more the better (minimum 6 to 8) (PHOCAD, 2005).

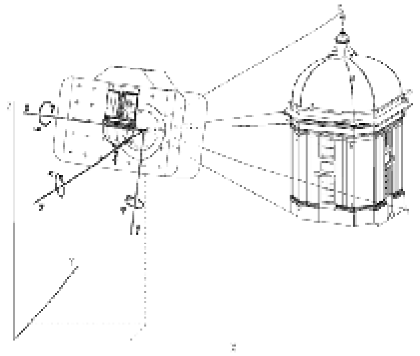


Figure 7 Space resection (PHOCAD, 2005)

2.2 Camera Calibration

For the consideration of convenience, stability, and cost, this study uses a non-metric digital camera as main imaging apparatus. To a better measure precision and accuracy of the spatial information from images, the non-metric digital camera needs to be calibrated carefully (Wolf and Dewitt, 2000). Camera calibration aims to correct camera systematic error and calculate its interior orientation parameters, called camera parameters in this study. There are three calibration methods in general: laboratory method, field method, stellar method (Wolf and Dewitt, 2000). Now, the frequently utilized method is the self-calibration of field method.

2.3 Self-calibration bundle adjustment

Self-calibration bundle adjustment is based on the collinearity condition as well. By using self-calibration bundle adjustment for camera calibration, the camera parameters can be obtained. For example, Brown (1956) used self-calibration bundle adjustment to calibrate cameras, and finally obtained calibrated focal length, principal point location, symmetric radial lens distortion, decentering lens distortion, etc. After that some researchers also put forward different models, e.g. Brown (1976) proposed 21 parameters model; Edner (1976) proposed 12 added parameters of orthogonal polynomial. By using self-calibration bundle adjustment for precise positioning and orientation, the camera parameters and the exterior orientation parameters are available simultaneously. For example, Hsieh (2011) used self-calibration in bundle adjustment for precise positioning and orientation of aerial images. The self-calibration bundle adjustment model is shown as below:

$$\begin{cases} x_a - x_0 + \Delta x = -f\left[\dfrac{m_{11}(X_A - X_L) + m_{12}(Y_A - Y_L) + m_{13}(Z_A - Z_L)}{m_{31}(X_A - X_L) + m_{32}(Y_A - Y_L) + m_{33}(Z_A - Z_L)}\right] \\ y_a - y_0 + \Delta y = -f\left[\dfrac{m_{21}(X_A - X_L) + m_{22}(Y_A - Y_L) + m_{23}(Z_A - Z_L)}{m_{31}(X_A - X_L) + m_{32}(Y_A - Y_L) + m_{33}(Z_A - Z_L)}\right] \end{cases} \tag{2}$$

In equation (2),
Δx, Δy: the systematic error of the image, generally it can be regarded as the function of the photo coordinates , which is aim to overcome the lens distortion exists in most of the digital cameras.

In this study, the following equation (3), called Australis model (Photometrix Pty Ltd, 2010), is used.

$$\begin{cases} \Delta x = \bar{x} + (K_1 r^2 + K_2 r^4 + K_3 r^6)\bar{x} + P_1(r^2 + 2\bar{x}^2) + 2P_2 xy + b_1 x + b_2 y \\ \Delta y = \bar{y} + (K_1 r^2 + K_2 r^4 + K_3 r^6)\bar{y} + P_1(r^2 + 2\bar{y}^2) + 2P_2 xy \end{cases} \tag{3}$$

Where
$\bar{x} = x - x_p$
$\bar{y} = y - y_p$
$r = \sqrt{\bar{x}^2 + \bar{y}^2}$
x_p,y_p: principal point coordinates,
K_1,K_2,K_3: radial lens distortion,
P_1, P_2: decentering lens distortion ,
b_1,b_2: linear distortion

Two software products are used in this study. One is iWitnessPRO, a close-range photogrammetry software product, for fully automatic camera calibration. The other one is PHIDIAS, a software product of photogrammetry, to performing bundle adjustment for precise positioning and orientation of close rang images. The camera parameter model in both software products is almost the same, except for the PHIDIAS only uses 5 parameters, K_1, K_2, K_3, P_1 and P_2. Therefore, the camera parameters calibrated by iWitnessPRO can be input to the PHIDIAS for bundle adjustment directly.

2.4 Straight line as tie line

Because of buildings in urban area, straight line features will be detected and extracted from those close-range images acquired in urban area. Therefore, straight line features will be useful as tie line or control line for bundle adjustment of close-range images. PHIDIAS is a software product of photogrammetry, it can use the lines as tie lines or control lines for bundle adjustment (PHOCAD, 2005), and PHIDIAS will be used in this study. In PHIDIAS, lines are represented by their two end points. Additionally, by adding straight lines in bundle adjustment it can increase redundancy and improve the geometric strength. There are several mathematical ways to describe the straight line no matter in two- or three-dimensional coordinate space. In PHIDIAS, image lines are defined by 2 parameters. It uses the classical normal form to represent a line in two-dimensional coordinate space. It can expressed as equation (4) (PHOCAD, 2005).

$$y = ax + b \tag{4}$$

x, y: image coordinate of end points
a: gradient ration of the line
b: axis intercept of y axis(mm)

Object lines are defined by 4 parameters. The line is done by 2-viewed projection. The line is projected onto two coordinate planes, and then defined the parameters as image lines. Therefore, there are four parameters, α, β, γ and δ. As shown in Figure 8, it expresses the projection of line in three-dimensional coordinate space and can be represented by equation (5) (PHOCAD, 2005).

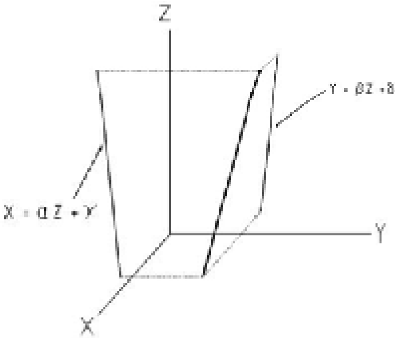


Figure 8.visualization of object line projection (PHOCAD, 2005)

$$S: \quad Y=\alpha_x.X+\gamma_x \quad \text{and} \quad Z=\beta_x.X+\gamma_x \qquad (5)$$

3. EXPERIMENTDESIGN

As mentioned in section2.3, there are two software products used in the study, iWitnessPRO and PHIDIAS. In additional, Canon EOS 5D SLR camera with 50 mm lens is employed to collect the test images, camera specifications are shown as the following Table 1.

Table 1.Camera specifications of Canon EOS 5DSLR camera

camera	Canon EOS 5D	
sensor	• 35.8 x 23.9 mm CMOS • 12.8 million effective pixels	
Image sizes	• 4368 x 2912 • 3168 x 2112 • 2496 x 1664	
Pixel size	8.2μm	
ISO range	ISO 50 - 3200 (when extended)	

Before discussing the accuracy of bundle adjustment with different camera parameters calibrated from different distances, the camera calibration should be done by iWitnessPRO software. After that, one indoor test site will be designed to take the close-range images with straight line features for tests of bundle adjustment by using PHIDIAS. Except for discussing the accuracy of bundle adjustment with different camera parameters calibrated from 3 different distances, the results of bundle adjustment with self-calibration or not, and with one straight line observation or not will be investigated by the RMSE of check points. The followings will describe the tests more detailed.

3.1 Camera Calibration Design

This study used a non-metric digital camera as main imaging instrument. Before the camera is used for tests, the camera should be calibrated by iWitnessPRO. As mentioned earlier, iWitnessPRO is a close-range photogrammetry software product, it can do the camera calibration fully automatically by employing coded target templates, see Figure 9. As shown in Figure 9, there are 20 coded target templates, and every template contained 8 dots, which are combined into different patterns. In order to carry out automatic calibration, there are some rules to abide by. It is preferable for the target field to have depth out of plane by 15-20 cm or more. It is importance to calibrate the camera at the same focus, and the focus is better to be set to infinity. The targets are not allowed to move during calibration. The iWitnessPRO calls for at least 6 convergent images and the convergence angle between the outer two rays should be 70 to 100 degrees. It must be careful that at least two rolled 90° images are needed (Photometrix Pty Ltd, 2010).

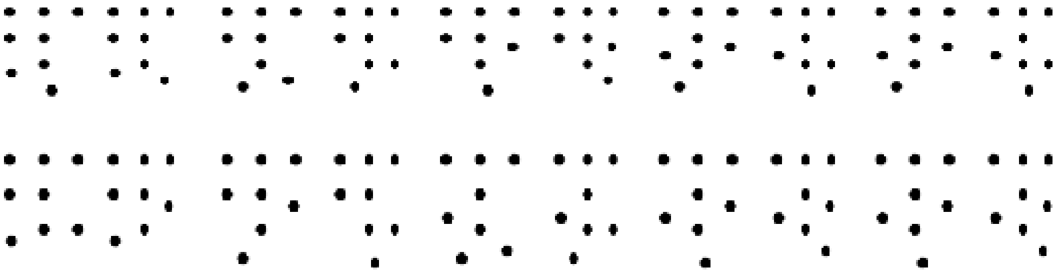
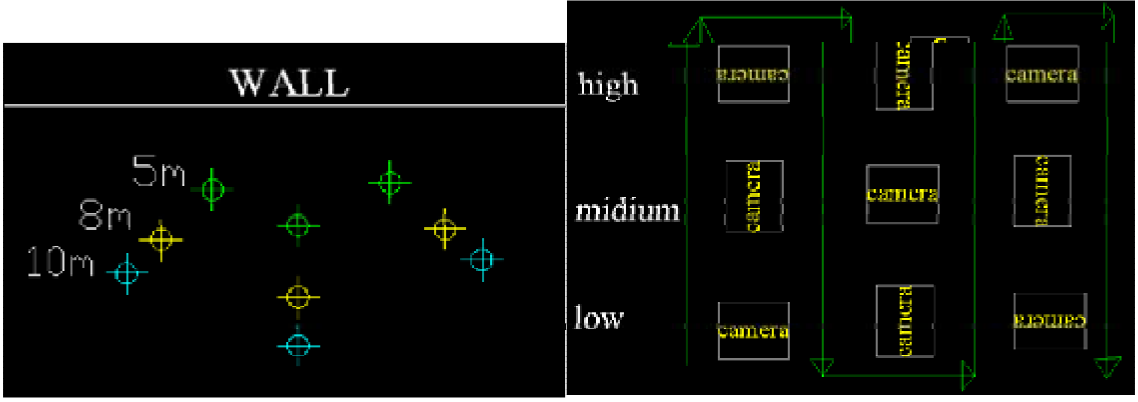


Figure 9. 20 coded target templates used in iWitnessPRO for automatic camera calibration

The calibration field is set up at 3rd floor of General Building of Colleges in National Chengchi University. The distribution of the templates is generally even distributed as Figure 10. Two boxes are put on the ground a little away from the wall to make the coded target templates with different depths.

Figure 10. Calibration Field

The camera is calibrated with three different distances, i.e. 5m, 8m, and 10m, see Figure 11(a). As shown in Figure 11(a), there are three different shooting sites in each distance. Meanwhile, 9 images are taken at 3 different heights, see Figure 11(b), on 3 shooting site. The camera will be rotated 90° at each exposure station, and the order of rotation is as the arrows in Figure 11(b).



(a) The top view of exposure stations

(b)the side view of exposure stations

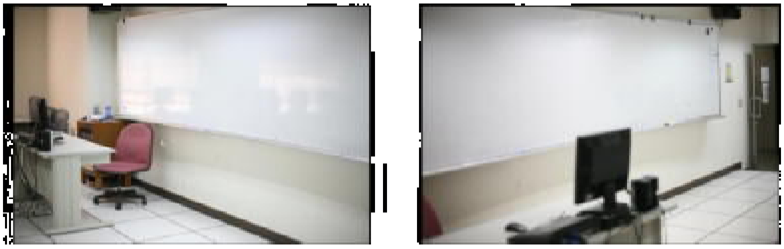
Figure 11. Calibration design

After gathering the calibration images, the iWitnessPRO can be executed to automatically calculate the camera parameters in 3 different distances by automatically finding the corresponding coded targets template for self-calibration bundle adjustment to determine camera parameters.

3.2 close-range images photogrmmetry design

After the camera is calibrated, the close-range image data will be collected for our tests. The test field was set up at the 6th floor of General Building of Colleges; see Figure 12, in National Chengchi University. In this study, two exposure stations were set and the close-range images are taken with approximate 60% overlap. The control points, check points and the two end points of the control line were measured by the total station with free station method.

Since the whiteboard in the test field is hard to identify point features, the crossmarks were drawn for identification, as shown in Figure 13.



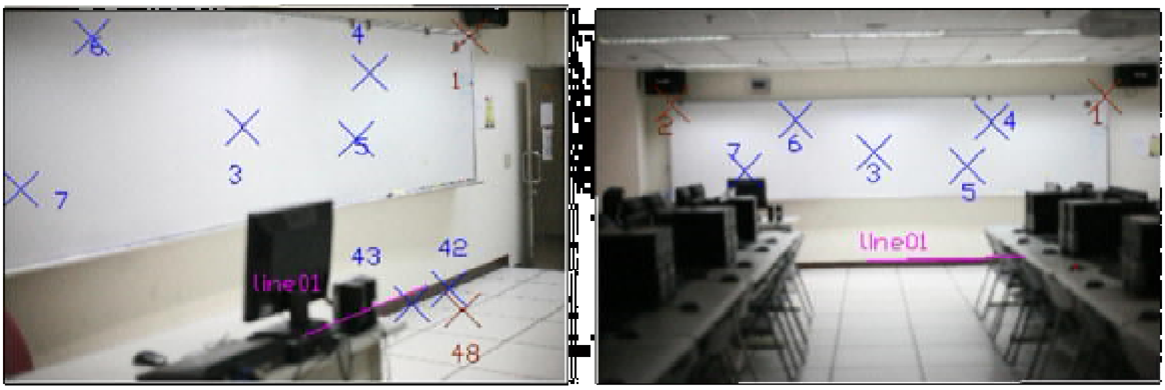
(a) The left side view of test field **(b) The right side view of test field**

(c) The middle side view of test field

Figure 12. The panoramic view of test field

Figure 13. crossmarks were drawn for identification

The distribution of control points, check points, and control line are shown in Figure 14. The upper side is the whiteboard area, and the lower side beneath the control line is the floor area. Moreover, the control line is sticks with the wall.



(a) The right side view of the test field with approximate image points distribution **(b) The middle side view of the test field with approximate image points distribution**

Figure 14. The distribution of control points, check points, and tie line
(brown: control point, blue: check point, pink: tie line)

4. RESULTS

First, the camera was calibrated by iWitnessPRO. As the experiment design depicted as before, there are 3 data sets of images, , taken at 5m, 8m, and 10m, for camera calibration. The calibration results are shown as Table 2. From Table 2, the different camera parameters are obtained.

Table 2. Results of camera calibration

	C(mm)	x_p(mm)	y_p(mm)	K_1(e-005)	K_2(e-009)	K_3(e-011)	P_1(e-006)	P_2(e-007)
5m	51.2882	-0.1533	-0.1748	3.3106	1.3355	8.6516	-2.3978	-1.8492
8m	51.2949	-0.1252	-0.1392	3.1729	1.4477	1.3423	-3.8722	-2.5053
10m	51.3300	-0.1279	-0.1036	3.6258	-4.7843	3.6992	-5.5421	-4.4505

For discussing the accuracy of bundle adjustment with different camera parameters calibrated from different distances, 27 images with approximate 60% overlap between any two adjacent images were taken from the test field at two locations. And the tie points and tie line were measured manually by PHIDIAS software. In this study, 86 tie points (including 3 control points, and 7 check points) and one tie line are measured. The measurement accuracy of tie points was default and set to 0.02mm. The measurement accuracy of tie line parameters ‘a’ and ‘b’ was set to 0.01mm and 0.05mm, respectively. In the processing of bundle adjustment, the blunder detection was executed. There are two methods for eliminating blunders, including re-weighting method and data-snooping method. In this study, the re-weighting method was chosen, and the maximum permissible number of outliers is set by default value 150.

The three-dimensional space coordinates of control points, check points and control line are measured by total station with free-station method. The X axis is set to along the whiteboard, refer to Figures 13 and 14; the Y axis is vertical to the whiteboard, i.e. the depth direction, therefore the XY plane is parallel with the floor. The Z axis is vertical to the XY plane, thus the XZ plane is parallel with the white board.

After using the PHIDIAS to performing bundle adjustment, the test results are obtained and shown in Tables 3 and 4. These results of bundle adjustment are calculated with different conditions, i.e. the combination of 3 different distances calibration camera parameters with/without self-calibration and with/without using one tie line. In Tables 3 and 4, RMSE in Y direction presents the depth accuracy of bundle adjustment.

Table 3. Results of bundle adjustment with/without self-calibration and without using one tie line

RMSE (m)	X		Z		XZ plane		Y	
	self-calibration	without self-calibration	self-calibration	without self-calibration	self-calibration	without self-calibration	self-calibration	without self-calibration
5m	0.018	0.008	0.003	0.008	0.019	0.012	0.008	0.022
8m	0.019	0.008	0.004	0.007	0.019	0.011	0.008	0.019
10m	0.012	0.009	0.002	0.005	0.012	0.010	0.006	0.017

Table 4. Results of bundle adjustment with/without self-calibration and with using one tie line

RMSE (m)	X		Z		XZ plane		Y	
	self-calibration	without self-calibration	self-calibration	without self-calibration	self-calibration	without self-calibration	self-calibration	without self-calibration
5m	0.011	0.007	0.001	0.006	0.011	0.010	0.007	0.021
8m	0.011	0.007	0.001	0.005	0.011	0.009	0.007	0.019
10m	0.016	0.007	0.003	0.004	0.016	0.008	0.008	0.015

5. CONCLUSIONS

From Tables 3 and 4, the following conclusions are made:

1. Accuracy of bundle adjustment with self-calibration and without self-calibration:
No matter if one tie line is used or not, the accuracy in Y direction is obviously prom pting by using self-calibration bundle adjustment. That means the self-calibration bundle adjustment can promote the depth accuracy in this study.

2. By comparing with the RMSE in XZ plane of Tables 3 and 4, it implies that whether self-calibration is used or not, by adding the tie line it can improve the accuracy of the XZ plane, vertical the depth direction... It is said that by adding tie line it can prompote improve the accuracy of bundle adjustment.

3. All in all, the best result is the self-calibration bundle adjustment with one tile line. This means the tie line will be very helpful for precise position and orientation while images with line features.

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