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PHOTOGRAMMETRIC BLOCK ADJUSTMENT WITHOUT CONTROL POINTS

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Abstract. A simple method for close range and aerial photogrammetry applications has been developed. The method is in the form of bundle block adjustment which utilizes only the measured distance(s) between points for generating adjusted relative three dimensional (3D) coordinate system. Software based on the proposed method has been developed and tested using simulated data. The effects of block size, number and location of measured distances, and random errors on bundle block adjustments using the proposed and the conventional methods have been studied using simulated and actual photogrammetric data. It was found that the accuracy of the bundle block adjustment using the proposed method is comparable or better than the results of conventional method. The proposed method, is suitable for photogrammetrists and non-photogrammetrists in different fields such as architectural, archaeological, forensic and aerial photogrammetry, where relative 3D coordinates system may be required. It has a significant effect on reducing the overall cost of the photogrammetric project. Merging the capabilities of the developed software and Computer Aided Design (CAD) technology, especially 3D drawing generation, widens its applications areas to include recording buildings and monuments which is necessary for architectural and archaeological applications.

Keywords: aerial photogrammetry, close range photogrammetry, bundle block adjustment, 3D relative coordinate system.

Introduction

Photogrammetry In photogrammetry, image blocks are connected by numerical methods of bundle adjustment (El-Ashmawy, 1999; Ghosh, 2005; Rupnik, Nex, Toschi, & Remondino, 2015; Gneeniss, Mills, & Miller, 2015; James, Robson, d'Oleire-Oltmanns, & Niethammer, 2017). To find the parameters of the exterior orientations and object space coordinates of new points, control points are necessary at the object; approximate values of the unknowns are used for adjustment.

The collection of object space coordinates of control points presents a significant problem in many practical applications, as an existing source of control points may not be available (Ghosh, 2005). It is often prohibitively expensive to collect new points, especially for areas inaccessible by road, or too impractical to acquire manually. Production of control points in medical and archaeological cases may be a difficult task.

Instead of using control points, direct measuring of camera exterior orientation parameters with a high accuracy Global Positioning System (GPS) has been used and introduced to photogrammeteric applications (Jacobsen, 1997; Jacobsen, 1999; Shi, Yuan, Cai, & Wang, 2017). Zhang, Zheng, X. Xiong, and J. Xiong (2015) used bundle block adjustment without control points for processing satellite imagery of China using rigorous sensor model method.

In some photogrammetric applications, such as architectural, archaeological applications, using relative 3D coordinates of points is possible.

In the past few decades, *CAD* systems have evolved from 2D tools that assist in construction design to the basis of software systems for a variety of applications, such as (re)design, manufacturing, quality control, and facility management. The basic functions of a modern *CAD* system are storage and retrieval of 3D data, their construction, manipulation, and visualisation. Nowadays, *CAD* vendors provide the possibilities of easy manipulation of 3D vector graphics. Furthermore, in *CAD* environments, friendly user interfaces using pop-up windows and dialog boxes give the user the ability to view 3D design files – in

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top, front, isometric and side views – at the same time (Omura & Benton, 2016). All these functions are needed in a photogrammetric measurement system. Therefore, photogrammetry benefits from integration with CAD, and thereby from developments in this field (Van Den Heuvel, 2000; Zhou & Deren, 2001).

The paper aims to:

– Reducing the survey work to measure only distance(s) between points instead of determination of object space coordinates of control points;
– Derivation of a proposed method based on the above mentioned assumption;
– Investigation of the accuracy of proposed method; and
– Comparing between the results of the proposed method with the results of conventional bundle block adjustment.

1. The proposed method

The main computational steps of the proposed method are shown in Figure 1 and consist of:

– Computation of relative 3D coordinates of points;
– Computation of the mean scale factor;
– Scaling the relative 3D coordinate system to object space system; and
– Least squares technique (LST) solution for obtaining the adjusted relative 3D coordinates of points.

1.1. Computation of the relative 3D coordinates of points

This step is based on an approach similar to analogical procedure for determining the model coordinates of points and using these to determine the values of exterior orientation parameters (El-Ashmawy, 1999).

The method consists of performing satisfactory relative orientation of each of the stereomodels such that each model yields three dimensional coordinates of all the required model points and the two perspective centres. The conformal transformation of the second model and the successive connections (i.e. scale transfer and co-orientation) of other models to the first model are then performed. This gives the complete block coordinates in an analytically created block of connected models.

The first step includes the formation of model which depends mainly on the determination of the five elements of relative orientation (dependent case). In dependent relative orientation method, the scale factor is the same (equated to unity) for all points in the two photographs of a stereopair, the arbitrary value of the X-component of the air base is designated b_x and the left hand side photograph is fixed, i.e. the elements of the relative orientation are Y-component of the air base, Z-component of the air base and the rotation angles $(b_y, b_z, \omega, \varphi, \kappa)$ of the right hand side photograph. These elements are computed generally by means of a coplanarity condition (Ghosh, 2005).

The results of the relative orientation give two sets of six exterior orientation elements, one set for each photograph. Based on these elements, the analytical model positions of all measured points can be computed by the process of space intersection (El-Ashmawy, 1999; Ghosh, 2005).

The sequential process of relative orientation and computation of model coordinate of points in the model overlap with respect to the coordinate system of the left hand photograph is then carried out for models 2-3, 3-4, and so on.

In formation of strip(s), the first photograph of first model in a strip of independent models defines the X, Y, Z coordinate axes. Each successive independent model is transformed into this system by seven-parameter transformation method and using the common points between models in order to form the strip (El-Ashmawy, 1999;

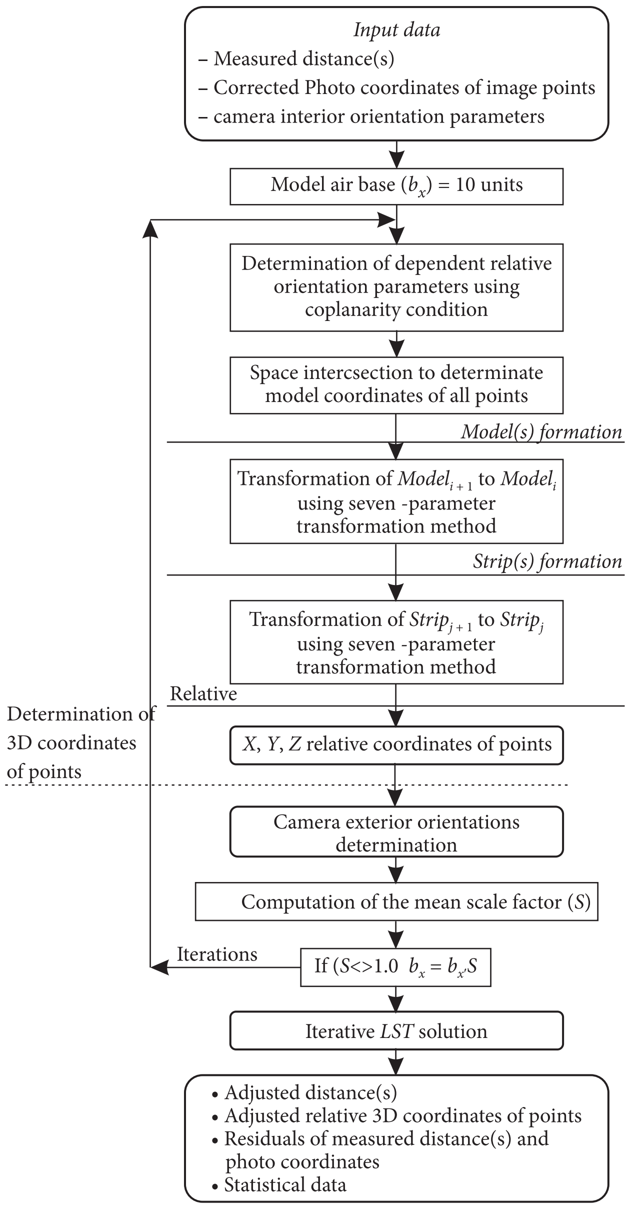

Figure 1. The main computational steps of the proposed method

Moffitt & Mikhail, 1980). By the aforementioned procedure, the second model is transformed to the first model. Next the same procedure is followed to transform the third model to the already transformed second model. This process is continued till the last model to form one strip where the strip coordinates of all points of interest are obtained in one coordinate system established by the fixed position of the first photograph of each strip.

Formation of the block consists of tying two successive strips together by means of common points in sidelap (tie points) using seven-parameter transformation method (El-Ashmawy, 1999; Moffitt & Mikhail, 1980). Thus all the coordinates of points in various strips are transformed to the first strip coordinate system i. e. the system of coordinates of the first photograph in the block.

Having determined the relative 3D coordinates of points, each photograph of the block will have three or more of known relative 3D coordinate points. The determination of the values of camera exterior orientation parameters can be performed using space resection method (Ghosh, 2005).

1.2. Computation of the mean scale factor

After computing the relative 3D coordinates of all points, the mean scale factor is determined by comparing the measured distance(s) in object space system and the computed relative distance(s) as follows:

$$S = \frac{1}{n}\sum_{i=1}^{n} d_{mi} / d_{ci}. \tag{1}$$

In which S is the mean scale factor; n is the number of measured distances; d_m is the measured distance, in object space system, between two specified points; and d_c is the computed distance, in relative 3D coordinate system, between the same two points and can be computed by:

$$d_c = \sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2}, \tag{2}$$

where $\Delta x, \Delta y, \Delta z$ are the differences in x, y, z relative 3D coordinates of the two points.

1.3. Scaling the relative 3D coordinate system to object space system

Scaling the block to comprise distances similar to object space distances is an iterative solution. After computing the scale factor, the model airbase is computed as follows:

$$b_{x_{i+1}} = b_{x_i} s_i . \tag{3}$$

Using the new value of the model airbase, the steps in Sections 2.1, 2.2 and 2.3 are repeated till the value of the mean scale factor becomes one or near to one.

1.4. Least squares technique (LST) solution

The developed mathematical model utilizes the well known collinearity equations to establish two equations for each measured image point, and provides a unique solution for the system of observation equations by the least squares method. The collinearity equations can be written as (Ghosh, 2005):

$$\left.\begin{aligned} x = (x_p - x_o) = \\ -f\frac{(X_P - X_o)m_{11} + (Y_P - Y_o)m_{12} + (Z_P - Z_o)m_{13}}{(X_P - X_o)m_{31} + (Y_P - Y_o)m_{32} + (Z_P - Z_o)m_{33}} \\ y = (y_p - y_o) = \\ -f\frac{(X_P - X_o)m_{21} + (Y_P - Y_o)m_{22} + (Z_P - Z_o)m_{23}}{(X_P - X_o)m_{31} + (Y_P - Y_o)m_{32} + (Z_P - Z_o)m_{33}} \end{aligned}\right\}, \tag{4}$$

where: x_p, y_p are the measured photo coordinates of image point p; x, y are corrected photo coordinates of image point p; x_o, y_o are the photo coordinates of the principal point; f is the camera focal length; X_o, Y_o, Z_o are the relative 3D coordinates of the camera station; X_P, Y_P, Z_P are the relative 3D coordinates of the object point P; and m_{11}, ..., m_{33} are the elements of photo orientation matrix (Ghosh, 2005).

The linearized form of the collinearity equations can be given by (El-Ashmawy, 1999; Ghosh, 2005):

$$V + B \cdot \Delta = \varepsilon , \tag{5}$$

where Δ is the correction vector to the current values set for the unknowns (the camera exterior orientation parameters of the photo, relative 3D coordinates of the points) in the iterative solution; B is the matrix of the partial derivatives of the collinearity equations with respect to the unknowns and its elements can be found in (El-Ashmawy, 1999; Ghosh, 2005); V is the residual vector, i.e., the correction vector to the measured photo coordinates; and ε is the discrepancy vector.

To increase the accuracy of the results, supplemental observation equations arising from a priori knowledge regarding the measured distance(s) can be considered. Such supplemental equations can be derived as described below.

The distance condition (Mikhail, 1976) between two points P and Q can be written as:

$$S_{PQ_m} + V_{S_{PQ}} = \sqrt{(X_Q - X_P)^2 + (Y_Q - Y_P)^2 + (Z_Q - Z_P)^2}, \tag{6}$$

where: S_{PQ_m} is the measured distance in object space system between points P and Q; $V_{S_{PQ}}$ is is the corresponding residual; and $X_P, \ldots, Z_Q$ are the relative 3D coordinates of points P and Q respectively.

The liberalized form of Equation (6) can be written as:

$$V_S + B_S . \Delta_S = \varepsilon_S , \tag{7}$$

in which: V_S is the residual vector, i.e., the correction vector to the measured distances; Δ_S is the correction vector to the current values set for the unknowns (the relative 3D coordinates of the two ending points of the measured distance) in the iterative solution; B_S is the matrix of the partial derivatives of Equation (6) with respect to the unknowns and its elements can be found in (Mikhail, 1976); and ε_S is the discrepancy vector.

Furthermore, constraints are suggested to consider supplemental observation equations arising from the relative 3D coordinates of points for which the scale factor for the distances between them is one or near to one. Such supplemental equations can be written as follows:

$$V_C - \Delta_C = \varepsilon_C\,, \tag{8}$$

where: Δ_C is the vector of observational corrections to the relative 3D coordinates of points; and ε_C is the discrepancy vector, between observed values and current (in iterative solution) values of the relative 3D coordinates of the points.

Observation equations can be obtained by merging Equations (5), (7) and (8) as:

$$\left.\begin{aligned} V + B\,\Delta &= \varepsilon \\ V_S + B_S\Delta &= \varepsilon_S \\ V_C - \Delta_C &= \varepsilon_C \end{aligned}\right\}. \tag{9}$$

Equation (9) can be rewritten as:

$$\overline{V} + \overline{B}\cdot\Delta = \overline{\varepsilon}\,, \tag{10}$$

in which

$$\overline{V} = \begin{bmatrix} V \\ V_S \\ V_C \end{bmatrix},\ \overline{B} = \begin{bmatrix} B \\ B_S \\ -I \end{bmatrix} \text{ and } \overline{\varepsilon} = \begin{bmatrix} \varepsilon \\ \varepsilon_S \\ \varepsilon_C \end{bmatrix}.$$

The parametric least squares solution of Equation (10) can be given as (Mikhail, 1976):

$$\Delta = N^{-1}C; \tag{11}$$

$$N = \overline{B}^t W^{-1} \overline{B}; \tag{12}$$

$$C = \overline{B}^t W^{-1} \overline{\varepsilon}, \tag{13}$$

where W is the weight matrix of observations.

2. Developing the necessary software

The current research includes the development of software for the utilization of the proposed method. The main functions of the developed software are:

Data preparation: It performs the necessary tasks for preparing the data to start block adjustment such as testing the geometry of the input data (El-Ashmawy, 1999), two dimensional affine coordinates transformation (El-Ashmawy, 1999; Ghosh, 2005), refinement of photo coordinates (El-Ashmawy, 1999; Ghosh, 2005), and computation of the initial values of camera exterior orientation parameters and relative 3D coordinates of points.

Iterative least squares method solution: This includes the computations of the adjusted values of unknowns, residuals of photo and measured distances, and variance of unit weight.

Computation of statistical data: It includes the computation of the necessary data for statistical analysis and error detection (El-Ashmawy, 1999) such as variance of unit weight, cofactor and covariance matrices for unknowns, adjusted photo coordinates and their cofactor matrix, residuals of photo coordinates, dimensions of error ellipses, etc.

For automatic processing and representation of the data and results, the software utilises efficient techniques of Data Structuring, Random File Access and Dynamic Memory Allocations. The software has been designed to make use of efficient user interfaces (window-driven) for facilitating its execution to the user (Malik, 2010).

3. Testing the developed software

Testing a photogrammetric system is a complex task. It involves, for example, availability of suitable data for testing, decision regarding number and type of tests to be carried out, photogrammetric tasks for which test may be carried out, and many other considerations (El-Ashmawy, 1999; El-Ashmawy & Azmi, 2003).

After the completion of the development stages, the software was subjected to a series of tests. These tests presented an opportunity to verify that the developed software satisfies general performance requirements, especially with regard to efficiency, flexibility and feasibility of processing the photogrammetric data.

Mathematical photogrammetric data can be advantageously used for testing of photogrammetric methodologies and systems since in this case error free input data and end results are both known (El-Ashmawy, 1999). Testing the developed software, therefore, was carried out by using the mathematically generated blocks of photographs of MATHP software (El-Ashmawy, 1999).

Out of the various mathematical photogrammetric blocks generated, the block having following specifications was used for testing the developed software:

a. Photograph scale: 1:1
b. Camera Format: 230.0 mm × 230.0 mm
c. Camera focal length: 150.00 mm
d. Longitudinal and Lateral overlaps: 65% and 30% respectively
e. Total number of points available per model: 18
f. Terrain configuration: hilly type with height variation of 25% of the flying height.

Six different block sizes were generated. The size of the blocks ranged from one model to a size of 5 strips each of 5 photographs.

For comparing the results of the proposed method, PHOTOMAP software (El-Ashmawy, 1999) was used. PHOTOMAP can be used for bundle block adjustment and its mathematical foundation is based on the collinearity equations with adding constraints to the control points coordinates.

The objectives set for this testing phase were:

– Testing the system error; and
– Testing the feasibility of the proposed method.

3.1. Testing the system error

Photogrammetric block adjustment involves extensive computations and the various steps of which are subjected to computational system error. System error consists of two parts (El-Ashmawy, 1999). The first part of this error is due to rounding off of values during intermediate computations. This part of error may be minimised by using double precision computations as far as possible. The second part of the system error occurs due to truncation of higher order terms while forming the linearized observation equations from the non linear condition equations.

To reduce the effect of the number and location of the measured distances during the testing phase of the system error, all distances between control points were used as measured distances. The block size was 5 strips each of five photographs. In this case, the block contained 55 and 110 control and check points respectively and hence the measured and check distances are 1485 and 12045 respectively.

In order to ascertain the accuracy of the results, the root mean square error (RMSE) was computed using the well known formulation:

$$RMSE = \sqrt{\sum_{i=1}^{n}(\text{known or actual value} - \text{computed value})_i^2 / n}. \quad (14)$$

The RMSE values for check distances have been obtained. The results showed that the maximum RMSE value is 0.0001 μm, at photo scale 1:1, which is negligible. From above, it is seen that the developed software is free from system error and that it is functional.

3.2. Testing the feasibility of the proposed method

The objectives of this testing phase were:

– Studying the effect of the LST solution on block adjustment, and

– Studying the effect of the random errors on block adjustment.

Simulated data with random errors was used and generated as following:

– Generating error free photogrammetric data of blocks of different sizes using MATHP software as explained earlier.

– Generating normally distributed error(s) with arbitrary mean(s) and standard deviation(s) as presented in (El-Ashmawy & Azmi, 2003). The obtained errors were then applied to the error free photo coordinates and ground coordinates of control points of the generated blocks. The configurations of the used blocks are shown in Table 1.

The distances and their standard deviations were computed from:

$$S_{PQ} = \sqrt{(X_Q - X_P)^2 + (Y_Q - Y_P)^2 + (Z_Q - Z_P)^2}. \quad (15)$$

The standard deviation of the measured distance ($\sigma_{S_{PQ}}$) can be computed using the theory of error propagation (Mikhail, 1976) as:

$$\sigma_{S_{PQ}} = ((\frac{\partial S_{PQ}}{\partial X_Q} \times \sigma_{X_Q})^2 + (\frac{\partial S_{PQ}}{\partial Y_Q} \times \sigma_{Y_Q})^2 + (\frac{\partial S_{PQ}}{\partial Z_Q} \times \sigma_{Z_Q})^2 + (\frac{\partial S_{PQ}}{\partial X_P} \times \sigma_{X_P})^2 + (\frac{\partial S_{PQ}}{\partial Y_P} \times \sigma_{Y_P})^2 + (\frac{\partial S_{PQ}}{\partial Z_P} \times \sigma_{Z_P})^2)^{1/2}, \quad (16)$$

where: S_{PQ_m} is the measured distance between points P and Q; $\frac{\partial S_{PQ}}{\partial X_Q}, \ldots, \frac{\partial S_{PQ}}{\partial Z_P}$ are the partial derivatives and their values are available in (Mikhail, 1976); $X_Q, \ldots, Z_P$ are object space coordinates of points Q and P respectively; and $\sigma_{X_Q}, \ldots, \sigma_{Z_P}$ are the standard deviations of object space coordinates of points Q and P respectively

Table 1. The configurations for mathematical photogrammetric blocks of photographs

Block Title	Block Size			Ground Points		No. of Image Points	Random Errors (μm)*											
							Photo Coordinates			Ground Coordinates of Control Points								
										X			Y			Z		
	No. of Strips	No. of Photos/Strip	No. of Photos/block	Control Points	Check Points		Range	Standard Deviation	Mean	Range	Standard Deviation	Mean	Range	Standard Deviation	Mean	Range	Standard Deviation	Mean
1Model	1	2	2	6	12	36	+/−8	3.47	0.0	+/−3	2.16	0.0	+/−4	2.38	0.0	+/−5	3.56	0.0
1Strip	1	5	5	15	30	117	+/−9	3.27	0.0	+/−8	2.71	0.53	+/−5	2.84	0.27	+/−7	3.86	0.0
2Strips	2	5	10	25	50	234	+/−11	3.51	0.0	+/−5	2.56	0.16	+/−7	3.02	0.12	+/−8	3.82	−0.08
3Strips	3	5	15	35	70	351	+/−11	3.35	0.0	+/−7	2.77	0.06	+/−7	2.95	0.06	+/−8	3.58	0.17
4Strips	4	5	20	45	90	468	+/−11	3.26	0.0	+/−6	2.55	−0.13	+/−7	3.19	−0.04	+/−8	3.46	−0.02
5Strips	5	5	25	55	110	585	+/−11	3.26	0.0	+/−7	2.75	0.04	+/−7	3.36	0.02	+/−8	3.44	−0.04

* Values at photo scale 1:1

3.3. Studying the effect of the LST solution on block adjustment

The aim of this test was comparing the results of obtaining the relative 3D coordinates of points of two cases:

- without using LST solution as described in Sections 2.1, 2.2 and 2.3, and
- using *LST* solution.

For each case, values of RMSE and maximum absolute error (MAE) were computed for the check distances and tabulated in Table 2.

From Table 2, the following conclusions can be drawn:

- The derived mathematical model is suitable for bundle block adjustment for a block of photographs of any size.
- The results of block adjustment using LST solution are much better than the results without using LST solution.
- Furthermore, using LST solution has many advantages such as weighting of observations, generating the necessary statistical data for blunder detection and quality control assessment.

3.4. Studying the effect of the random errors on block adjustment

Bundle block adjustments using the proposed method and PHOTOMAP software were performed to adjust the available blocks and the results, in the form of standard deviation of unit weight ($\hat{\sigma}_o$) and RMSE and MAE values at check distances, were obtained and tabulated in Table 3.

From Table 3, the following conclusions can be obtained:

- There is no significant difference between the a posterior standard deviation ($\hat{\sigma}_o$) and the a priori standard deviation (σ_o) and hence that the correct simulation assumptions and block adjustment have been achieved.
- The results of bundle block adjustment using the proposed method are much better than the results of the conventional block adjustment. This is due to stronger geometry when processing lines than discrete points. The limitation of using the proposed method may be the large number of the measured distances.

4. Applications of the proposed method for aerial and close range photogrammetry

The proposed method should be able to be applied both in aerial and close- range photogrammetry. The first experiment was designed to test the ability while applying to aerial photographs. A pair of stereo photographs of Canton de Vaud, Switzerland was taken by Wild Avioplot RC10 Automatic Camera System of Echallens of wide

Table 2. Results of block adjustment with and without *LST* solution

Block Size	Control Points	Measured Distances	Check Distances	Values in (μm)*			
				With *LST* Solution		Without *LST* Solution	
				RMSE	*MAE*	*RMSE*	*MAE*
Model	6	15	138	6.30	22.55	7.50	24.12
1 Strip	15	105	885	6.10	20.13	9.70	30.27
2 Strip	25	300	2475	4.20	16.18	9.30	33.65
3 Strip	35	595	4865	4.50	25.49	10.20	35.73
4 Strip	45	990	8055	4.10	20.04	10.50	42.38
5 Strip	55	1485	12045	4.30	17.89	15.00	59.74

* Values at photo scale 1:1

Table 3. The results of bundle block adjustment

Block Size	Control Points	Measured Distances	Check Distances	σ_o	Values in (μm)*					
					Proposed Method			*PHOTOMAP* Software		
					$\hat{\sigma}_o$	RMSE	MAE	$\hat{\sigma}_o$	RMSE	MAE
Model	6	15	138	1.00	1.02	6.30	22.55	0.93	7.50	24.12
1 Strip	15	105	885	1.00	0.93	6.10	20.13	1.04	9.70	30.27
2 Strip	25	300	2475	1.00	0.88	4.20	16.18	1.00	9.30	33.65
3 Strip	35	595	4865	1.00	0.93	4.50	25.49	1.03	10.20	35.73
4 Strip	45	990	8055	1.00	0.94	4.10	20.04	1.01	10.50	42.38
5 Strip	55	1485	12045	1.00	0.92	4.30	17.89	0.98	15.00	59.74

* Values at photo scale 1:1

angle coverage on a 23× 23 cm format at 620 m height with focal length 153.18 mm lens, as a result, the average photo scale is about 1:4300. The camera calibration data e.g. calibrated focal lens, calibrated fiducial marks and radial lens distortion are available (El-Ashmawy, 1999). The area contains 16 well-distributed and identified control points. The control point numbers, ground coordinates and standard errors are also available.

The coordinate measurement of image points was carried out on the stereo comparator of Aviolyt BC2, Leica, Switzerland, having a least count of 1μm. Two iterations were made in pointing on the fiducial and control points to eliminate the possibility of blunders and improving the precision of observations (El-Ashmawy, 1999).

The second experiment was designed to test the performance of the proposed method in close- range photogrammetry. The available photogrammetric data in Appendix C of (Ghosh, 2005) was used in this test. Four overlapped photographs were taken by a camera with focal length 49.15 mm lens and 1 m apart from the object. The object consisted of eight control points. The object space coordinates of control points, image coordinates of points and camera interior orientation parameters are also available.

Tables 4 and 5 list the results of the two experiments in the form of RMSE and MAE of all distances. From these tables, the following conclusions can be drawn:

- The proposed method is not only capable for aerial images but also for close-range images;
- The proposed method can be used when one distance only is measured rather than three control points in the conventional block adjustment;
- Increasing the number of the measured distances improves the obtained accuracy; and
- The results of the proposed method, even using number of measured distances similar the number of control points, are comparable or better than the results of bundle block adjustments using control points;

Discussion and conclusions

In this paper a simple method for close range and aerial photogrammetry applications has been developed. Unlike the conventional bundle block adjustment, the proposed

Table 4. The results of the proposed method compared to conventional method (case of aerial photogrammetry)

Number of Control Points	Number of All Distances	*PHOTOMAP* Software		Proposed Method		
		Values in (m)		Number of Measured Distances	Values in (m)	
		RMSE	*MAE*		*RMSE*	*MAE*
2	120	–	–	1	0.0999	0.2894
3	120	0.0917	0.2232	3	0.0909	0.1874
6	120	0.0907	0.2130	15	0.0868	0.2197
				6	0.0872	0.2328
9	120	0.0905	0.2275	36	0.0862	0.2237
				9	0.0898	0.2543
12	120	0.0909	0.2349	66	0.0874	0.2436
				12	0.0868	0.2217
16	120	0.0903	0.2350	120	0.0824	0.2302
				16	0.0864	0.2201

Table 5. The results of the proposed method compared to conventional method (case of close range photogrammetry)

Number of control points	Number of All Distances	*PHOTOMAP* software		Proposed Method		
		Values in (m)		Number of Measured Distances	Values in (m)	
		RMSE	*MAE*		*RMSE*	*MAE*
2	28	–	–	1	0.0006	0.00111
3	28	0.0005	0.00118	3	0.0005	0.00105
4	28	0.0005	0.00109	6	0.0005	0.00105
				4	0.0005	0.00104
6	28	0.0003	0.00100	15	0.0003	0.00096
				6	0.0005	0.00101
8	28	0.0002	0.00035	28	0.0001	0.00030
				8	0.0004	0.00091

method does not need the known object space coordinates of control points but needs measured distance(s) between points. Therefore the proposed method can reduce the survey work, which in most cases is costly and time consuming, to measure only distance(s) between points, which in some applications can be done using tape.

The tests show that the results of the proposed method is comparable or better than the results of conventional bundle block adjustment.

The proposed method, and the software, is suitable for photogrammetrists and non-photogrammetrists in different fields such as in architectural, archaeological, and forensic photogrammetry. Furthermore, it is suitable for some applications of aerial photogrammetry which depend on determination of distances between points such as road length and its width, areas, building dimensions, etc.

The developed software is a helpful tool for archaeologists and architects to make measured drawings of buildings and monuments. With the advent of convergent-line software systems, such as AutoCAD software (Omura & Benton, 2016), features such as 3D viewing, rendering, photo texturing, and multiple formats (DXF, DWG) are available. These features can be used for obtaining final drawings.

This paper shows the necessity for the mathematical photogrammetric data for testing the photogrammetric methods and softwares.

References

El-Ashmawy, K. L. A. (1999). *A cost-effective photogrammetric system for engineering applications* (PhD Thesis). Department of Civil Engineering, University of Roorkee, Roorkee, India.

El-Ashmawy, K. L. A., & Azmi, M. (2003). Photogrammetric simultaneous and self calibration block adjustments using coplanarity condition. *Engineering Research Journal*, Faculty of Engineering, University of Helwan, Egypt, *87*, 85-101.

Ghosh, S. K. (2005). *Fundamentals of computational photogrammetry*. Concept Publishing Company, New Delhi, India.

Gneeniss, A. S., Mills, J. P., Miller, P. E. (2015). In-flight photogrammetric camera calibration and validation via complementary lidar. *ISPRS Journal of Photogrammetry and Remote Sensing*, *100*, 3-13. https://doi.org/10.1016/j.isprsjprs.2014.04.019

Jacobsen, K. (1997). Operational block adjustment without control points. *Proceedings of ASPRS Annual Convention*. Seattle, U.S.A.

Jacobsen, K. (1999). Combined bundle block adjustment with attitude data. *Proceedings of ASPRS Annual Convention*. Portland.

James, M. R., Robson, S., d'Oleire-Oltmanns, S., & Niethammer, U. (2017). Optimising UAV topographic surveys processed with structure-from-motion: Ground control quality, quantity and bundle adjustment. *Geomorphology*, *280*, 51-66. https://doi.org/10.1016/j.geomorph.2016.11.021

Malik, D. S. (2010). *Data structures using C++* (2nd ed.). Cengage Learing, Inc., USA.

Moffitt, F. H., & Mikhail, E. M. (1980). *Photogrammetry* (3rd ed.). Harper and Row Publishers, Inc., New York, N. Y.

Mikhail, E. M. (1976). *Observations and least squares*. Iep-A Dun-Donnelly Publishers, New York, U.S.A.

Omura, G., & Benton, B. (2016). *Mastering AutoCAD® 2017 and AutoCAD LT® 2017*. John Wiley & Sons, Inc, USA. https://doi.org/10.1002/9781119415510

Rupnik, E., Nex, F., Toschi, I., & Remondino, F. (2015). Aerial multi-camera systems: accuracy and block triangulation issues. *ISPRS Journal of Photogrammetry and Remote Sensing*, *101*, 233-246. https://doi.org/10.1016/j.isprsjprs.2014.12.020

Shi, J., Yuan, X., Cai, Y., & Wang, G. (2017). GPS real-time precise point positioning for aerial triangulation. *GPS Solutions*, *21*(2), 405-414. https://doi.org/10.1007/s10291-016-0532-2

Van Den Heuvel, F. A. (2000). Trends in CAD-Based Photogrammetric Measurement. *Proceedings of the XLX ISPRS Congress*, Vol. XXXIII-B5 of International Archives of Photogrammetry and Remote Sensing (pp. 852-863), Amsterdam.

Zhang, Y., Zheng, M., Xiong, X., & Xiong, J. (2015). Multistrip bundle block adjustment of ZY-3 satellite imagery by rigorous sensor model without ground control point. *IEEE Geoscience and Remote Sensing Letters*, *12*(4).

Zhou, G., & Deren, L. (2001). CAD-Based object reconstruction using line photogrammetry for direct interaction between GEMS and a Vision system. *Photogrammetric Engineering and Remote Sensing*, *67*(1), 107-116.