EVALUATION OF GEOMETRICAL ACCURACY IN DISPLACEMENT MONITORING OF ENGINEERING STRUCTURES USING CLOSE-RANGE PHOTOGRAMMETRY

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ABSTRACT:

Almost every part of the earth's surface and even man-made structures are subject to variations of size, shape and position with time. The period of these changes differs from case to case depending on the individual characteristics of the deformable body.
The determination and sometimes interpretation of these movements is the objective of deformation surveys. Photogrammetric methods are suitable for monitoring displacements, because a photograph represents a remote, complete and instantaneous record of an object. An instantaneous record of particular situation which may be changing in time, together with a complete coverage, is most appropriate for a phenomenon such as a moving object.
Here, rotary kiln in Abyek cement factory has been chosen for study. The main purpose of monitoring these kilns is to determine the displacement of the centre of the kiln in the place of rollers. On the other hand, we want to monitor the displacement of the kiln in order to avoid dangers due to horizontal and vertical movements. Close-Range photogrammetric technique was chosen to carry out this research.
The results according to the ground coordinate of the check points, accuracy derived from variance-covariance matrix and computing the displacements for four points instead of one point, are acceptable and mm accuracy for determining the coordinates shows that this method is suitable for monitoring studies, especially for specific cases like this case which popular geodetic methods are not applicable due to high temperature of the kiln area.

1. INTRODUCTION

Almost every part of the earth's surface and even man-made structures are subject to variations of size, shape and position with time. The period of these changes differs from case to case depending on the individual characteristics of the deformable body. The determination and sometimes also the interpretation of these movements is the objective of deformation surveys.
Usually, for monitoring purposes the entire deformable body is represented by a number of properly distributed discrete points called detail points. Under certain circumstances, forces applied either by the surrounding matter or by direct contact or by gravity cause the body to alter position and shape. The determination of these changes can be carried out by monitoring the position of the detail points with respect to a reference system at time intervals depending on the frequency and rate of motion.

2. EXPRESSIONS OF DISPLACEMENTS

The position of a detail point **P** with respect to a Cartesian coordinate system may be defined in terms of magnitude (length) and direction of the radius vector **p** , That is, the position vector **OP = p** (Figure 1) and it is determined as :

$$p = xi + yj + zk \tag{1}$$

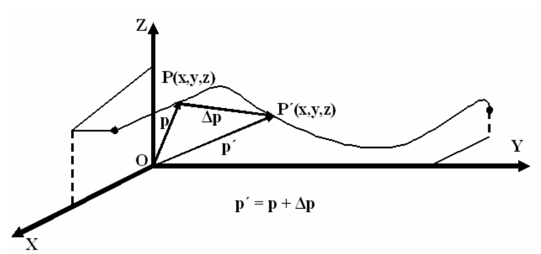

Figure 1. Position vectors p and p´ and displacement vector Δp

A general displacement is expressed as the difference of the coordinates between the two positions of point P. Thus,

$$\Delta p = OP' - OP = (x'-x \;\; y'-y \;\; z'-z)^T = (\delta x \;\; \delta y \;\; \delta z)^T \tag{2}$$

3. METHODS OF DISPLACEMENTS MONITORING

The aim of the monitoring campaign is to determine the magnitude and the direction of motion of the detail points representing the object. There are three major factors upon which the selection of a measuring method highly depends:

- magnitude of displacements
- frequency (rate) of movements
- accuracy requirements

Methods of displacement monitoring is graphically shown in figure 2.

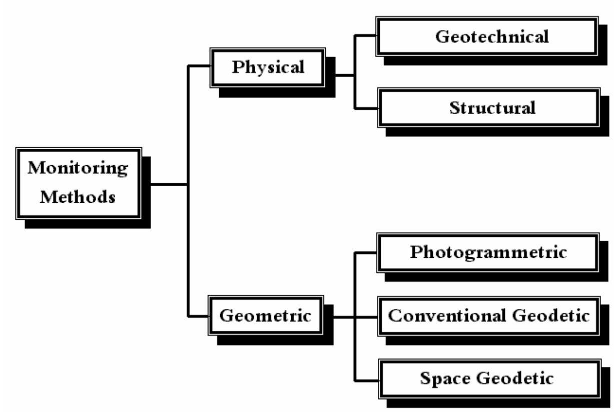

Figure 2. Methods for monitoring displacements (Armenakis, C. 1987)

Physical methods are used to measure - usually unidimensional -relative displacements using various linear mechanical instruments in contact with the object. Geometric methods are capable of monitoring both relative and absolute movements with respect to a given reference datum. Depending on the design criteria, these methods range from photogrammetric approaches to conventional- and satellite geodesy techniques.
The selection of a particular method is a matter of design considerations to obtain an optimal monitoring scheme.
The type of monitoring networks affects the analysis of the results. There are two types of geometric monitoring networks: absolute and relative (Chrzanowski et al., 1981). If the detail points are connected to stable (reference) points outside the deformable body; then we have a so-called absolute or reference network. The main concern in this kind of geometric network is the affirmative verification of the stability of the reference points. If however, the limits of the deformation effects are vague,then, all points are subject to movements. This type of geometric network is called a relative or object network. The main problems here are the identification of the deformation model and the definition of the reference datum.

3.1 Photogrammetry as a monitoring method

Photogrammetric methods are suitable for monitoring displacements, because a photograph represents a remote, complete and instantaneous record of an object. An instantaneous record of particular situation which may be changing in time, together with a complete coverage, is most appropriate for a phenomenon such as a moving object.
As a non-contact monitoring method, photogrammetry can safely measure inaccessible or dangerous areas as well as objects in hostile environments. The data acquisition time ranges from short to instantaneous, thus allowing the capture of even high frequency displacements because all points are recorded simultaneously.
As far as the accuracy is concerned, sub-centimetre (with aerial photogrammetry; Fraser and Stoliker, 1983) and sub-millimeter (with close-range photogrammetry; Brown, 1980; Fraser and Brown, 1986) accuracies are achievable.

4. CASE STUDY

To evaluate the photogrammetric method, for displacement monitoring, rotary kilns in Abyek cement factory (Ghazvin provience, Iran) have been chosen for study. The main purpose of monitoring these kilns is to determine the displacement of the center of the kiln in the place of rollers. On the other hand we want to monitor the displacement of the kiln in order to avoid dangers because of the horizontal and vertical movements. Two epochs were chosen for observation, once before changing the bricks of the kiln and the other, after changing the bricks of the kiln,14 days later.
Here, it is necessary to describe the elementary rules and informations about maintenance technology and monitoring the displacements, by close-range photogrammetric method .

4.1 Rotary Kiln Maintenance Technology- Kiln Monitoring

A complete understanding of the mechanical condition of a kiln is required to effectively schedule repair work. One of the best ways to reach this understanding is through a monitoring analysis. This operation must be performed every six months.
Kiln Mechanical Analysis, performed on a kiln in its normal operating condition, has been proven reliable and completely accurate in every application, but as a research, close –range photogrammetry method is tested.

4.2 Design Aspects of Photogrammetric Monitoring Network

The significant aspect of optimal design for a photogrammetric monitoring network is underlined. This enables us to set the requirements for the observations in order to estimate the unknown parameters and achieve the desired accuracy within reasonable cost limits. The widely accepted classification scheme of these problems is (Grafarend, 1974):
- Zero-order design (ZOD) problem. It is concerned with the optimal definition of the reference datum. The zero-order design problem will be solved here,by determining the datum and having base point in a reference coordinate system.
- First-order design (FOD) problem. It is concerned with the optimal configuration of the network. The first-order design problem is significant for a photogrammetric monitoring network. The configuration problem is characterized by a given weight matrix of the observations and an ideal of desired variance-covariance matrix of the estimated parameters and pursues an optimal design matrix. The photogrammetric aspects which have to be examined in order to solve this optimization problem are those which affect the formulation and structure of the design sub matrices. These are:
● Intersection of optical rays at the object points
● Number of camera stations
● Number of photographs on which a point appears (overlap)
● Base-to-object distance
● Focal length in each image
● Additional parameters for interior orientation
● Density and distribution of detail- and of control points
● Target clusters
● Multi-control constraints
- Second-order design (SOD) problem. It is concerned with the optimal designation of weights to the observations. For the second-order design the following parameters contribute to the improvement of the weight matrix of the observations:
● Images of high photographic quality
● Size, shape, and reflectance properties of targets
● Multiple exposures from each camera station

● Multiple measurements of image points

- Third-order design (TOD) problem. It is concerned with the optimal improvement of a network if extra points or observations are added to it. For the photogrammetric monitoring networks the third-order design problem can generally be reduced and solved for as the configuration problem (FOD).At the beginning, the proper functions have to be derived expressing each criterion and their subsequent optimization has to be performed under certain constraints. The latter is solved either directly or by trial and error procedures (Vanicek and Krakiwsky, 1986).Now all of these steps in this project, will be described completely.

4.2.1 Network designing : In each photogrammetric project, it is necessary to design a network for stations of photography, so that we can retrieve accurate and homogeneous measurements.

4.2.2 Choosing the camera : Usually in geomatic projects, specially in photogrammetric projects, available facilities, make us not to choose what we want .in choosing the camera, according to the area: kilns with high temperature that will affect the analogue images by making film distortion and the benefits of using digital, we choose digital camera (canon PowerShot Pro90 IS) among two available camera in our faculty.

The specifications of the camera are shown in table 1:

Focal length	7-70mm
Camera Type	Point and Shoot
Digital Zoom	40x
Disk Media Type	Compact Flash
Film Type	Digital
Flash	Yes
Port Capability	USB
Storage Capacity (MB)	128 MB
Type	Digital
Horizontal Resolution	180 dpi
Vertical Resolution	180 dpi
Width	1856 pixel
Height	1392 pixel
Geometry of photography	An instantaneous photograph saved in CCD

Table 1. Specifications of the Canon-powershot camera

4.2.3 Calibration of the camera : For using the camera, it is necessary to determine the accuracy of the camera, resolution and calibration parameters in order to design the suitable places for stations.

In this project, self calibration method is chosen and it is being tried to solve all camera parameters during the self-calibration procedure. The calibration parameters of the camera are:

● Interior orientation parameters of the camera (x,y,c,k),k approximately equals with 1.

● Additional Parameters:

● Radial Lens Distortions

$$drx=(K1r^2 + K2r^4 + K3r^6)(x-x0) \quad (3)$$
$$dry=(K1r^2 + K2r^4 + K3r^6)(y-y0)$$

● Decentring Lens Distortions

$$dpx = P1[r^2 + 2(x-x0)^2] + 2P2(x-x0)(y-y0) \quad (4)$$
$$dpy = P2[r^2 + 2(y-y0)^2] + 2P1(x-x0)(y-y0)$$

The computed calibration parameters are listed in the tables 2 and 3.

Photo	K1	K2	K3
1	0.00000412	-0.00007854	0.00003401
2	-0.00000731	0.00002158	0.00002581
3	0.0001191	-0.0001238	-0.000126
4	-0.00007115	-0.00005585	0.00003187
5	0.00000804	-0.00000595	0.0000045
6	-0.00002009	0.00000499	0.00002091
Photo	P1		P2
1	0.00007934		-0.00008645
2	0.00000593		0.00002565
3	0.00041021		-0.0001165
4	0.00004621		-0.0001121
5	-0.0000031		-0.00000236
6	0.00001248		-0.00002505
Photo	X	y	c
1	0.00000371	-0.00007068	0.007
2	-0.00000658	0.00001942	0.007
3	0.00010719	-0.0001114	0.006
4	-0.00006403	-0.00005027	0.07
5	0.00000723	-0.00000535	0.07
6	-0.00001808	0.00000449	0.05

Table 2. Computed additional parameters in first epoch of observation

Photo	K1	K2	K3
1	0.00026327	-0.0003996	0.00030621
2	0.00008132	-0.001143	0.0009769
3	-0.0001142	-0.0001598	0.00015805
4	-0.001208	0.00037847	0.0013068
5	-0.0006625	-0.0008283	-0.0007716
Photo	P1		P2
1	0.00050801		-0.0001042
2	0.00028369		0.0007428
3	-0.00009303		0.00000806
4	0.00040703		-0.001371
5	0.00073331		-0.0001635
Photo	x	y	c
1	0.00023694	-0.0003596	0.07
2	0.00007319	-0.001029	0.06
3	-0.0001028	-0.0001438	0.06
4	-0.001087	0.00034062	0.05
5	-0.0005962	-0.0007454	0.04

Table 3. Computed additional parameters in second epoch of observation

4.2.4 Determining number and position of stations for camera : Depending on the imaging geometry adopted, the use of additional stations for camera can be expected not only to improve precision, but also to significantly enhance the network's reliability. According to the geometry of the kiln and limitations due to the work place, the angles of beams and number of stations were determined, and also according to the higher geometric stability, homogeneity of accuracy in 3 axes(X,Y,Z)(Fraser,Brown,1986) and less depth error (Hommainejad, 1997, 1998),it is better to use convergence system than stereo pairs. Limitations in work place, and the geometry of the object, restrict the angle of convergency, therefore we could use the camera stations with around 40 degree of convergency. Because of the rough nature of the area, only 5 places were suitable for shooting and taking photographs and at least 9 control points and all of the unknown points on the kiln can be observed in each picture .The generic scheme of photography stations is shown in figure 3.

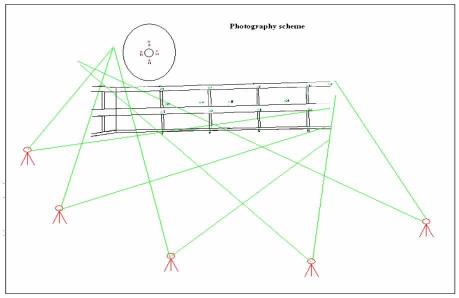

Figure 3. Scheme of five stations for photography

With the focal length of 7-70mm at the distance of 10-20m the scale of photography differs between 1/1400 for three pictures and 1/140 and 1/280 for the others according to the focal lengths computed and shown in the tables 2 and 3.

4.2.5 Targets' designing : Shape of the targets on the kiln is shown in figure 4:

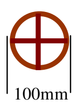

Figure 4. Shape of the targets

We chose the circular form because of its homogeneity and also independency of measurements in directions and the cross in the middle of the circle helps us to target it easily with theodolites, and accordingly calculate the coordinates of the centre of the circle, with surveying methods. The size of the targets depends on the resolution and due to the high resolution of the pictures, perfect specifications of the camera that is shown in table 1 and a test photography that is performed before the project in the same distances, the radius of the target was selected: 50 mm.

Because of the high temperature and the rough shell in the place of targets, we decided to draw the targets by colour through a designed shablon.

According to the resolution of the camera, the size of each pixel on the images, equals to 0.14mm, so with considering the scale of photographs (1/150, 1/300, 1/1500) and zooming availability in computer this size of targets was suitable. A sample image is shown in figure 5.

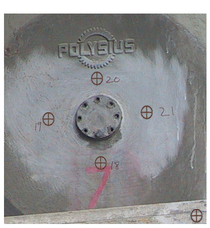

Figure 5. A sample image

4.2.6 Designing control points places : In bundle adjustments of well-designed photogrammetric networks, the number of object points has surprisingly great impact on the mean standard error (Fraser, 1984). Due to this practical dependency of object point precision and the number of target points, network that is planned to include points can be examined and optimized at designing stage by considering **17** well-distributed targets. This leads to considerable savings in the computations.

Whereas the accuracy attained in a standard bundle adjustment is significantly influenced by the number of target points, the precision yielded in a self-calibration adjustment is considerably affected by both the density and the distribution of the object points.

For designing points and satisfying project goals, it was necessary to select stable points while roller is rotating, to be assured of their fixed position during kiln movements. So, it was necessary to have fixed control points on the kiln. It is better to have an absolute monitoring system. For having an absolute displacement monitoring system, two base points are established in the area with high stability by steel bolts which have great resistancy against environmental conditions. Distance and direction observations between these two base points are measured by the most accurate instruments available. Distances are measured by ME5000 mecometer with (0.2mm+0.2ppm) accuracy and directions are measured by T2002 with (0.5") accuracy. For considering temperature and pressure corrections on the distances, temperature measurements with 1°c accuracy and pressure measurements with 3 mbar accuracy were performed.

After establishment two base points, direction observations from these two base point to 17 control point on the object were performed in 4 couples and the ground coordinates of the control points were calculated by intersection method . Position of the two base points and control points is shown in figure 6.

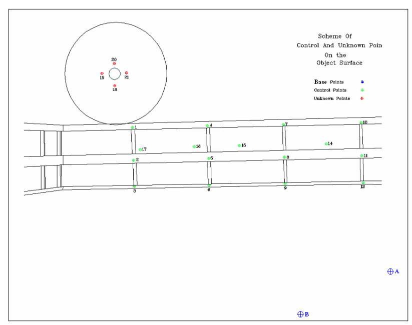

Figure 6. Position of the two base point and control points

Vertical and horizontal angles from two base points to 17 control points were observed. According to the 0.5" accuracy of the T2002 instrument the expected accuracy for control points coordinates was 0.5 mm.The ground coordinates of the control points were calculated by intersection method. After writing a program for calculating the ground coordinates of control points on the object, the results retrieved.

4.2.7 Location and number of unknown targets : Since main goal of this project is to present capability of close-range photogrammetry for monitoring and measuring point movements in a structure, a suitable layout of points on the structure was selected.

One of the capabilities of Close-range photogrammetry is to determine any movement of points on the structure. Therefore, four points with a descent density were marked on the kiln. All these points were involved in computation of camera parameters and the amount of displacements and directions of displacements were determined.

Because of the quality of the object (a solid mass), mean value of computed displacements for four points on the object can be considered as displacement of the roller.

For having control on the results, the coordinates of unknown points were calculated independently by direct geodetic method.

4.2.8 Pixel Size and Resolution : The size of the object which is imaged on a single CCD element is dependent on the optical properties of the sensor and on the actual size of the CCD. In this project, CCD system with a fixed locus contains arrays of 1856*1392 CCDs with 180 dpi resolution for images, each element is 0.14mm and, with the focal length of 7-70mm at the distance of 10-20m the sizes of 19.6mm,39.2 mm and 196mm on the object is recorded. This size is known as the instantaneous field of view (IFOV) and in many cases, corresponds to the area on the object covered by a single element of the image.

4.3 Photographic data acquisition

After taking photos according to network design and preparing images, it was needed to extract information of these photos **.**
Photos that were taken in the area, are imported in the photomode photogrammetric work station and the 2D coordinate of each control point was determined. According to the pixel size (0.14 mm) and 8x zoom availability in photomod system, it was possible to centre in each target point with the accuracy about 0.002 mm.

4.4 Data processing

All image coordinate of control points and unknown points were used as input for the software "Self Calibration" and adjustment calculating were applied in "photo variant" mode(Fiag and Amer, 1996).
Self calibration bundle adjustment computations were used once for first epoch of observation and once for second observation. After that, the displacement of desired points, are calculated. In these computations unknown parameters were:
- External orientation and calibration parameters of the camera
- Unknown points coordinate

Result of calculations are shown in tables 4,5,6,7 and 8.

Point	dX(m)	dY(m)	dZ(m)
18	+0.0015203	+0.0033874	+0.0001556
19	+0.0017333	+0.0040771	+0.0001910
20	+0.001582	+0.004541	+0.0002130
21	+0.00138	+0.0039733	+0.0001861

Table 4. The Displacements Computed between Two epochs of Observations

By statistical analysis of the results, the accuracy value from variance-covariance matrix is retrieved:

	SX(mm)	SY(mm)	SZ(mm)
Average	0.99	0.98	0.90

Table 5. Average value of accuracies for Computed Coordinates by Close-range Method In First Observation

	SX(mm)	SY(mm)	SZ(mm)
Average	0.97	0.96	1.00

Table 6. Average value of accuracies for Computed Coordinates by Close-range Method In second Observation

To have a control on the accuracies of the computation, the ground coordinate of unknown points, were calculated, and the differences between results were computed. As can be seen in tables 7 and 8, there is an acceptable difference between the adjusted coordinates of these four points by geodetic method, and photogrammetric method, and also the difference along X-axis, Y-axis and Z-axis in both of the epochs for all of the four points are similar.

Point	dX(m)	dY(m)	dZ(m)
18	0.0027153	0.0018019	0.0013975
19	0.0027198	0.0017883	0.0013975
20	0.0027243	0.0017883	0.0013975
21	0.0027198	0.0017746	0.0013975

Table 7. difference between Computed Coordinates by Close-range method and Ground Coordinates Obtained by Geodetic Method In First Observation epoch

Point	dX(m)	dY(m)	dZ(m)
18	0.0016901	0.0019948	0.0088388
19	0.0016901	0.0019948	0.0088388
20	0.0016901	0.0019948	0.0088388
21	0.0016901	0.0020009	0.0089758

Table 8. difference between Computed Coordinates by Close-range method and Ground Coordinates Obtained by Geodetic Method In Second Observation epoch (14 days later)

The displacement along X-axis represents the horizontal displacement that shows the amount of distance that rollers must be moved toward each other or against each other.
The displacement along Y-axis represents the vertical displacement that shows the amount value of misalignment of the kiln.
The displacement along Z-axis represents the amount of displacement of the two rollers along the kiln. It must be very small, and if the value of this component becomes greater than 1 mm, it is too dangerous and safety operation must be done. On the other hand, the displacement along Z-axis shows a great trouble in the kiln and shell profile must be prepared.

For realizing the results, it has been tried to represent the displacement values for the unknown points in figure 7.

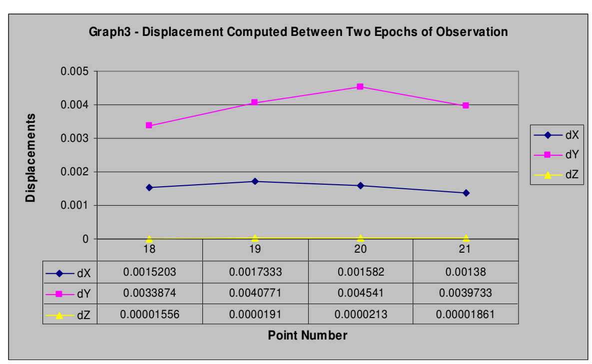

Figure7. Displacement computed between two epochs of observation

5. CONCLUSIONS

Monitoring movements of natural or man-made environments over time is one of the most important contributions of the geomatic engineering profession to society.

Photogrammetry has been selected as the geometric monitoring method in this study. On the other hand, we have tried to show the capability of close range photogrammetric method for monitoring analysis, in this project. The proper design of a monitoring network, considering the peculiarity of the photogrammetric factors, renders the results to be within preset specifications.

The method that is being used on-stream, is a relative method. In relative methods the displacements of the rollers are measured relatively and there isn't any constant and base point for having control on displacements from the designing step, we think in this method, it is possible in each observation step and measuring the displacements relatively and adjusting the rollers with the displacements that are being measured, a major distance from designing step occurs.

On the other hand, using an absolute method to retrieve the displacements of rollers from stable and constant points looks more suitable. Because of this suggestion, it seems to be more suitable if we use geomatic methods for displacement among different methods. Close-range photogrammetry as one of the geomatic methods for monitoring the movements is a fast, economical and practical approach. The benefits of this approach compared to the classic geodetic methods, is the less cost and the less time.

The Kiln Monitoring Analysis is an excellent preventive maintenance tool. Problems will be discovered before they become emergencies. Discovering problems early will allow more accurate budget planning and scheduling of shutdowns to achieve maximum efficiency.

In this case(monitoring the rotary kiln position), the calculated movements, are given to the bolts of the kiln in the place of rollers and any error in calculating of the displacements may cause a disaster and may cause a breaking in the bell of the kiln. So it is advisable to establish a correct geometry in photography design, to get better accuracies. Metric cameras are more suitable in this project and we had a metric camera in our university, but we had a problem that was the analogue nature of the camera. The camera couldn't be used in this study, because the high temperature of the area may cause a great deformation in the film, and may produce wrong conclusion.

As can be seen in the results, the results according to the ground coordinate of the unknown points, accuracy from variance-covariance matrix and computing the displacements for four points instead of one point, are acceptable.

Close range photogrammetry method can be used for monitoring any displacement in these sizes such as the displacement of the kiln in the place of rollers. Due to the following reasons, the close range method looks suitable:

- A photograph represents a remote, complete and instantaneous record of an object.
- By measuring the photographic images of the detail points we can obtain reliable information about the status of the object
- This method can be done in our country without need for foreign experts.
- This method is very economic.
- It is an absolute method, and the movements can be measured according to the constant points. So the possibility of being far from the designing step will be decreased.

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