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The analysis process of robotic total station data to determine structural deformations

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ABSTRACT

Monitoring structural deformations and taking measures for building safety are considered almost synonymous with important concepts such as human health, public safety and prevention of economic losses. For this reason, new structural monitoring application techniques are being developed in parallel with the developments in building construction technologies and architecture. In particular, GNSS satellite-based measurement systems have found wide application areas for determining structural oscillations and deformations. In addition, the direction of the studies in this field has focused on lower cost and more practical measurement systems. One of the alternative measurement devices used for this purpose is angle and distance measurements with the classical total station. Total stations, which have been automated and gained robotic features in recent years, are easily used in the determination of the most critical structural monitoring and deformations with their programmable structure. In this study, angle-distance measurements performed with a robotic total station at a simultaneous and constant sampling interval for 6 hours were processed and analyzed. Coordinate values and position errors were calculated by balancing according to the least-squares method for each measuring range. Structural displacement values were determined from the coordinate values calculated as a function of time.

1. INTRODUCTION

In structural monitoring, electronic theodolites (ET) or total stations (TS) are commonly used to calculate the time-dependent changes of Cartesian coordinates of observation points. These instruments are the most basic geodetic measuring instruments used in engineering measurements and scientific studies. Firstly, with the development of electronic theodolites, TSs emerged and later with automatized Robotic total stations (RTS), which allow new generation robotic measurements, have found a wide area of use (Schofield and Breach 2007).

RTS or Robotic theodolites are a modern version of TS. In sampling intervals determined according to the features of the program used, RTS can direct itself to the target point, make measurements and record. Nowadays, by programming RTSs, it has been reached the level of observing with a sampling interval of 5-10 Hz and monitoring moving reflectors. Because of these advantages, it is widely used in many surveying and other engineering projects (Psimoulis and Stiros 2008; Psimoulis and Stiros 2011; Moschas et al. 2012; Lienarth et al. 2016). In addition to general engineering research, it can also be used in more scientific experiments to record oscillations with a high frequency greater than 1 Hz and small amplitude (a few mm). With this capacity, RTS can also be used for monitoring large engineering structures under the influence of wind or traffic load (Pehlivan 2009).

In this study; horizontal angle, vertical angle and oblique distance measurements were carried out in order to model the building movements by using a robotic featured total station from the control points located at long distances. Post-process and instant data were analyzed in order to determine the changes (structural deformations) in the positions of the monitoring points, and the details in the data analysis were examined.

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2. MEASUREMENTS WITH TOTAL STATION

The RTS sends laser light to the prism mounted on the observed structure and can record the horizontal distance and the horizontal and zenith angles values using the round trip time of the returning light. Each observation record can be converted into coordinate values and its change over time helps us calculate the direction and trace of motion. Under normal atmospheric conditions, be making angle measurements with 0.5' and distance measurements with 1mm + 1ppm accuracy allows us to determine the position with 1mm accuracy. Repeated measurements at regular intervals defined by a total station with automatic target recognition (ATR) system; It automatically performs the process of guiding to the target point, measuring and recording, as programmed. The speed of this automated measurement and recording process is directly proportional to the sampling rate of the measurement process (Psimoulis and Stiros 2011; Moschas et al. 2012; Pehlivan et al. 2013)

Distance and angle values from the observation point to the points to be measured can be measured automatically at certain intervals with RTS. Modern RTSs can measure the angle value with 0.5^{cc}. While angle measurements in the range of $5\text{-}10^{cc}$ can be performed with normal total stations, precise distance measurements can be performed with an accuracy of 0.1 mm and normal distance measurements with an accuracy of 1 mm. With this sampling range and measurement accuracy, RTS will continue to maintain its place as an indispensable measuring instrument in many engineering works as well as in many SHM (Structural Health Monitoring) works (Pehlivan 2019).

3. DATA PROCESSING STRATEGY IN DETERMINE STRUCTURAL DEFORMATIONS

Different data processing strategies can be used depending on the expected type of movement in structural motion tracking studies. If slow deformation is expected at a constant rate, the data can be processed in static sessions from a few hours to several days, generally assuming no movement during the session. If the building movement or deformation in question does not pose an imminent threat to the structure or its surroundings or people living in the area, this is usually done after the procedure (Pehlivan 2009).

However, if the movement expected from the structure is expected to be "sudden deformation" for a short period of time and/or "continuous deformation" changes over time, the sampling interval should be increased accordingly. If the deformation could cause the deformed body to fail, a real-time solution is desired to detect the deformation as soon as it occurs and initiate the warning and evacuation processes. In the test study of this work, structural deformations are expected to have a slow character. In normal weather conditions, while the movement is slow, increasing impact loads such as temperature, wind, etc. will cause an increasing effect on the building movements. For these reasons, it is thought that in monitoring the constant and regular motion expected in normal atmospheric conditions, performing our observations with a few minutes sampling interval of RTS measurements will give us the opportunity to capture the expected movements. However, over a relatively short period of time, it can be preferred as a solution in real-time monitoring to detect movements of the structure.

3.1. Determining the Coordinates of the Monitored Point with the Least Squares Method

The linear-angular intersection method has been used in order to determine the accuracy of the coordinates to be determined by the angle-distance measurements performed with the total station to the Observation Point (Prism P) and to benefit from the advantages of the least-squares method (Ehigiator et al. 2010; Okwuashi et al. 2014). In the test measurements, four observations so two distances and two angular directions were carried out with the automated total station instrument from two fixed station points. With an angular-linear intersection, the number of observations is greater than the unknown, so the least-squares method can be used to determine the coordinates of the 3rd point (Figure 1.).

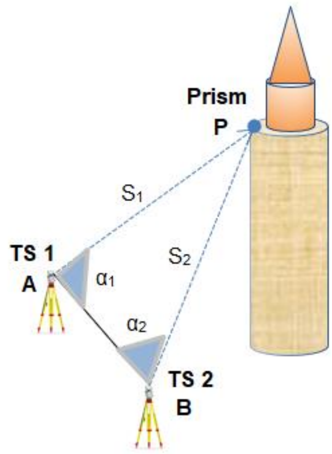

Figure 1. Test measurements and the geometry of angular-linear intersection.

The weight of all measurements performed was assumed to be equal (W = I). Observations were made to Prism point with two total stations installed and levelled at TS1 and TS2 points. Horizontal and vertical angle values and oblique length values were recorded in equal time intervals for six hours. Vertical angles and oblique length measurements and horizontal distances S_1 and S_2 were calculated. Horizontal angles α_1 and α_2 and horizontal distances S_1 and S_2 measurements were obtained as time series for each measurement interval. Using these data, the coordinates of the Prism point were be determined by observations made from TS1 and TS2. Balancing of the calculated coordinates will be done using the observation equation method. The coordinates of the observed Prism point are (Xp, Yp), the coordinates of the fixed station points TS1 and TS2 are (X_A, Y_A) and (X_B, Y_B), respectively.

The adjustment will be carried out in this case by using the observation equation method. In this adjustment model (observational least square), the number of equations is equal to the number of observations (n=4), each equation contains one observation and one or more unknowns. In this case, observations are (S_1, S_2, α_1, α_2) and unknowns (Xp, Yp). The two lengths (S_1, S_2) of the lines in the horizontal projection can be written in a coordinate form as follows:

$$S_1 = \sqrt{(X_P - X_A)^2 + (Y_P - Y_A)^2}$$
$$S_2 = \sqrt{(X_P - X_B)^2 + (Y_P - Y_B)^2} \qquad (1)$$

The horizontal angles (α_1 and α_2) from figure 1 can be calculated as follows:

$$\alpha_1 = cos^{-1}\left(\frac{\overline{AP}^2 + \overline{AB}^2 - \overline{PB}^2}{2\,\overline{AP}\,\overline{AB}}\right)$$
$$\alpha_2 = cos^{-1}\left(\frac{\overline{BA}^2 + \overline{BP}^2 - \overline{AP}^2}{2\,\overline{BA}\,\overline{BP}}\right) \qquad (2)$$

Using the coordinates of the points, we can write equations 2 as follows:

$$\alpha_1 = cos^{-1}\left[\frac{(X_P - X_A)^2 + (Y_P - Y_A)^2 + AB^2 - (X_P - X_B)^2 + (Y_P - Y_B)^2}{2\,AB\,\sqrt{(X_P - X_A)^2 + (Y_P - Y_A)^2}}\right] \qquad (3)$$
$$\alpha_2 = cos^{-1}\left[\frac{(X_P - X_B)^2 + (Y_P - Y_B)^2 + \overline{AB}^2 - (X_P - X_A)^2 + (Y_P - Y_A)^2}{2\,\overline{AB}\,\sqrt{(X_P - X_B)^2 + (Y_P - Y_B)^2}}\right]$$

The four observational equations given in equations 1 and 3 are nonlinear functions of both parameters and observations; they can be processed by the least-squares adjustment technique. Before starting the solution, approximate values of unknown parameters are calculated. Approximate values of the coordinates of the P point are calculated using the angular intersection according to the following formulas (Ehigiator et al., 2010):

$$X_P^0 = \frac{X_A \cot\alpha_2 + X_B \cot\alpha_1 - Y_A + Y_B}{\cot\alpha_1 + \cot\alpha_2}$$
$$Y_P^0 = \frac{Y_A \cot\alpha_2 + Y_B \cot\alpha_1 - X_A + X_B}{\cot\alpha_1 + \cot\alpha_2} \qquad (4)$$

Using these X_P and Y_P values, the approximate values of the observation equations (Lo) are calculated. Then the misclosure vector (L) is calculated as:

$$L = L^0 - L_{abs} \qquad (5)$$

We can express the linearized model in matrix form as follows:

$$V_{4\times1} = A_{4\times2} \cdot X_{2\times1} + L_{4\times1} \qquad (6)$$

Where, A: The coefficients matrix of parameters, L: The misclosure vector, V: The residuals vector. Matrix A may be computed by differentiation of the four equations with respect to the two unknowns and can be written in the form:

$$A_{(4\times2)} = \begin{bmatrix} \frac{\partial S_1}{\partial X_P} & \frac{\partial S_1}{\partial Y_P} \\ \frac{\partial S_2}{\partial X_P} & \frac{\partial S_2}{\partial Y_P} \\ \frac{\partial \alpha_1}{\partial X_P} & \frac{\partial \alpha_1}{\partial Y_P} \\ \frac{\partial \alpha_2}{\partial X_P} & \frac{\partial \alpha_2}{\partial Y_P} \end{bmatrix} \qquad (7)$$

With the Matlab program, the elements of the matrix A (a_{ij}) can be found by differentiating the four observation equations. Then the normal equation system using the Matlab program can be solved.

The positional error at point P can be computed using the following equation (Allan 1988):

$$M_P = \frac{b\, m_\alpha^{"}}{\rho^{"} \sin\gamma}\sqrt{sin^2_{\alpha_1} + sin^2_{\alpha_2}} \qquad (8)$$

Where; b: Base line (the distance between total stations) (b=AB in fig. 1); m_α^{cc}: Mean square error of measuring horizontal angles (taken from specifications of the using total stations); ρ^{cc}=206265, γ: The horizontal angle at point P.

In order to accept the observations of the point P from the triangle ABP and its adjusted coordinates to be sufficiently accurate, the coordinates must satisfy the following condition (Ashraf 2010).

$$r_P = \sqrt{\Delta_X + \Delta_Y} \leq 3\,M_t \qquad (9)$$

Where;

$$\Delta_X = X_i^P - X_k^P\ ,\ \Delta_Y = Y_i^P - Y_k^P \text{ ve } M = \sqrt{M_i^2 - M_k^2}\ ,$$

X_i^P , Y_k^P: The adjusted coordinates of the point P at the time i of measurement; X_j^P, Y_k^P: The adjusted coordinates of the point P at the time k of the measurement; M_i, M_k: The position errors of the point P at time i and k (Ashraf 2010).

4. EVALUATION OF EXPERIMENTAL TESTS RESULTS

As seen in Figure 1; From the fixed station points (TS1 and TS2), observations were made to the P observation point every 2 minutes and the data sets (2 edges and 2 angle values) were recorded as a function of time. Each observation data set was analyzed within itself and it was aimed to determine the change of total displacement with respect to time by creating 30-minute observation sets. For this purpose, the balanced coordinate values and position errors of the P observation point for each half-hour time between 11:00 and 17:00 were calculated using the MATLAB program. And also, the positional errors (M_p) at point P was calculated by equation (8) for each adjusting time. The position errors for each epoch are approximately equal to each other, as they depend on approximately the same parameters. The results are presented in Table 1 below.

Table 1. The adjusted coordinates and position errors of the observed point

Time	x	y	M_p
11:00	914.90597	449.46749	2.4791642
11:30	914.90584	449.46670	2.4791642
12:00	914.90571	449.46591	2.4791642
12:30	914.90545	449.46434	2.4791642
13:00	914.90532	449.46355	2.4791642
13:30	914.90507	449.46197	2.4791642
14.00	914.90480	449.46122	2.4791642
14:30	914.90467	449.46045	2.4791641
15:00	914.90391	449.45903	2.4791638
15:30	914.90433	449.45824	2.4791642
16:00	914.90421	449.45745	2.4791642
16:30	914.90395	449.45587	2.4791642
17:00	914.90382	449.45508	2.4791642

Table 2. The displacement changes of the observed point

Time	Δx (mm)	Δy (mm)	dn (mm)	pn (mm)
11:30	-0.12938	-0.78940	0.80	3.51
12:00	-0.12938	-0.78940	0.80	3.51
12:30	-0.25877	-1.57881	1.60	3.51
13:00	-0.12938	-0.78940	0.80	3.51
13:30	-0.25876	-1.57881	1.60	3.51
14.00	-0.26506	-0.74507	0.80	3.51
14:30	-0.12735	-0.77701	0.79	3.51
15:00	-0.76594	-1.41306	1.61	3.51
15:30	0.42666	-0.79438	0.90	3.51
16:00	-0.12938	-0.78940	0.80	3.51
16:30	-0.25876	-1.57881	1.60	3.51
17:00	-0.12938	-0.78940	0.80	3.51

The adjusted coordinates obtained during the observation period are presented in Table 1. Measurements, which started at 11 o'clock, were completed at 17:00, and coordinate values were calculated for each 30 minutes. Coordinate differences are calculated for each measurement moment in Table 2. Since the adjusted coordinates of the P point provide equation (9), it is accepted as correct. Accordingly, from the adjusted coordinate differences, the total displacement during the observation period was calculated as 1.29 cm in the X-direction.

5. CONCLUSION

Monitoring structures and determining their deformation characteristics will provide an important prediction for preventing catastrophic events. In addition, taking into account the structural features, the monitoring period and the most appropriate measurement system should be selected and evaluated with the most appropriate analysis methods. Because it is a known fact that incorrect analysis of measurement data prevents some deformations from being noticed. The analysis process of the data recorded with RTS also requires an accurate deformation analysis.

For this purposes; Within the scope of this study, structural monitoring data was recorded with RTS under normal meteorological conditions for 6 hours. The coordinate values balanced by the least-squares method and their mean errors were calculated and the displacement vectors for each measurement instant were calculated. As a result of analysis and evaluation; It was concluded that the movement of the structure was within known and predicted limits and the measurements were made with sufficient accuracy.

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