Improving the accuracy of geometric model to the mark out networks for high-rise buildings

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Abstract. This article describes the various options for using angular and linear-angular triangulation to create the mark out networks on the floors for high-rise buildings construction. A polynomial addition of geometric data is proposed to obtain an estimate of accuracy. The method for estimating the accuracy of geometric constructions using gradients of directions, angles and distances is considered. The numerical example shows the simplicity and high efficiency of this method. The calculations were performed using spreadsheets.

1. Introduction

The program of renovation in construction provides, in particular, the construction or reconstruction of high-rise (up to 75 meters) buildings. The main bearing elements of reinforced concrete structures in-situ of high-rise buildings are columns and floors. At the same time, it is necessary to take-away the axes grid on the floors with two types of geometrical objects – direct corner triangulation and reverse corner triangulation [1].

For this purpose, certain designated targets are installed on the day surface, for example, #1, #2, #3. On the floor, points T1, T2 and so on can be marked (figure 1). Their projections during construction will be located on each floor above this. On the floor, the auxiliary basis D-E of known length is located. Using the direct angle triangulation method the coordinates of the original points 1, 2, 3 in the building coordinate system are determined. Using the reverse corner triangulation, the coordinates of the points T1, T2, and so on are determined. From the known coordinates of the points D and E, using the principle of reduction [2], the points T1 and T2 on the floor are marked.

A method for analyzing the accuracy of the set of corner triangulation using fairly complex formulae is known [3-10]. The time spent associated with the assessment of accuracy significantly exceed the amount of information received in the form of standard deviation mx and my of point T1 in the building's coordinate system. In addition, in the described method, only angular measurements are provided and there is no control over the field measurements and computational operations.

We propose an abbreviated version of the above method of increasing geometric accuracy, providing for control operations. An accuracy estimate is proposed, which allows obtaining information about the errors of the position of the point being determined.

In order to reduce the field measurements it is proposed to use points T1 and T2 as the end points of the D-E basis (figure 2).
2. Proposed method to improve accuracy

At the planned points $T_1$ and $T_2$, six horizontal angles $\beta_1, \beta_2, \ldots, \beta_6$ are measured. By adopting a provisory system (building coordinate system), the coordinates of target points #1, #2, #3 are calculated in this system. We note that in this case, it is not necessary to determine the coordinates of $T_1$ and $T_2$ points, which are already known, by the method of reverse angular intersection. It greatly improves the accuracy of the method.

On the upstream floor, the geometric coordinates of an auxiliary point $T$ located approximately above the point $T_1$ are found using the method of reverse corner triangulation. At the same time, for the control one should measure three angles $\beta_7, \beta_8$ and $\beta_9$ (figure 3, b). The elements of the reduction displace the point $T$ to the design position $T_1$.

Further, by the angle $\beta_1$ and the distance $b$, the point $T_2$ can be taken out, controlling its location with the aid of the angles $\beta_3$ and $\beta_5$. In addition, if we determine the coordinates of the remote point $T_2$ by the method of reverse angular triangulation, then they should be equal to $\theta$ and $b$, respectively. For control, you can use the same method to determine the geometric coordinates of the outside point $T_1$, which should be equal zero.

$\beta_i$ – measured horizontal angles;
$\alpha_i$ – directional angles;
$S_i, D_i$ – distances.

Figure 1. Determining the point $T_1$ on the building floor

Figure 2. The abbreviated schema on the source installation horizon
To assess the accuracy of the described method, an algorithm for constructing triangulation with angular and linear measurements is proposed.

Measured horizontal angles and distances in our case include vector values, called gradients. A visual representation of the gradients \( q_{\alpha} \) and \( q_{\beta} \) is shown in figure 3. In this figure it can be seen that for the sides with the length \( S_i \), the direction gradients are calculated by the formula

\[
q_{\alpha i} = \rho \frac{S_i}{D_1D_2},
\]

where \( \rho \) is a constant equal to 206265".

The directional angles in this case are chosen as follows: the measured angles \( \beta_2 \), \( \beta_4 \) and \( \beta_5 \) are right in relation to the initial side \( T_1-T_2 \). For the measured angles, the directional angles \( q_{\alpha 2} \), \( q_{\alpha 4} \) and \( q_{\alpha 5} \) will be \( \alpha_{T2-1} \), \( \alpha_{T2-2} \) and \( \alpha_{T3-3} \). The measured angles \( \beta_1 \), \( \beta_3 \) and \( \beta_6 \) will be left in relation to the same side \( T_1-T_2 \). Then the directional angles \( q_{\alpha 1} \), \( q_{\alpha 3} \) and \( q_{\alpha 6} \) will be \( \alpha_{1-T1} \), \( \alpha_{2-T1} \) and \( \alpha_{3-T2} \) (figure 3, a).

![Figure 3. Gradient orientation patterns](image)

If the angles \( \beta_7 \), \( \beta_8 \) and \( \beta_9 \) are measured at point \( T \) (figure 3, b), then the gradients \( q_{\beta 7}, q_{\beta 8} \) and \( q_{\beta 9} \) of these angles can be constructed by defining the modules of the gradients \( q_1, q_2, q_3 \) on the sides of these corners. After that, the resulting points \( a, b \) and \( c \) can be connected. The vector \( ab \) is equal to the gradient \( q_{\beta 7} \), the vector \( bc \) is equal to the gradient \( q_{\beta 8} \), and the vector \( ac \) is the gradient of \( q_{\beta 9} \).

The gradients of angles \( q_{\beta i} \) are calculated by known formulae:

\[
q_{\beta 7} = \sqrt{q_1^2 + q_2^2 - 2q_1q_2\cos\beta_7} = \rho \frac{S_{1-2}}{D_1D_2},
\]

\[
q_{\beta 8} = \sqrt{q_2^2 + q_3^2 - 2q_2q_3\cos\beta_8} = \rho \frac{S_{2-3}}{D_2D_3},
\]

\[
q_{\beta 9} = \sqrt{q_1^2 + q_3^2 - 2q_1q_3\cos\beta_9} = \rho \frac{S_{1-3}}{D_1D_3},
\]

where \( S_{1-2}, S_{2-3} \) and \( S_{1-3} \) are the distances between points 1 and 2, 2 and 3, 1 and 3, respectively, and \( q_1, q_2 \) and \( q_3 \) are gradients of the directions of the edges \( 1-T_1, 2-T_1 \) and \( 3-T_1 \). Gradients are calculated by equation (1).

The directions of the gradients are determined graphically or analytically. However, to calculate them by known methods, it is necessary, in addition to the distance between the source points, to know also the angles at points 1, 2, 3. Let us show by an example from [1] (figure 3, b) a simple way of
simultaneously determining the gradients $q_{\alpha i}$ and $q_{\beta i}$, based on $\alpha_i$ and $S_i$ values. Initial data, triangulation and gradient calculation results are presented in table 1.

The authors have compiled a spreadsheet in which the directional angles and lengths of the triangulation are entered as source data (columns 2 and 3 of table 1).

Table 1. Reference data, gradients of directions and angles

| Directions | $\alpha_i$,° | $S_i$, m | $q_{\alpha}$, $\alpha_{\alpha}$, m | $q_{\beta}$, $\beta_{\beta}$, m | $\Delta\alpha$ | $\Delta\beta$ | $\rho_{\alpha}$ | $\rho_{\beta}$ | $\alpha_{\alpha}^\prime$,° |
|------------|-------------|----------|-------------------------------|-------------------------------|----------------|----------------|-------------|-------------|----------------|     |
| T-1        | 328         | 206.2    | 1.000                         | -0.5300                       | 0.8483         | 0.9362         | 0.2097      | 0.96        | 77.4          |     |
| T-2        | 21          | 182.0    | 1.133                         | 0.4061                        | 1.0580         | -0.5186        | -1.9736     | 2.04        | 194.7         |     |
| T-3        | 187         | 223.6    | 0.922                         | -0.1124                       | -0.9156        | -0.4177        | 1.7639      | 1.81        | 346.7         |     |

Gradient directions $q_{\alpha i} = \rho_{\alpha}''/S_i$ are calculated in the table 1 (column 4). Their projections on the coordinate axis $q_{xi} = q_{\alpha i} \sin(\alpha_i)$, $q_{yi} = q_{\alpha i} \cos(\alpha_i)$ (columns 5 and 6), the projections on the coordinate axis of each gradient $\Delta xi = (q_{yi(i+1)} - q_{yi})$, $\Delta xi = q_{yi(i+1)} - q_{yi}$ (columns 7 and 8), gradient $q_{\beta i} = \sqrt{\Delta_2 y_i + \Delta_2 x_i}$ (column 9), their bearing $\tan(\Delta_y/\Delta_x)$ are calculated too. So we get the direction angle $\gamma_{\alpha_i}$ of gradient $q_{\beta i}$ (column 10). Similar results are obtained by graphical construction.

The values of gradients and their directional angles are used to determine the perimeter $P_{\alpha}$ and the closing line $QZ$ of the polynomial polygon. In the case under consideration, only angular measurements of the perimeter $P_{\alpha}$ of the polygon of each right angle triangulation (figure 3, a), and perimeter $P_{\beta}$ of reverse corner triangulation (figure 3, b) will be equal to:

$$P_{\alpha} = \sum q_{\alpha i}^2, \quad P_{\beta} = \sum q_{\beta i}^2$$

(3)

The line connecting the end and start points of each polygon $QZ$ and its bearing $2\varphi'$ are determined by the formulae given in [2]:

$$(q_x)^2 = (q_x)^2 + (q_y)^2 = [q_{\alpha,B} \sin(2\alpha)]^2 + [q_{\alpha,B} \cos(2\alpha)]^2,$$

(4)

$$2\varphi' = \tan^{-1} \left[ \frac{q_{\beta}}{q_{\alpha}} \right] = \tan^{-1} \left[ \frac{q_{\alpha,B} \sin(2\alpha)}{q_{\alpha,B} \cos(2\alpha)} \right],$$

where $q_x$ and $q_y$ are projections of the vector, $\alpha$ is the directional angle of the gradient $q_{\alpha}$ or $q_{\beta}$ respectively.

The bearing $2\varphi'$ is determined by the sings of $q_x$ and $q_y$. According to these indicators, the directional angle $\varphi$ of the semi-major axis $A$ of the error ellipse is found. The semi-major and semi-minor axes of the ellipse are based on the magnitude of the perimeter $P$ and closing line $q_z$:

$$A = m_{\beta} \sqrt{\frac{2}{P-q_z}}, \quad B = m_{\beta} \sqrt{\frac{2}{P+q_z}},$$

(5)

where $m_{\beta}$ is the standard deviation of the angles.

The accuracy of determining the position of the point $T$ on the floor of the building by the combined method of angular triangulation depends on the accuracy of determining the coordinates of the targets 1, 2, 3 (figure 3, a), and also from precisely the opposite corner triangulation 1-2-3-T (figure 3, b). Here, the most "weak links" are three right angle triangulation 1-T1-T2, 2-T1-T2 and 3-T2-T1-T2. Their geometry has a major impact on the accuracy of determining the coordinates of targets 1, 2, 3 and on the shape and size of the error ellipse of each triangulation. The semi-major axis of the ellipse is always located inside the acute angle of the notch at points 1, 2, 3, being the most "dangerous" direction of the error of the defined point position. In order to determine the degree of
influence of right angle triangulation on the shape and size of the error ellipse, a sign simulation was performed (figure 4).

The model is a sharp triangle $l-T_1-T_2$, in which the edge $T_1-T_2$ was taken to be 50 m, and the directional angle is $90^\circ$. The method of modeling was that the edge of the $l-T_1$ triangle was consistently given values of 100, 200, 300 m at an angle $\beta_1$ equal to 10, 20, 40, 60, 80, 100 and $120^\circ$. The length of the other edge $S_2$ and the angle $\beta_2$ were calculated by the cosine theorem, and the directional angles $\alpha_1$ and $\alpha_2$ of the directions $T_1-I$ and $T_2-I$ are $270^\circ+\beta_1$ and $270^\circ+\beta_2$, respectively. The studies were limited only to the North-Western (NW) quarter of the rectangular coordinate system, since the considered forms of triangles can take place in the North-Eastern (NE), South-Eastern (SE) or South-Western (SW) quarters of this system. The source data of triangulation and the results of the error ellipses calculation are presented in table 2.

A spreadsheet was used in which directional angles and lengths of the triangulation sides were entered as input data (columns 2-5). Direction gradients were calculated using the above formulae (not shown in the table), the sum of the projections of the polygon edges on the $y$- and $x$-axes (columns 7, 8), the end line of the polygon (column 9), the semi-major and semi-minor axes of the ellipse and its orientation (columns 10-12) too. From the bearing $2\varphi'$ we can pass to the directional angle of the ellipse major axis (not shown in the table). All the results of the calculations are presented in the numerator of cells in table 2.

If we restrict ourselves only to angular measurements, then with standard derivation $m_\beta = 5''$ the values of the minor axis of the ellipse $B$ of straight angular triangulation in the range of 100-300 m will be only 2-6 mm, while the values of the semi-major axis $A$ at $S_1 = 100$ m will be 6 - 76 mm, with $S_1 = 200$ m will be 27 - 222 mm, and with $S_1 = 300$ m it will be 61 - 457 mm (see table 2).

These data suggest that it is not possible to reduce the values of the semi-major axis $A$ by improving the geometry of the direct angle triangulation, since the lengths of the triangulation edges are several times longer than the length of the $T_1-T_2$ basis.

By the construction of high-rise buildings, the most effective way to improve the accuracy of triangulation is to perform linear-angle measurements using reflectorless total station theodolite.

To estimate the accuracy of such linear-angular triangulation, it is necessary to establish first the weights of linear $p_s$ and angular $p_\alpha$ measurements. If we take $p_s = 1$, then $p_\alpha = \mu^2/m_{\alpha,\beta}^2$, but if we take $p_\alpha = 1$, then $p_s = \mu^2/m_\alpha^2$, where $\mu$ is the unit weight error. In both cases, we will get the same accuracy assessment results. The edges of the polygon in this case are the values of $p_s$ and $p_\alpha q_\alpha^2$, the orientation of which $p_s$ is carried out at angles $(2\alpha + 180^\circ)$, and $p_\alpha q_\alpha^2$ – at angles $2\alpha$. Now the perimeter of the polygon will be equal to:

$$P = \Sigma p_s + \Sigma p_\alpha q_\alpha^2,$$

(6)
Table 2. Baseline and Accuracy Characteristics straight angular and linear-angular triangulation with \( m_\beta = 5^\circ, m_\Sigma = 3 \text{ mm} \)

| Angle \( \beta_1,^\circ \) | \( S_1, \text{ m} \) | \( S_2, \text{ m} \) | \( \alpha_1,^\circ \) | \( \alpha_2,^\circ \) | \( P_\Sigma ("/\text{mm})^2 \) | \( [q_\Sigma \sin 2\alpha] \) | \( [q_\Sigma \cos 2\alpha] \) | \( q_z \) ("/\text{mm})^2 | \( A \), mm | \( B \), mm | Bearing \( 2\varphi',^\circ \) and their directions |
|-----------------|---------|---------|---------|---------|-----------------|-----------------|-----------------|-----------------|--------|--------|-----------------------------|
| 100             | 149.5   | 100     | 276.7   |         | 6.16            | -1.90           | -5.85           | 6.15            | 76     | 2      | 18.0 SW                      |
| 10              | 200     | 249.4   | 100     | 278.0   | 1.75            | -0.55           | -1.66           | 1.75            | 222    | 4      | 18.4 SW                      |
| 300             | 349.4   | 100     | 278.6   |         | 0.82            | -0.26           | -0.78           | 0.82            | 457    | 6      | 18.8 SW                      |
| 100             | 148.0   | 110     | 283.4   |         | 6.42            | 2.99            | 3.30            | 4.45            | 5      | 2      | 54.9 SW                      |
| 20              | 200     | 247.6   | 110     | 286.0   | 1.76            | -1.05           | -1.40           | 1.75            | 111    | 4      | 36.8 SW                      |
| 300             | 347.4   | 110     | 287.2   |         | 6.43            | 3.50            | 3.06            | 4.65            | 5      | 2      | 37.6 SW                      |
| 100             | 142.0   | 130     | 296.9   |         | 6.36            | -5.89           | -1.98           | 6.22            | 18     | 2      | 49.4 SW                      |
| 40              | 200     | 240.5   | 130     | 302.3   | 1.80            | -1.71           | -0.50           | 1.78            | 56     | 4      | 43.2 SW                      |
| 300             | 339.8   | 130     | 304.6   |         | 6.44            | 4.23            | 2.18            | 4.76            | 6      | 2      | 75.3 SW                      |
| 100             | 132.3   | 150     | 310.9   |         | 6.69            | -6.09           | 1.78            | 6.35            | 12     | 2      | 62.7 NO                      |
| 60              | 200     | 229.1   | 150     | 319.1   | 1.87            | -1.72           | 0.65            | 1.84            | 39     | 4      | 26.1 NW                      |
| 300             | 327.9   | 150     | 322.4   |         | 6.47            | 4.34            | 1.02            | 4.46            | 5      | 2      | 66.9 NW                      |
| 100             | 119.3   | 170     | 325.6   |         | 7.24            | -4.24           | 5.08            | 6.62            | 9      | 2      | 76.7 NO                      |
| 80              | 200     | 214.4   | 170     | 336.7   | 1.99            | -1.04           | 1.64            | 1.94            | 31     | 4      | 57.8 NW                      |
| 300             | 312.6   | 170     | 340.9   |         | 7.59            | -0.80           | -2.43           | 2.56            | 3      | 2      | 18.2 SW                      |
| 100             | 103.7   | 190     | 341.7   |         | 8.21            | -0.90           | 7.17            | 7.23            | 7      | 2      | 89.8 SO                      |
| 120             | 200     | 197.6   | 190     | 355.6   | 2.15            | 0.20            | 2.08            | 2.09            | 27     | 3      | 7.2 NW                       |
| 300             | 295.4   | 190     | 0.4     |         | 7.75            | -1.17           | -2.84           | 3.07            | 3      | 2      | 5.4 NO                       |
| 100             | 86.6    | 210     | 0.0     |         | 9.93            | 3.68            | 7.80            | 8.63            | 6      | 2      | 10.3 NO                      |
| 300             | 278.4   | 210     | 21.1    |         | 1.02            | 0.78            | 0.64            | 1.01            | 64     | 5      | 31.3 NO                      |

The closing line \( q_z \) and its bearing \( 2\varphi' \) are calculated by (4), in which its projections \( q_x \) and \( q_y \) on the axes coordinate are:

\[
(q_x)^2 = [p_x q_x^2 \sin 2\alpha] + [p_x \sin(2\alpha + 180^\circ)]^2,
\]

\[
(q_y)^2 = [p_x q_y^2 \cos 2\alpha] + [p_x \cos(2\alpha + 180^\circ)]^2.
\]

(7)
The results of evaluating the accuracy of linear-angular triangulation are presented in the denominator of each cell, column 6-12 (see table 2).

The data of table 2 convincingly indicate that the most effective way to improve the accuracy of triangulation should be considered as performing linear-angle measurements. Indeed, the values of the semi-major $A$ and semi-minor $B$ of the ellipse in the range of 100–300 m will now be only 2–6 mm and 2–2.5 mm, respectively. At the same time, the geometry of the triangulation has practically no effect on their accuracy.

In the proposed triangulation method, points 1, 2, 3 should be considered as starting points with respect to the point $T$ determined by the method of reverse triangulation. Therefore, the accuracy of the position of this point should be assessed taking into account the errors of the source data. The presence of $A$, $B$ and $\phi$ allows us to recommend for this a polynomial addition of geometric criteria that characterize the accuracy of the position of point $T$ in a graphical or analytical way.

Consider this methodology for assessing the accuracy on the example taken from [1]. The initial data (columns 1, 2, 3, 4) and the results of estimating the accuracy of three straight lines and two reverse angular lines (figure 3) using formulae (1)...(5) with standard derivation $m_\beta = 5''$ are given in [9].

The analytical solution of the polynomial addition of geometric criteria is carried out according to the above formulae, which in this case will look like:

$$P = \left[ (A_i^2 + B_i^2) \right],$$

$$q^2_i = \left[ (A_i^2 - B_i^2) \sin 2\phi_i \right]^2 + \left[ (A_i^2 - B_i^2) \cos 2\phi_i \right]^2,$$

$$2\phi_i = \arctg \frac{[A_i^2 - B_i^2] \sin 2\phi_i}{[A_i^2 - B_i^2] \cos 2\phi_i},$$

$$A = \frac{P + q_i}{2n}, \quad B = \frac{P - q_i}{2n}. \quad (8)$$

The results of the polynomial addition of the four above-mentioned geometric criteria using the equations (8-10) are presented in table 3.

| Points | $A_i$, mm | $B_i$, mm | $2\phi_i$, degree | $q_i$, (sec/mm)$^2$ | $P$, (sec/mm)$^2$ | $2\phi_0$, degree | $A_0$, mm | $B_0$, mm |
|--------|-----------|-----------|-------------------|---------------------|------------------|-------------------|-----------|-----------|
| 1      | 35.3      | 3.7       | 315               |                     |                  |                   |           |           |
| 2      | 35.1      | 3.7       | 2                 | 2641                | 3366             | 356               | 27.4      | 9.5       |
| 3      | 28.4      | 3.5       | 49                |                     |                  |                   |           |           |
| Reverse angle (2) | 6.0 | 2.4 | 42 |                     |                  |                   |           |           |
| Reverse angle (3) | 4.41 | 1.88 | 42 | 2631                | 3347             | 355               | 27.3      | 9.5       |
| 1      | 3.6       | 2.1       | 66.8              |                     |                  |                   |           |           |
| 2      | 3.6       | 2.1       | 115.3             |                     |                  |                   |           |           |
| 3      | 3.4       | 2.1       | 91.0              | 20.41               | 58.89            | 178.9             | 3.1       | 2.2       |
| Reverse angle (2) | 2.3 | 1.7 | 71.7 |                     |                  |                   |           |           |
| Reverse angle (3) | 1.8 | 1.7 | 54 | 18.58               | 56.84            | 179.5             | 3.1       | 2.2       |

Table 3 shows two options for reverse corner triangulation. With polynomial addition, both variants yielded almost identical results (columns 10-12). Thus, the prevailing influence on the accuracy of the position of the point $T$ has the accuracy of determining the coordinates of the original points 1, 2, 3.
3. Conclusion

The data of table 2 and 3 convincingly indicate that the most effective way to improve the accuracy of the combined method should be the performance of linear-angular measurements.

As the examples reviewed showed, the accuracy assessment algorithm is applicable to any single or multiple triangulations. It is distinguished by simplicity, since for its implementation it is only necessary to determine the gradients of the corresponding geometric construction. The simplicity of the method makes it available even for workers who do not have special theoretical training, and the provided control operations ensure the reliability of the results obtained. It allows you to take into account all the observed linear-angular relationships of the point being defined with the reference points.

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