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ORIGINAL PAPER

Research on error accumulation control of three-dimensional adjustment with offset constraint

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Abstract

Background Currently, laser tracker is the primary instrument used to carry out three-dimensional position measurement in accelerator alignment. Theoretically, three-dimensional measuring data processed by three-dimensional adjustment are more rigorous, however, error accumulation is found in practice.

Purpose In order to control error accumulation and further improve the measurement accuracy of accelerator alignment, this research introduces the laser alignment system into the activity of measurement and data processing.

Methods A measurement scheme combining laser tracker and laser alignment system is proposed. To construct the constraint condition, the offset values from the measuring points to the laser straight-line datum were used. To carry out the three-dimensional adjustment with offset constraint, the laser tracker observations were used.

Results A three-dimensional adjustment function model of laser tracker observations is given. The construction method of the constraint equation is researched, and the calculation formulas of the three-dimensional adjustment with offset constraint are derived. A 200 m linac tunnel control network is designed, using simulation measurement method, the measuring data of laser tracker and the offset values from the measuring points to the laser straight-line datum were generated. The simulated data are calculated by the method given in this paper and the result is analyzed.

Conclusion Simulation result shows introducing the laser alignment system into laser tracker measurement and applying the three-dimensional adjustment with offset constraint can effectively suppress the error accumulation caused by long distance move station measurement.

Keywords Accelerator alignment · Error accumulation · Laser alignment system · Laser tracker · Three-dimensional adjustment · Offset constraints · Simulation measurement

Introduction

In order to improve the beam strength and reduce the beam loss, accelerator physics requires higher and higher alignment accuracy of the component position. Currently, the alignment of accelerator components is primarily carried out by using laser tracker [1, 2] and the measuring data are processed by two-dimensional plus one-dimensional adjustment which is carried out in horizontally and vertically separately [3] or by three-dimensional adjustment [4–6]. A laser tracker carries out three-dimensional measurement, theoretically, three-dimensional measuring data processed by three-dimensional adjustment are more rigorous [7], however, error accumulation was found in practice. Along with the measurement length increase, the measuring station number increases, and the three-dimensional adjustment result will deviate from the reasonable values obviously [8].

To control the error accumulation, in large-scale accelerator alignment scheme, the ground network and backbone network are usually used to provide the constraint data for the laser tracker measuring data adjustment [9]. Although this is

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an effective error accumulation control method, because the accuracy of the constraint data provided by the ground network and the backbone network is not high, normally only millimeter or submillimeter level, it can only be used for the large range measurement in which error accumulation is significantly larger than the error of the constraint data. For the small range measurement which error accumulation generally is small, the accuracy of the constraint data is obviously not enough.

The laser alignment system can generate a laser straight-line datum and by measuring the offset of the accelerator component to the straight-line datum, all of the components can be aligned relative to this straight line. The laser alignment system has been used in many accelerators around the world to achieve a high accuracy for the straight-line section alignment. In the American SLAC laboratory, the laser alignment system had been used to achieve a 100 μm accuracy in the two miles long linac alignment [10]. In Germany DESY, 100–200 μm accuracy was achieved by using the laser alignment system in the 570 m straight-line section's alignment of European XFEL [11]. Japan KEKB injection comprises a 132 m and a 500 m straight-line section, using the laser alignment system, the straight-line section's alignment achieved 100 μm accuracy [12]. Shanghai XFEL has developed a laser alignment system for the 400 m length undulator section alignment, their purpose is to achieve 200 μm straightness alignment accuracy [13].

Compared with the control network, the laser alignment system has the advantage of higher accuracy. Its laser straight-line datum can cover a range of hundreds of meters long, in this range, all of the components can be aligned relative to a unified straight-line datum and no error accumulation occurs. The disadvantage of a laser alignment system is its datum is a straight line, using this straight line as a datum, it can only control the transversal and vertical position of a component and cannot control the longitudinal position along the line. So generally, it is only used for the relative position alignment of the straight-line section components and cannot provide the three-dimensional coordinate of a point in the global coordinate system. Accelerator complexes have various layout, including linac, ring, beam transport line and so on, laser alignment system can only meet the requirement of local straightness control but cannot meet the global various layout alignment requirements. Although the accuracy of a control network is relatively low, it has the advantages of easy layout, can cover the whole accelerator facility, can provide the global unified coordinate system for all components, and realize the global unified position control. How to combine these two methods effectively to solve the problem of controlling long distance measurement error accumulation between constrained control points and improving the coordinate measurement accuracy of the measuring points in the global coordinate system is a worthy research direction.

The position of an accelerator component is generally measured by a laser tracker. Although laser tracker is a typical high-precision instrument for large size space measurement, the measuring range of a single station is still very limited. In order to realize the position measurement of all components in the whole accelerator, laser tracker has to carry out a move station measurement, when doing this, it relays on the common points between adjacent stations to transfer spatial position relations and easily produce error accumulation [14]. If a laser alignment system is introduced into the measurement, it will be able to provide a unified datum for the local stations, this unified datum can be applied to constrain the positions and orientations of these stations. Considering the above reasons, in the work of accelerator alignment measurement and data processing, according to the principle of control from global to local, the following strategy can be applied using the constraint control points to realize large range long distance absolute position control, using the laser alignment system to realize local relative position control of the laser tracker measurement, and carry out a three-dimensional adjustment with constraint for the laser tracker observations. By doing these, the purpose of controlling the error accumulation and improving the accuracy and reliability of adjustment will be realized. Next, this paper will introduce the measurement scheme and the three-dimensional adjustment model separately.

Measurement scheme design

In acceleration tunnel along the beam direction, install a laser alignment system as long as possible. For the linac tunnel when the tunnel length is longer than a laser alignment system, the overlap method can be used to install more than one system to realize the extension of the laser alignment system as shown in Fig. 1. For the circular tunnel, the same method can be used that is to install several laser alignment systems by overlap method. The position of the laser alignment system can be installed freely, with no strict position requirement.

There are several measuring boxes in each laser alignment system used to measure the laser beam center. The structure of a measuring box is shown in Fig. 2, there are several fiducials on the surface of the box, inside the box, there is a beam center detector used for measuring the laser beam center position. The position relation between the fiducials and the detector can be determined by fiducialization, then through measuring the fiducials and combining the measurement of the detector, the coordinate of the center point in the beam line can be gotten.

When using a laser tracker to carry out a measurement in tunnel, in each station, besides measuring the general points, two or more measuring boxes of a nearby laser alignment

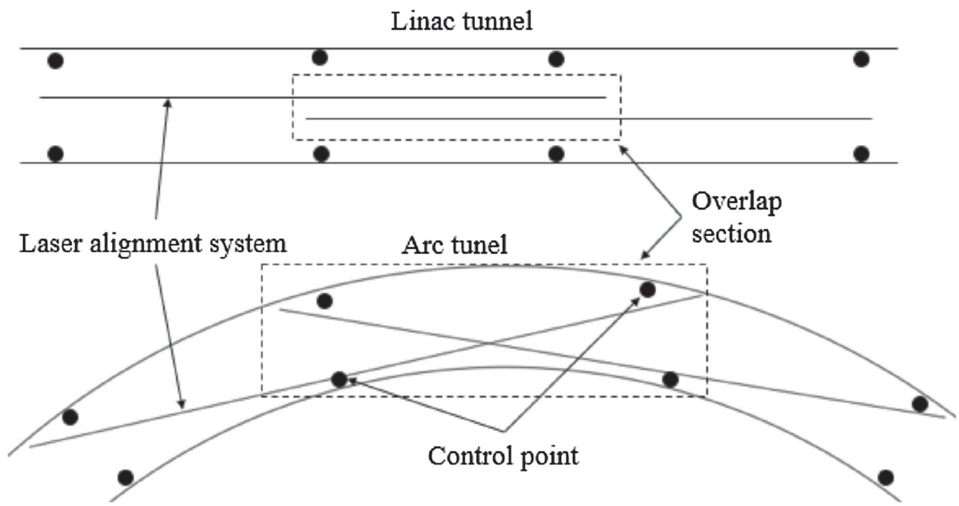

Fig. 1 Layout of laser alignment system

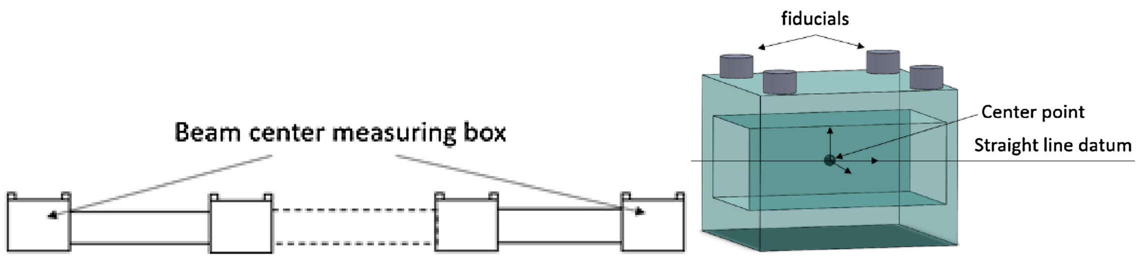

Fig. 2 Beam center measuring box and laser alignment system

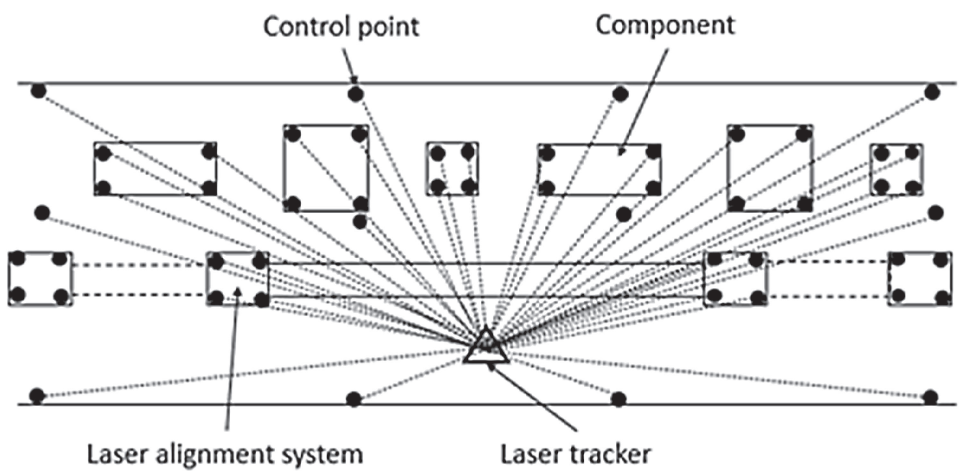

Fig. 3 The combined measurement of laser tracker and laser alignment system

system should also be measured as shown in Fig. 3, then two or more center points of this laser beam line can be gotten. When the station is in the overlap section, the laser tracker should measure two or more center points of each beam line, respectively. Using the center points best-fit a line, then the position of the laser straight-line datum in the measuring station coordinate system can be gotten. According to the point's measuring coordinate, the offset value from the point to the laser straight-line datum can be calculated.

Three-dimensional adjustment with offset constraint model

Based on the laser tracker 3D measuring data adjustment, and adding the offset values from the measuring points to the laser straight-line datum as a constraint condition, a three-dimensional adjustment model with offset constraint will be formed. This model includes two parts, one is the three-dimensional adjustment function model, and the other is the constraint function model, in the following, the construction

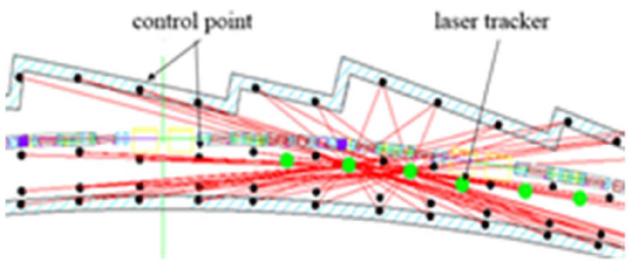

Fig. 4 Laser tracker measurement of the tunnel control network

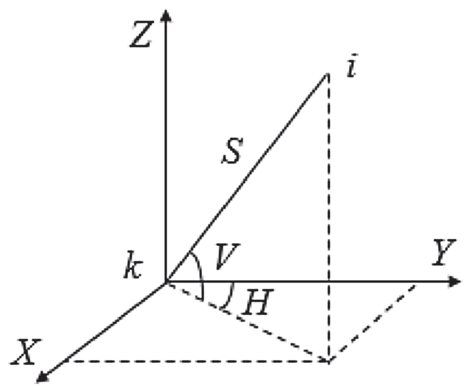

Fig. 5 Laser tracker coordinate measuring principle

method and the related formula deduction of them will be introduced.

Three-dimensional adjustment function model

Take the laser tracker measurement an accelerator tunnel control network as an example to illustrate the construction method of the three-dimensional adjustment model. As shown in Fig. 4, there is a control network which has n control points, using the move station measurement method, a laser tracker measured m stations, and between the adjacent stations, there are several common measuring points. Suppose a control point i which coordinate in the global coordinate system and in the kth station coordinate system is $\left(X_i\ Y_i\ Z_i\right)$ and $\left(X_{ki}\ Y_{ki}\ Z_{ki}\right)$ respectively. The origin of the kth station coordinate system in the global coordinate system is $\left(X_k\ Y_k\ Z_k\right)$. $\boldsymbol{M}$ is the rotation matrix which transforms the global coordinate system to the kth coordinate system and $\left(\theta_{xk}\ \theta_{yk}\ \theta_{zk}\right)$ is the angle parameters of $\boldsymbol{M}$.

Laser tracker applying the spherical coordinate measurement principle, by measuring the horizontal angle H, the vertical angle V and the distance S, the coordinate of control point i in the measuring station coordinate system can be gotten, as shown in Fig. 5.

Then, the following functional relationship can be gotten:

$$\begin{bmatrix} X_{ki} \\ Y_{ki} \\ Z_{ki} \end{bmatrix} = \boldsymbol{M} \begin{bmatrix} X_i - X_k \\ Y_i - Y_k \\ Z_i - Z_k \end{bmatrix} \tag{1}$$

$$\begin{cases} S_{ki} = \sqrt{X_{ki}^2 + Y_{ki}^2 + Z_{ki}^2} \\ H_{ki} = \arctan\left(\frac{X_{ki}}{Y_{ki}}\right) \\ V_{ki} = \arctan\left(\frac{Z_{ki}}{\sqrt{X_{ki}^2 + Y_{ki}^2}}\right) \end{cases} \tag{2}$$

where S_{ki} is the distance from origin k to point i, H_{ki} is the horizontal angle, V_{ki} is the vertical angle.

Taking Eqs. (1) into (2), the observation equation of point i can be gotten, and the parameters to be solved are $\left(X_k\ Y_k\ Z_k\right)$,$\left(\theta_{xk}\ \theta_{yk}\ \theta_{zk}\right)$ and $\left(X_i\ Y_i\ Z_i\right)$.

For the distance, horizontal angle and vertical angle observations of all the stations, the observation equation can be abstracted as $\boldsymbol{L} = f(\overline{\boldsymbol{X}}) + \boldsymbol{\Delta}$, where $\boldsymbol{L}$ is the observation value vector, $\overline{\boldsymbol{X}}$ is the truth value vector of the parameters to be solved in the global coordinate system. $\boldsymbol{\Delta}$ is the error vector of the observations. Suppose $\boldsymbol{X}^0$ is the approximation of $\overline{\boldsymbol{X}}$, let $\overline{\boldsymbol{X}} = \boldsymbol{X}^0 + \overline{\boldsymbol{x}}$, according to the Taylor formula, the linearization result is $\boldsymbol{L} - f(\boldsymbol{X}^0) = \boldsymbol{B}\overline{\boldsymbol{x}} + \boldsymbol{\Delta}$, where $\boldsymbol{B} = \frac{\partial f(X)}{\partial X}\Big|_{X^0}$, then the error equation is

$$\boldsymbol{V} = \boldsymbol{B}\hat{\boldsymbol{x}} - \boldsymbol{l} \tag{3}$$

where $\boldsymbol{V}$ is the observation correction vector, $\boldsymbol{B}$ is the coefficient matrix, $\hat{\boldsymbol{x}}$ is the approximation correction vector of the parameters to be solved, $\boldsymbol{l} = \boldsymbol{L} - f(\boldsymbol{X}^0)$ is the constant vector.

Constraint function model

Suppose there are two points P_1 and P_2 in the laser beam center which are gotten by measuring two measuring boxes of a laser alignment system. Suppose their coordinates in the global coordinate system are $\left(X_{1L}\ Y_{1L}\ Z_{1L}\right)$ and $\left(X_{2L}\ Y_{2L}\ Z_{2L}\right)$, then the equation of the laser straight-line datum in the global coordinate system is

$$\frac{X_L - X_{1L}}{X_{2L} - X_{1L}} = \frac{Y_L - Y_{1L}}{Y_{2L} - Y_{1L}} = \frac{Z_L - Z_{1L}}{Z_{2L} - Z_{1L}} \tag{4}$$

where $\left(X_L\ Y_L\ Z_L\right)$ is the coordinate in the global coordinate system of an arbitrary point in the laser straight-line datum, then the distance equation from a point i to the laser straight-line datum is

$$d_i = \frac{\sqrt{((X_i - X_{1L})(Y_{1L} - Y_{2L}) - (X_{1L} - X_{2L})(Y_i - Y_{1L}))^2 + ((X_i - X_{1L})(Z_{1L} - Z_{2L}) - (X_{1L} - X_{2L})(Z_i - Z_{1L}))^2 + ((Y_i - Y_{1L})(Z_{1L} - Z_{2L}) - (Y_{1L} - Y_{2L})(Z_i - Z_{1L}))^2}}{\sqrt{(X_{1L} - X_{2L})^2 + (Y_{1L} - Y_{2L})^2 + (Z_{1L} - Z_{2L})^2}} + \Delta_{di} \tag{5}$$

where d_i is the offset from a point i to the laser straight-line datum, $\left(X_{1L}\ Y_{1L}\ Z_{1L} \right)$,$\left(X_{2L}\ Y_{2L}\ Z_{2L} \right)$ and $\left(X_i\ Y_i\ Z_i \right)$ are the parameters to be solved, Δ_{di} is the observation error. After linearization, we can get

$$d_i = \boldsymbol{a_i}\left[\hat{x}_{1L}\ \hat{y}_{1L}\ \hat{z}_{1L}\ \hat{x}_{2L}\ \hat{y}_{2L}\ \hat{z}_{2L}\ \hat{x}_i\ \hat{y}_i\ \hat{z}_i \right]^{\mathrm{T}} + \boldsymbol{l'_i} + \Delta_{di} \tag{6}$$

where $\boldsymbol{a_i}$ is a coefficient matrix, $\left[\hat{x}_{1L}\ \hat{y}_{1L}\ \hat{z}_{1L}\ \hat{x}_{2L}\ \hat{y}_{2L}\ \hat{z}_{2L}\ \hat{x}_i\ \hat{y}_i\ \hat{z}_i \right]$ is the approximation correction vector of the parameters to be solved, $\boldsymbol{l'_i}$ is the constant term. For all of the offsets from the measuring points to the laser straight-line datum, the observation equation is

$$\boldsymbol{D} = \boldsymbol{A}\hat{\boldsymbol{x}}' + \boldsymbol{l}' + \boldsymbol{\Delta_D} \tag{7}$$

where $\boldsymbol{D}$ is the offset observation vector $\boldsymbol{D} = \left[d_1\ d_2 \cdots \right]^{\mathrm{T}}$, $\boldsymbol{A}$ is the coefficient matrix, $\boldsymbol{\Delta_D}$ is the observation error vector, $\boldsymbol{l'} = \left[l'_1\ l'_2 \cdots \right]^{\mathrm{T}}$ is the constant vector, $\hat{\boldsymbol{x}'} = \left[\hat{x}_{1L}\ \hat{y}_{1L}\ \hat{z}_{1L}\ \hat{x}_{2L}\ \hat{y}_{2L}\ \hat{z}_{2L}\ \hat{x}_1\ \hat{y}_1\ \hat{z}_1\ \ \hat{x}_2\ \hat{y}_2\ \hat{z}_2 \cdots \right]^{\mathrm{T}}$.

According to the classical indirect adjustment equations, from Eq. (7), the error equation can be derived.

$$\boldsymbol{V_D} = \boldsymbol{A}\hat{\boldsymbol{x}}' - \boldsymbol{l_D} \tag{8}$$

where $\boldsymbol{V_D}$ is the offset observation correction vector, $\boldsymbol{l_D}$ is the constant vector.

Construct the offset constraint equation, the objective is to minimize the quadratic sum of the offset observation corrections in the adjustment: $\boldsymbol{V_D^T V_D} = \min$. According to (8), $\frac{\partial V_D^T V_D}{\partial \hat{x}'} = 2V_D^T \frac{\partial V_D}{\partial \hat{x}'} = 2V_D^T A = 0$ can be derived, and the constraint equation is

$$\boldsymbol{A}^T \boldsymbol{V_D} = 0 \tag{9}$$

For the $\boldsymbol{A}^T$ is usually a nonrow full rank matrix, to meet the later calculation requirement, it should be transformed to a full row rank matrix. Suppose there is an elementary row transformation matrix $\boldsymbol{p}$ and an elementary column transformation matrix $\boldsymbol{q}$, then

$$\boldsymbol{p}A^T\boldsymbol{q}\boldsymbol{q}^{-1}\boldsymbol{V_D} = \begin{bmatrix} \boldsymbol{A}' & \times \\ 0 & 0 \end{bmatrix}\boldsymbol{q}^{-1}\boldsymbol{V_D} = 0 \tag{10}$$

where $\boldsymbol{A'}$ is a full row rank matrix. The p and q can be gotten by the Gaussian all-choice pivot elimination algorithm. Taking the nonzero rows $\left[\boldsymbol{A}'\ \times \right]\boldsymbol{q}^{-1}\boldsymbol{V_D} = 0$ and let $\left[\boldsymbol{A}'\ \times \right]\boldsymbol{q}^{-1} = \boldsymbol{C}'$, then get $\boldsymbol{C}'\boldsymbol{V_D} = \boldsymbol{C}'\boldsymbol{A}\hat{\boldsymbol{x}}' - \boldsymbol{C}'\boldsymbol{l_D} = 0$. Let $\boldsymbol{C}'\boldsymbol{A} = \boldsymbol{C}''$ and $-\boldsymbol{C}'\boldsymbol{l_D} = \boldsymbol{W}''$, the constraint Eq. (9) is transformed to

$$\boldsymbol{C}''\hat{\boldsymbol{x}}' + \boldsymbol{W}'' = 0 \tag{11}$$

where $\hat{\boldsymbol{x}}'$ is a subset of the $\hat{x}$ in Eq. (3), to unify the parameter items, using $\hat{\boldsymbol{x}}$ substitute $\hat{\boldsymbol{x}}'$ and let the elements in $\boldsymbol{C}''$ and $\boldsymbol{W}''$ corresponding to the parameters which are not in the $\hat{\boldsymbol{x}'}$ to be zero, then Eq. (11) can be rewritten as

$$\boldsymbol{C}\hat{\boldsymbol{x}} + \boldsymbol{W} = 0 \tag{12}$$

Combining Eqs. (3) and (12), the adjustment model with offset constraint is

$$\begin{cases} \boldsymbol{V} = \boldsymbol{B}\hat{\boldsymbol{x}} - l \\ \boldsymbol{C}\hat{\boldsymbol{x}} + \boldsymbol{W} = 0 \end{cases} \tag{13}$$

According to the classical indirect adjustment with constraint conditions formulas, the solution of (13) is

$$\hat{\boldsymbol{x}} = \left(\boldsymbol{N}_{BB}^{-1} - \boldsymbol{N}_{BB}^{-1}\boldsymbol{C}^{\mathrm{T}}\boldsymbol{N}_{CC}^{-1}\boldsymbol{C}\boldsymbol{N}_{BB}^{-1} \right)\boldsymbol{W}_l - \boldsymbol{N}_{BB}^{-1}\boldsymbol{C}^T\boldsymbol{N}_{CC}^{-1}\boldsymbol{W} \tag{14}$$

where $\boldsymbol{N}_{BB} = \boldsymbol{B}^T\boldsymbol{P}\boldsymbol{B}$, $\boldsymbol{P}$ is the weight matrix of the observations, $\boldsymbol{N}_{CC} = \boldsymbol{C}\boldsymbol{N}_{BB}^{-1}\boldsymbol{C}^T$, $\boldsymbol{W}_l = \boldsymbol{B}^T\boldsymbol{P}\boldsymbol{l}$.

Simulation analysis

Taking a laser tracker measurement an accelerator control network as an example, the laser tracker observations are

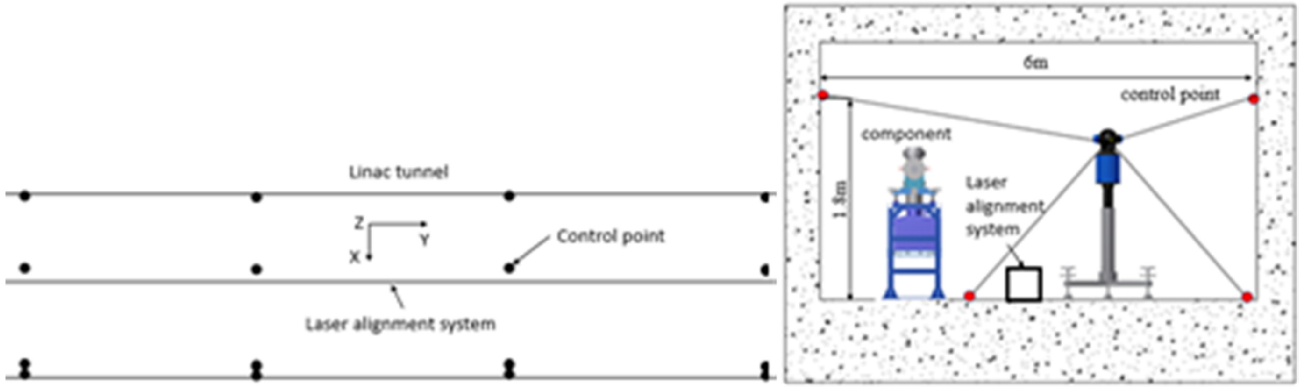

Fig. 6 Tunnel control network

used to do the adjustment and verify the effect of the three-dimensional adjustment with offset constraint. Because in reality measurement, it is always accompanied by measuring errors, so the truth value of the measurement object cannot be gotten. In order to intuitively compare the difference between the adjustment result and the truth value of the control network, the simulation method can be used, that is to compare the difference between the adjustment result and the designed values of the control network.

Design a linac tunnel control network, the XY plane of the control network coordinate system is the horizontal plane, the Y is the beam direction and the Z is the vertical direction. The control network is distributed by sections along the tunnel. In each section, there are four control points as shown in Fig. 6, the distance between the two floor points is 2.5 m, the distance between the two wall points is 6 m, the height of the wall point is 1.8 m. The interval of adjacent sections is 6 m, totally, 34 sections, and the length of the control network is 198 m. Design a 198 m long laser alignment system on the tunnel ground along the beam direction. The coordinates of all control points and the beginning and end point of the laser straight-line datum are designed in the control network coordinate system.

Using a laser tracker to carry out the tunnel control network measurement by move station method, measuring stations are set in the middle of each adjacent section in turn, in total, 33 stations and the coordinates of all the station points in the control network coordinate system are designed. In each station, the three front sections and the three back sections were measured and the nominal observations of distance and angles of each measuring point in the station coordinate system are calculated. The simulated observations of each station were generated by the Monte Carlo method. According to the research of Yang fan [15], Yang zhen [16], Liang jing [17], the measuring precision is set as follows: distance precision 0.015 mm + 2 μm/m, horizontal angle precision 2″, vertical angle precision 3″.

In order to verify the effect of the adjustment model on improving the accuracy of data processing, software was developed based on the adjustment model. The same group of simulated observations was calculated by the three-dimensional adjustment without offset constraint and the three-dimensional adjustment with offset constraint, respectively, and the results were compared with the designed coordinates of the control network. For these two calculations, they all use the XYZ coordinates of a control point which is on the floor near the components in the first section, the Z coordinate of another control point on the floor in the first section and the XZ coordinates of a control point which is on the floor near the components in the 34th section as the known data. Figure 7 shows the XYZ errors of the result calculated by the three-dimensional adjustment without offset constraint compared with the designed coordinates of the control network.

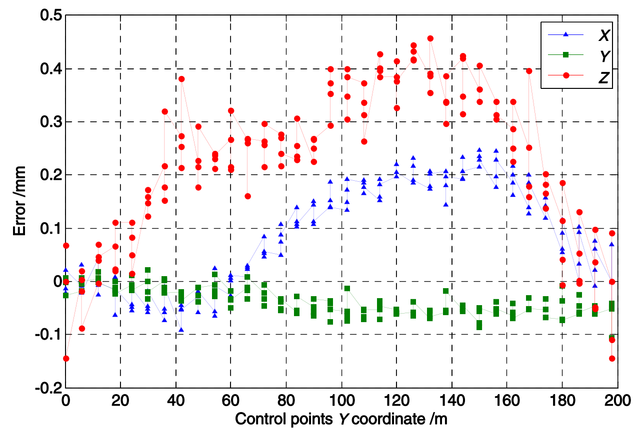

Fig. 7 Adjustment result of the three-dimensional adjustment without offset constraint

It can be found that the error of X coordinates is between − 0.09 and 0.25 mm, the error of Y coordinates is between − 0.11 and 0.02 mm, and the error of Z coordinates is between − 0.15 and 0.46 mm. There are obvious error accumulations in the X and Z adjustment result.

Apply the three-dimensional adjustment with offset constraint method to do the calculation. Firstly, using the

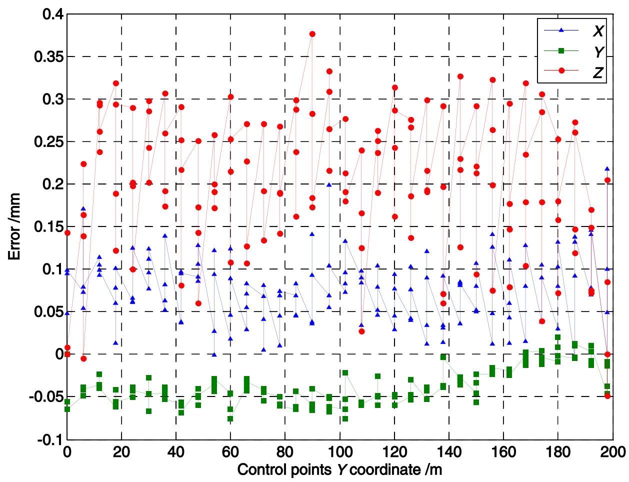

Fig. 8 Adjustment result of the three-dimensional adjustment with offset constraint

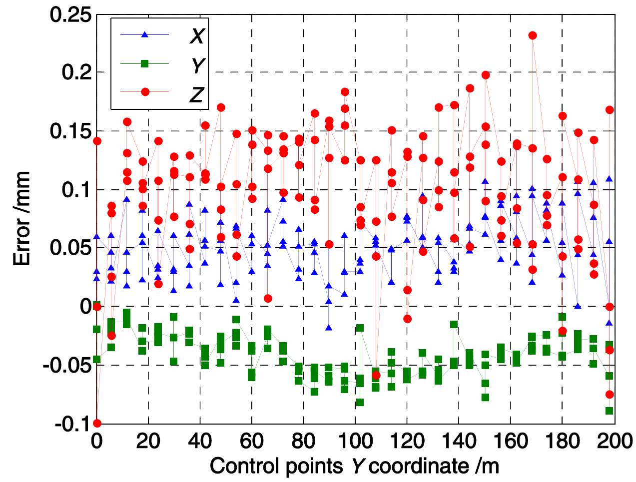

Fig. 9 Adjustment result of using the new offset values

simulated coordinates of all measuring points i ($i = 1,2, \ldots$) of each station to calculate the offset values di which are from the points to the designed laser straight-line datum. Then, according to Eq. (13), to do the adjustment, the result is shown in Fig. 8.

From Fig. 8, it can be found that most of the errors in X direction are between 0 and 0.15 mm, in Y direction are between − 0.07 and 0.02 mm, in Z direction are between 0 and 0.35 mm, and the error accumulation was significantly suppressed. The original large error accumulations in the X and Z direction of the three-dimensional adjustment without offset constraint are changed flatter, and each of the errors is in the form of narrow oscillation along a certain axis parallel to the horizontal axis, they are no longer in the shape of wave curves.

Considering the angle measuring error of a laser tracker will increase the measuring error of a point far away from it, and using the point with big error to calculate the offset will make the offset value error become larger which will decrease the accuracy of the offset constraint data and not good for improving the adjustment accuracy. Therefore, it is changed to only use the control points in the front and back two sections which are closest to the laser tracker to calculate the offset for each station. Using these offset values as constraint to carry out the adjustment, the result is shown in Fig. 9.

It can be found that although the number of offset values used for constraint has been greatly reduced, however, due to the high accuracy of these values, the accuracy of the adjustment result is improved significantly. This shows the accuracy of the offset values is more important than the number of them. From Figs. 8 and 9, it can also be seen none of the XYZ errors oscillate near the zero line, they all occur at different degree of deviation. Considering the constraint

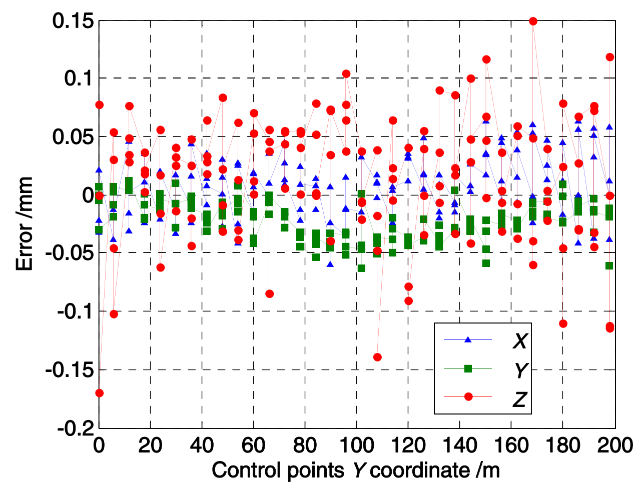

Fig. 10 Adjustment result of using the designed coordinates of the laser straight-line datum as the known data

function of the laser straight-line datum, an experiment that constrains the X and Z coordinates of the beginning and end points of the laser straight-line datum in the adjustment was done. The purpose is to see whether it can let the big X Z error deviation go back to the zero line. The method is to use the X- and Z-designed coordinates of the beginning and end points of the laser straight-line datum as the known data to carry out the three-dimensional adjustment with offset constraint, and the result is shown in Fig. 10.

It can be found that the errors of X and Z of the adjustment result changed to oscillate around the zero line. This shows if the accurate position of the laser straight-line datum in the control network coordinate system can be given, the accuracy of the adjustment result will be further improved.

Conclusion

Introducing the laser alignment system into accelerator alignment measurement and combined with laser tracker, it can give full play to the advantages of the high measuring accuracy of a laser tracker in a small range and the high long-distance relative position control accuracy of a laser alignment system. By carrying out a measurement in this way, it will provide a solution for how to control the error accumulation of the laser tracker move station measurement. Using the offset values from the measuring points to a laser straight-line datum as a link, it will make the measuring stations have a unified straight-line datum in transforming the spatial position relationships beside the common points between adjacent stations, and the offset values only have relation with the local station and the straight-line datum but have no relation with the whole range to be measured. The simulation measuring experiment shows that using the offset values as constraint to do the three-dimensional adjustment can effectively control the error accumulation of laser tracker move station measurement. By testing different numbers and accuracy of offset values as constraints, it shows the accuracy of offset values is more important to the adjustment result, the higher the accuracy of offset values, the higher the accuracy of adjustment results will be. On the contrary, if the accuracy of offset value is low, even if the number of offset values is large, it is not as obvious as a small amount of high-accuracy offset values to improve the accuracy of adjustment. Using the offset values as constraint can effectively control the fluctuation of the adjustment result error and make the error tends to be a narrow oscillation around an axis parallel to the zero line in XYZ directions. The experiment result shows that using the offset values as constraint may let the adjustment result occur a different degree deviation relative to the design value, this deviation is related to the solution of the position of the laser straight-line datum. If the accurate position of the laser straight-line datum in the control network coordinate system can be given in the adjustment, it will greatly eliminate the deviation. How to get the accurate position of the laser straight-line datum in the control network coordinate system needs further study.

The surface control network and backbone control network can realize global and large range position control, the laser alignment system can provide local position control between the constraint points in a relatively small range, this from global to local multiple levels control strategy can provide a solution for improving alignment accuracy of the large accelerator complex.

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