Assessment of uncertainty in laser tracker

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In the field of large-scale measurement, the traceability system is often established to evaluate the accuracy of the measurement. In this study, a traceability method is proposed, where quaternion spatial registration arithmetic is used to transform the measuring values of all other sensors to the coordinate system of laser tracker which is introduced to implement the task of traceability. The results show that the uncertainty of laser tracker is $10\mu m + 0.8\mu m/m$ *. The traceability method presented is qualified for lots of tasks in large-scale metrology.*

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NOMENCLATURE

1. Introduction

Currently, the main instruments and methods for large-scale metrology include laser tracker, photogrammetric system and so on [1]. Due to the difference in precision, the values acquired by various devices and methods are inconsistent. However, for the measurement, the consistence and traceability of the values are necessary [2]. The formal definition of traceability is given in the International Vocabulary of Basic and General Terms in Metrology (VIM 1993) as: "property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparison all having stated uncertainties."[3]

For conventional dimensional measurement, the traceability procedures just need the standard instrument with higher precision, such as gauge block, stop block, ball plate, orifice and standard ruler. However, many problems will come with the application of this idea to large-scale measurements. For one thing, it is difficult to manufacture and carry standard instrument in large-size. For another, instruments for larger-scale measurement such as gantry CMM and measuring network with multi-sensors proposed in this paper, are too large or complicated to locate in the laboratory. What's worse, under the harsh environment, the measurement will be affected by the fluctuation of the temperature. For these reasons, the research of traceability in field is in urgent need. Many institutes and universities have made extensive studies and researches on this topic. The UK's National Measurement Institute (NPL) assesses the performance of the laser tracker and photogrammetry system with a scale bar of three meters [4]. In USA, the National Institute of Standards and Technology (NIST) focuses on the research of calibrating the laser tracker by means of a 60 m laser rail. Tokyo Denki University proposes a calibration method for a coordinate measuring machine (CMM) using a laser tracking system [5]. In China, Beijing Changcheng Institute of Metrology and Measurement develops a large-scale laser plane calibration system which is used as a lab standard to calibrate portable coordinate measuring machines by measuring the target on the plane. Tianjin University seeks to ensure metrological traceability of the results acquired by the car measurement system by the use of theodolites. In this paper, a traceability procedure with a laser tracker is presented to calibrate the large-scale measurement system in field condition.

2. Instrument for Traceability

Before evaluating the other instruments with laser tracker, the performance of the tracker should be assessed [6]. Currently, the only standard suitable for laser tracker is ASME B89.4.19 standard which defines three kinds of tests to be performed: ranging tests, two-face tests, and reference length tests. Generally, every test is repeated three times and the laser tracker passes the tests only when all the values, the maximum results of every test, are below the maximum permissible error (MPE) offered by the manufacture [7].

As is shown in Fig.1, The range tests assess the range measuring capability of the tracker by means of measuring several lengths along a purely radial direction. Through comparing the results with the standard values, the displacement errors are easily obtained.

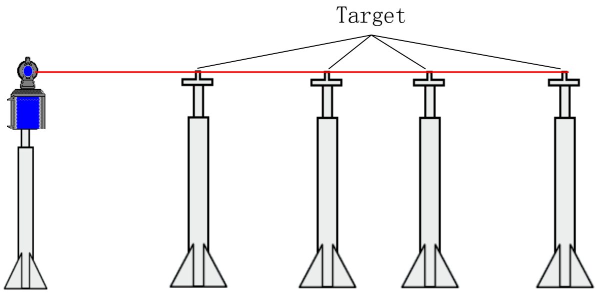

Fig. 1. Performance evaluation of range measurement

The two-face tests involve measuring a fixed target using the front face and then the back face of the tracker after the tracker rotating by 180^{o} about the horizontal and vertical axis, respectively [8]. The deviation between the two values is called back-sight error, which is sensitive to the geometric error sources, so it is of importance for laser tracker and theodolite as well. The Standard requires that, at each distance, the target is located at three different heights: at ground level, at tracker level, and at twice the tracker height. And at each height, the tracker is rotated by 90° about the horizontal axis and the process repeats until all four (0°, 90°, 180° and270°) quadrants of the tracker orientation have been evaluated.

Reference length tests contain a series of measurements which are partitioned according to the orientation of the reference length, for example, horizontal, vertical, and right and left diagonals [9]. Within each orientation group the measurements are further classified by the distance from the tracker to the reference length, which is represented by "D" shown in Fig. 1; the value of D is typically 3 m or 6 m. Similar to the two-face tests, for each orientation the tracker is also rotated about the horizontal axis and the process repeats until all four (0°, 90°, 180° and 270°) quadrants have been evaluated.

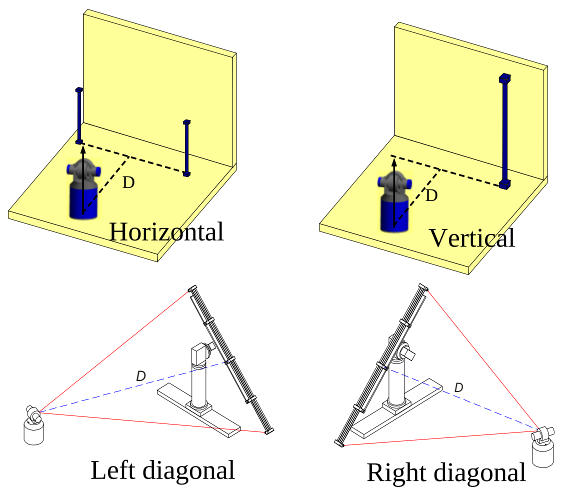

Fig. 1 Performance evaluation of reference length measurement

Having passed the tests, the laser tracker is proved to possess higher precision and can be used to calibrate the measuring system. Comparing the result of the measurement system with that of the tracker, which is considered as the standard value, then the uncertainty of the system will be calculated. After transforming all the data to the global coordinate system, the difference value between the laser tracker and every sensor can be detected and the traceability of the sensors is accomplished.

5. Traceability of the measuring network

Having passed the tests, the laser tracker is proved to possess higher precision and can be used to calibrate the sensors of the measuring network presented in this paper. As is shown in Fig 3, comparing the result of the measurement system with that of the tracker, which is considered as the standard value, then the uncertainty of the system will be calculated.

In the measurement system, each sensor has its own corresponding co ordinate system in which the coordinates of the points observed by it are given. Therefore, it is necessary to transform all the coordinates to the global coordinate system, that is, the coordinate system of the tra cker. In this study, the transformation is implemented by measuring th e common points with all of the sensors and the tracker, then processi ng the data with the formulation shown as equation:

$$F = RM + T$$

Where $R = \begin{pmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{pmatrix}$ is the orthogonal rotation matrix and the nine parameters are the functions of the rotation angles: α, β and γ; T is the translation vector; $\mathrm{F} = (x_w, y_w, z_w)^T$ is the data of the common points in the global coordinate system, while $\mathrm{M} = (x, y, z)^T$ is the corresponding data acquired by the sensors. The optimal solutions of the six parameters involved in the rotation matrix and translation vector can be found by calculating the objective function as follows:

$$e(\alpha, \beta, \gamma, x, y, z) = \sum \| F - (M \cdot R + T) \|^2$$

Then, the spatial registration algorithm based on quaternion is performed. In order to avoid computing translation vector, the two groups of coordinate data should have the same centroid by subtracting the coordinate of the centroid from each group:

$$\overline{F} = \frac{\sum F}{n}, \quad \overline{M} = \frac{\sum M}{n}$$

$$F_C = F - \overline{F}, \quad M_C = M - \overline{M}$$

Order that

$$S_{ab} = \sum M_C F_C^{\mathrm{T}}$$

Where F_C^T is the transposed matrix of F_C

Construct one new matrix denoted by P:

$$P = \begin{bmatrix} S_{xx}+S_{yy}+S_{zz} & S_{yz}-S_{xy} & S_{zx}-S_{xz} & S_{xy}-S_{yx} \\ S_{yz}-S_{zy} & S_{xx}-S_{yy}-S_{zz} & S_{xy}+S_{yx} & S_{zx}+S_{xz} \\ S_{zx}-S_{xz} & S_{xy}+S_{yx} & S_{yy}-S_{xx}-S_{zz} & S_{yz}+S_{zy} \\ S_{xy}-S_{yx} & S_{zx}+S_{xz} & S_{yz}+S_{zy} & S_{zz}-S_{xx}-S_{yy} \end{bmatrix}$$

The optimal quaternion is the eigenvector corresponding to the biggest eigenvalue of the matrix P, and the rotation matrix R is given by

$$R = \begin{bmatrix} q_0^2+q_1^2-q_2^2-q_3^2 & 2(q_1q_2-q_0q_3) & 2(q_1q_3+q_0q_2) \\ 2(q_1q_2+q_0q_3) & q_0^2-q_1^2+q_2^2-q_3^2 & 2(q_2q_3-q_0q_1) \\ 2(q_1q_3-q_0q_2) & 2(q_2q_3+q_0q_1) & q_0^2-q_1^2-q_2^2+q_3^2 \end{bmatrix}$$

Then the translation vector *T* can be calculated by

$$T = F_C - R \cdot M_C$$

After transforming all the data to the global coordinate system, the difference value between the laser tracker and every sensor can be detected and the traceability of the sensors is accomplished. In order to evaluate the uncertainty of the measurement task further, the comparison of the standard values obtained by least square method and those obtained by the method of parallel chords proposed in this paper is also performed.

3. The Results

In the tests of range measurement, the tracker's performance is evaluated by measuring the distance calibrated by a laser interferometer in advance. The result is shown in Fig. 2.

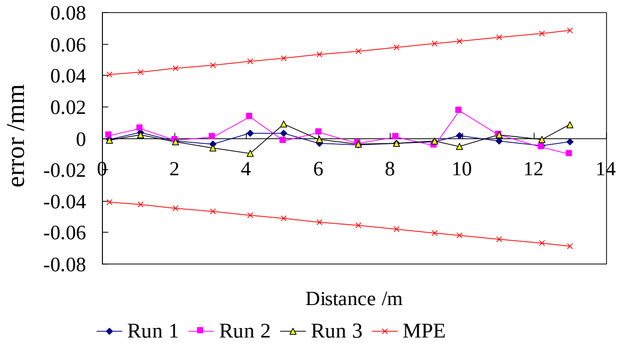

Fig. 2 Traceability result of range measurement

The result of Two-face measurement is shown in Fig.3.

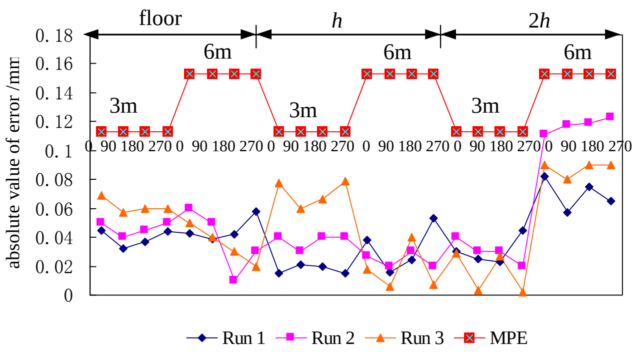

Fig. 3 Result of Two-face measurement

For reference length tests, the length measurements between every two points are conducted by the use of two stable tripods for supporting the targets. The standard length 2382.4606mm is given by laser interferometer and the result is shown in Fig. 4.

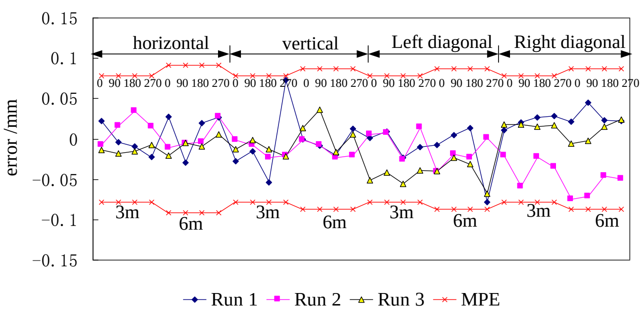

Fig. 4 Traceability result of reference length measurement

Obviously, all the errors are below the MPE, which means the performance of the tracker in field condition conforms to the standard.

Further, the traceability of the theodolite is performed, where the values of the measurement system consisting of two T1800 theodolites and those of the tracker are compared, thus the uncertainty of the theodolite is assessed, as is given in table 1.

Table 1. Traceability result of theodolite.

theodolite [mm]	laser tracker[mm]	uncertainty[ppm]
3175.274	3175.3852	34.3
3612.543	3612.6903	40.4
4656.329	4656.0088	68.6
5326.812	5326.9673	28
6899.23	6898.5836	93.6

4. Conclusions

The large-scale traceability system plays an important role in the development of the industrial metrology. The results of experiments show that the laser tracker that passes all of the tests described in ASME B89.4.19 standard has high precision and has the capability of implementing the task of traceability in field condition.

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