Traceable large-scale metrology based on laser tracker

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Abstract

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.

Keywords: Large-scale metrology, traceability, laser tracker

1. Introduction

Currently, the main instruments and methods for large-scale metrology include laser tracker, theodolite measuring system, photogrammetric system and so on. 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 [1]. 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”.

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. 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 [2]. 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

A laser tracker mainly consists of a tracking head, a retroreflector target, a controller and a sophisticated proprietary software. The tracking head contains a laser interference system, two precision encoders, a servo motor and an optoelectronic receiver, etc. The laser interference system directs the He-Ne laser with the wavelength of 633nm to the retroreflecting target by means of a two-axis (horizontal and vertical) rotary steering mechanism, afterwards, the laser is reflected in the same direction and divided by the spectroscope into two parts: one part enters the laser interference system to form the interference fringes, thereby the distance \( d \) the retroreflecting target moves is given. The other part reaches the quadrant photoelectric detector, which will output electrical signal when the light exposing on the retroreflecting target deviates from its center. Then, under the control of the electrical signal, the two motors will drive the two-axis rotary steering mechanism until the light arrives at the center, that is, the laser tracks the target successfully. Meanwhile, the angular positions of the two rotary axes: horizontal angle \( \alpha \) and vertical angle \( \beta \) are monitored by the encoders, thereby forming a spherical coordinate metrology system.

For the advantages of high precision, perfect tracking ability and automatic measurement, laser trackers are quite appealing and have been widely applied in the fields of airplane and ship manufacture. Therefore, it is reasonable to choose the laser tracker as the instrument to calibrate the others.

Before evaluating the other instruments with laser tracker, the performance of the tracker should be assessed. 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 [3].

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.

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° about the horizontal and vertical axis, respectively. 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° and 270°) 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. 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.
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.

In the measurement system, each sensor has its own corresponding coordinate 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 tracker. In this study, the transformation is implemented by measuring the common points with all of the sensors and the tracker, then processing the data with the formulation shown as equation (1).

\[ F = RM + T \]  

(1)

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: \( \alpha, \beta \) and \( \gamma \); \( T \) is the translation vector; \( F = (x_w, y_w, z_w)^T \) is the data of the common points in the global coordinate system, while \( M = (x, y, z)^T \) 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 (2) as follows:

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

(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:

\[ \bar{F} = \frac{1}{n} \sum^n F_n, \quad \bar{M} = \frac{1}{n} \sum^n M_n \]

\[ F_C = F - \bar{F}, \quad M_C = M - \bar{M} \]  

(3)

Order that \( S_{ab} = \sum M_C F_C^T \), construct one new matrix denoted by \( P \):
The optimal quaternion is the eigenvector corresponding to the maximum eigenvalue of the matrix \( P \), and the rotation matrix \( R \) is given by

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

(4)

The optimal quaternion is the eigenvector corresponding to the maximum eigenvalue of the matrix \( P \), and the rotation matrix \( R \) is given by

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

(5)

Then the translation vector \( T \) can be calculated by

\[
T = F_C - R \cdot M_C
\]

(6)

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.

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.](image)

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. 3.

![Fig. 3. Traceability result of reference length measurement.](image)
Obviously, all the errors are below the MPE, which means the performance of the tracker in field condition conforms to the standard.

4. Conclusion
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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References