Error Analysis of a Kind of 3D Laser Ball Bar

Liang Xu¹, Yuchen Tian¹, Zhifeng Lou¹*, Kuangchao Fan¹, ², Liding Wang¹, Xiaodong Wang¹ and Tongqun Ren¹

¹ School of Mechanical Engineering, Dalian University of Technology, Dalian 116023, China
² Department of Mechanical Engineering, National Taiwan University, Taipei 10617, Taiwan, China

Corresponding author: louzf@dlut.edu.cn

Abstract. Laser tracker instruments are used wildly in the measurement of spatial position, but the instruments have complicated structure and high manufacture cost. In this paper, a kind of 3D laser ball bar instrument for measuring spatial position was introduced, of which measuring principle is a passive laser tracking method. Based on the analysis of error sources, the compensation model of 3D laser ball bar was established according to multi-body system error modelling method. Then, a series of calibration methods for measurement errors are proposed, such as the angular error of two rotary stages, transit tilt and laser axis tilt. Measurement experiments indicate that the positioning error of X-axis is reduced from 20μm to 8μm, and the positioning error of Z-axis is reduced from 61μm to 28μm after error compensation.

1. Introduction
Laser Tracker was invented by Lau at the National Institute of Standards and Technology (NIST) in the mid-1980s [1-2]. Many scholars analyzed the measurement accuracies of laser trackers. Lau et al. carried out the early work of error analysis of laser tracker, and studied the influence of the axes’ non-orthogonality and beam misalignments on measurement accuracy [2]. Loser and Muralikrishnan analyzed the error sources and proposed a geometrical error model for laser trackers with and without beam steering mirrors respectively [3-4]. Conte establishes a kinematic model of the laser tracker based on D-H method [5]. In addition, some scholars researched on the angular error, multi-station measurement method of laser tracker [6-7], etc.

Nowadays, laser tracking measurement has been used in precision manufacturing and instrument calibration. However, laser trackers have complicated structures and high manufacture cost, and it is difficult to be used in industry wildly. In this paper, a kind of 3D laser ball bar instrument for measuring spatial coordinate was introduced, of which measuring principle is a kind of passive laser tracking method, and structure is very simple.

2. 3D laser ball bar

2.1. Establishment of coordinate systems
As shown in figure 1, the 3D laser ball bar system consists of a two-dimensional rotary stage and an extendable sliding guide that passes through the intersection of two rotational axes. A standard ball is fixed on the end of the guide, which can be held by the motion target and move with it. The system uses a laser Doppler displacement meter (LICS100) for measuring displacement of the extendable
sliding guide, and two encoders for measuring rotatory angle of the stages, and then a 3D spherical coordinate system is established.

2.2. The main error of the 3D laser ball bar
As shown in figure 2, the non-orthogonality between the standing axis and transit axis of the two rotary stages is defined as transit tilt ($\alpha$). The non-orthogonality between the transit axis and laser axis is defined as laser axis tilt ($\beta$), the straightness errors of the extendable guide are defined as $\delta_x$ and $\delta_z$.

2.3. Error compensation model of 3D laser ball bar
According to the kinematic relationship of 3D laser ball bar in figure 3, the measurement of the spatial position can be described as follows. The moving target holds the standard ball to move, and extendable device makes a radial translation $R$ along the pitch component ($Y_2$). Then the pitch component rotates $\varphi$ around the transit axis ($X_1$). The azimuth rotating component rotate $\theta$ around the base ($Z_0$). Therefore, the actual coordinate of the standard ball is expressed as Eqs.1 [8].

$$
X_b = -(R_0 + R)(\cos \varphi \sin \theta + \beta \cos \theta - \alpha \sin \varphi \cos \theta) + \delta_x \cos \theta + \delta_z \sin \varphi \cos \theta \\
Y_b = (R_0 + R)(\cos \varphi \cos \theta - \beta \sin \theta + \alpha \sin \varphi \sin \theta) + \delta_x \sin \theta - \delta_z \sin \varphi \cos \theta \\
Z_b = (R_0 + R) \sin \varphi + \delta_z \cos \varphi
$$

Figure 1. 3D Laser ball bar

Figure 2. The main geometric error in 3D laser ball bar (a) Transit axis tilt; (b) Laser axis tilt

Figure 3. Kinematic relationship of 3D laser ball bar

Figure 4. Angular error calibration
3. Errors’ measurement and analysis

3.1 Calibration of angular error of two rotary stages

The angular error calibration system is shown as figure 4. When the rotary stage rotates an angle, the multi-tooth indexing reverses the same angle, and then the angular error of the axes will be displayed in the autocollimator. Finally, discrete data is fitted by Eqs.2 based on the harmonic fitting methods [9]. After compensation, the angular error is less than ±1″.

\[ \varepsilon(\theta) = c_0 + \sum_{i=1}^{n} [a_i \cos(i\theta) + b_i \sin(i\theta)] \]  

(2)

3.2 Calibration of base length \( R_0 \)

The base length is the distance between the standard ball and the intersection of the standing axis and the transit axis when the extendable guide is at initial position. As shown in figure 5, the standard ball is in different positions, and related parameters are obtained. The base length \( R_0 \) can be computed according to equation (3).

\[ (R_0 + R_1)^2 + (R_0 + R_2)^2 - 2(R_0 + R_1)(R_0 + R_2)\cos \theta_2 = H^2_2 \]  

(3)

In Eqs.3, \( R_1 \) and \( R_2 \) are extending displacement from initial position when the standard ball is in position A and position B respectively. Measurement experiment of the base length is shown in figure 6. The laser ball bar was fixed on a three-axis machine’s table, and the standard ball was held by the tool holder. Firstly, the position of the laser ball bar was adjusted in order that the indication of the vertical encoder did not change when the precision three-axis machine tool moved along the X-axis. Then, the displacement in X direction, rotation angle of standing axis, and measurement value of the LDDM were measured. Finally, \( R_0 \) can be obtained according to Eqs.3.

3.3 Calibration of the tilt errors

If the transit tilt error and the laser axis tilt error exist, the measurement data of horizontal encoder will change continuously when the standard ball moves along Z direction as shown in figure 6. The change of horizontal angle \( \Delta \theta \) can be expressed as Eqs.4, where \( \alpha \) and \( \beta \) are the transit tilt angle and the laser axis tilt angle respectively, \( \phi \) is the reading of vertical encoder.

\[ \Delta \theta = \alpha \tan\phi - \beta(\sec \phi - 1) \]  

(4)

As shown in figure 6, it is necessary to adjust the base of the 3D laser ball bar to ensure that the reading of the vertical encoder remains unchanged when the 3D laser ball bar moves along the X axis of the machine tool. Then, when the 3D laser ball bar moves along the Z-axis of the machine tool, the change of horizontal angle at different vertical angles can be obtained. After data acquisition, a least-squares fit method is performed to analyze the transit tilt error and the laser axis tilt error according to Eqs.4.
3.4 Straightness measurement of the guide
The straightness errors of the extendable guide were measured by a collimator system [10], and are shown in figure 7.

![Figure 7. Straightness measured in horizontal plane](image)

Figure 7. Straightness measured in horizontal plane

![Figure 8. Comparison of positioning error](image)

Figure 8. Comparison of positioning error

3.5 Parameters in the 3D ball bar
After measurement experiments, the main parameters can be obtained and are shown in table 1.

| Parameter | Description      | Value       |
|-----------|------------------|-------------|
| $R_0$     | Base length      | 567.408 mm  |
| $\alpha$  | Transit axis tilt| 108.6 arcsec|
| $\beta$   | Laser axis tilt  | -5.6 arcsec |

4. Calibration experiments
Calibration experiments were conducted on a precision three-axis machine tools, and the coordinate transformation between the machine and the ball bar was carried out firstly. After error compensation, the measurement errors of the ball bar in X direction of the machine were reduced from 20μm to 8μm, and measurement errors in Z direction were reduced from 61μm to 28μm, as shown in figure 8.

5. Conclusion
In this paper, a kind of 3D laser ball bar for measuring spatial coordinate was proposed, and error compensation model and the main errors’ measurement methods were developed. Calibration with a precision machine tools indicated that measurement errors of the laser ball bar were reduced greatly.

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