

Design Analysis and Applications of a 3D Laser Ball Bar for Accuracy Calibration of Multiaxis Machines

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Abstract

Conventional techniques for measuring the volumetric errors of Cartesian coordinate machine tools are time consuming using a laser interferometer or step gauges. For multiaxis machines, where the spindle can swing, volumetric error calibration is even more difficult. In this study, a novel 3D laser ball bar (3D-LBB) has been developed for the easy setup and rapid measurement of the tool position relative to the worktable at any working point of multiaxis machines. The instrument makes use of one laser ball bar and two rotary laser encoders to detect the target path in the spherical coordinate system. The design of the instrument is discussed, and the error attributes are analyzed to enhance the instrument's accuracy. Applications to the volumetric error measurement of a robot and two types of machine tools have demonstrated the high-precision capability of this 3D laser ball bar.

Keywords: 3D Laser Ball Bar, Accuracy Calibration, Volumetric Errors, Multiaxis Machines

Introduction

Techniques for performing accuracy testing of CNC machine tools can be found in many standards, such as ISO 230 or ASME B5.54 (1993). Most of the existing linear measurement instruments are one dimensional, such as a laser interferometer or step gauge. For the circular test of 2-D motion, as specified in ISO 230-4 (1998), some instruments have been developed, such as the double ball bar (DBB) (Bryan 1982), Contisure (Burdekin and Jwye 1992), and the latest laser ball bar (LBB) (Ziegert and Mize 1994, Schmitz and Ziegert 2000). Although these instruments are capable of two-axis error measurements, they are still sensitive to one dimension only.

For the measurement of volumetric errors of machine tools, most methods detect 21 component errors and then use the homogeneous transformation matrix (HTM) method or kinematic analysis method (Soons, Theuws, and Schellenkens 1992) to derive the spatial errors off-line. Wang (2000) follows the ASME B5.54 standard to measure volumetric errors directly. The standard employs a laser Doppler displacement meter (LDDM) and a large, flat mirror to measure four body diagonals, and assesses volumetric errors using the vector method. The standard is time saving but only valid for traditional, serial-type CNC machines. Hexapod machine tools have received a great deal of attention due to their flexibility in five-axis movement (Patel and Ehmann 1997). However, owing to the spindle swing in the pitch and yaw directions, more sensors are needed to make the volumetric motion measurement possible (Parenti and Gregorio 1999). In practice, however, this equipment is too expensive to be implemented in industry. So far, there are some good laser tracking systems (LTSs) designed in spherical coordinate systems that can directly detect 3D motion error (API 2002). These systems must be operated in an active way, which requires feedback sensors and servo control to track the moving target in real time. These systems require very fast control systems, resulting in higher cost.

A novel design that integrates the merits of a LBB and LTSs is proposed in this research for the three-dimensional measurement of moving objects in real time. The system, called the 3D Laser Ball Bar (3D-LBB), is based on the spherical coordinate principle containing only one precision laser linear measurement device and two precision laser rotary encoders

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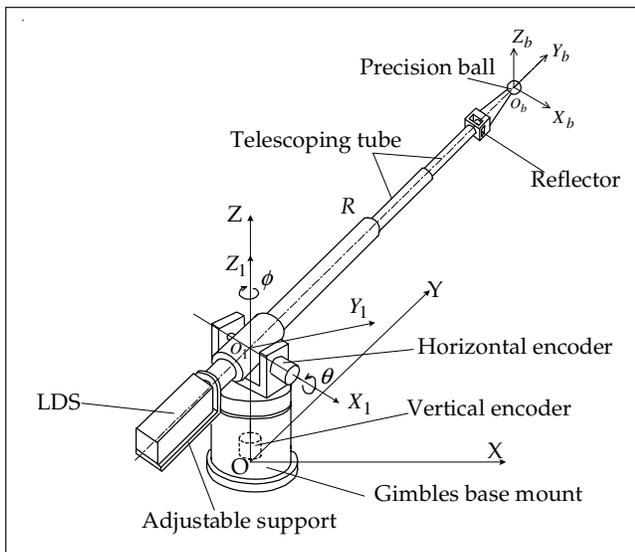


Figure 1
 Structure of 3D Laser Ball Bar

in the gimbal base with an extendable ball bar. Such a system can be dragged by any 3D moving target with a magnetic head and freely moved in the space. Three sensors simultaneously record the ball positions and transform into the Cartesian coordinate in real time. Having been calibrated by a HP laser interferometer, the system accuracy can be compensated and enhanced to a higher degree. As this system is operated in the passive mode in 3D space, the cost is inexpensive.

Design Principle of 3D Laser Ball Bar (3D-LBB)

Structure Design

Figure 1 illustrates the system configuration of the 3D-LBB. The system is constructed in a spherical coordinate of which the center of the gimbal mount is the origin (O). Mounted onto the gimbal center is an extendable telescoping tube (made of aluminum alloy and hardened in the interior surface) that can be designed in two or three sections depending on the required radial length of motion. Between the inner and outer tubes of a sliding pair is one linear bearing mounted at the far end of the outer tube and a copper sliding bearing fixed at the near end of the inner tube to prevent side motion during bar extension.

The movement of the 3D-LBB is generated by the precision end ball, which can be dragged by a magnetic socket carried by any moving object. The radial motion (R) of the ball is detected by a small-

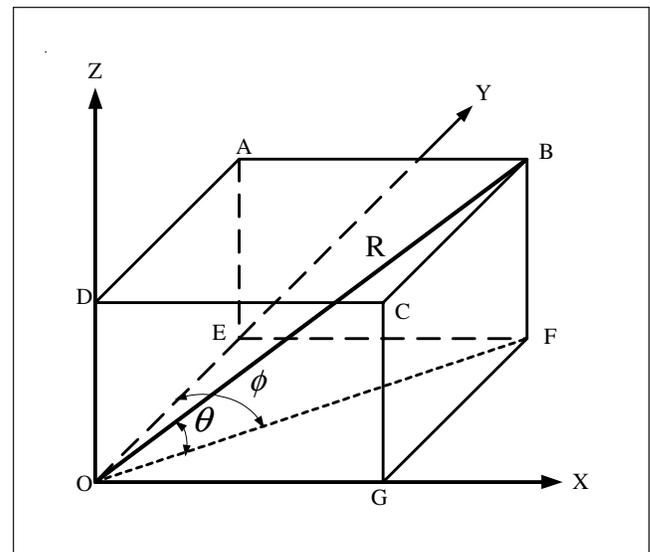


Figure 2
 Spherical and Cartesian Coordinates

sized laser linear measurement system whose beam passes through the telescope tubes and is reflected back by a reflector at the bar end. A conical stainless steel piece connecting the reflector and the ball allows a wider angle of rotation between the magnetic socket and the ball. The laser linear system is required to be as small as possible to reduce the system weight. This design was, therefore, changed to a compact laser Doppler scale (LDS, model 109N, made by Optodyne Co.) with wavelength stability to 0.1 ppm and system accuracy to 1.0 ppm.

The pitch (θ) and the yaw (ϕ) motions of the bar with respect to the gimbal base are detected by two precision laser rotary encoders (model K-1, made by Canon Co.) individually. Each encoder has very fine scales of 81,000 ppr. With an additional 16-division interpolator board (model 16-2), the resolution can reach one arc-sec.

Coordinate Transformation

To obtain the tool-point Cartesian coordinates, the equations of coordinate transformation can be easily derived as shown in Figure 2.

$$\left. \begin{aligned} X &= R \cos \theta \sin \phi \\ Y &= R \cos \theta \cos \phi \\ Z &= R \sin \theta \end{aligned} \right\} \quad (1)$$

where $R = R_0 + r$. R_0 is the initial length of the bar, which is obtained during the initialization process, as explained in a later section, and r is the extended

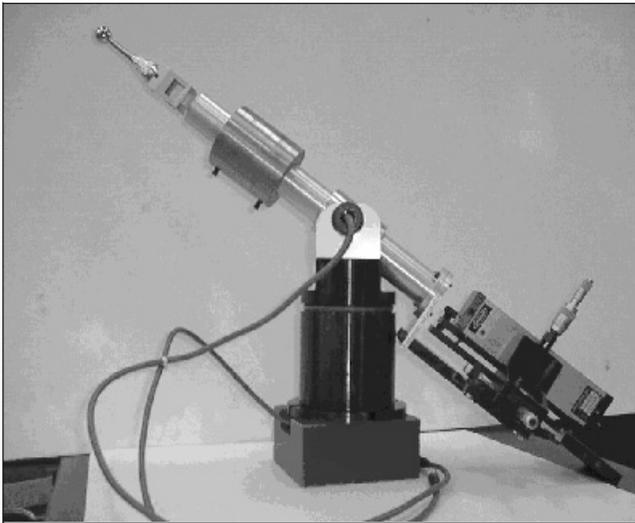


Figure 3
 Prototype of 3D-LBB

length. Figure 3 shows the picture of the developed prototype 3D-LBB. The nominal physical dimensions of this prototype are: gimbal base diameter 150 mm, gimbal center height 300 mm, initial R length 142 mm, and moving length of telescope tubes 550 mm. To balance the weight while the telescope tube is extending, a counterweight balancer is mounted onto the base tube near the origin. Moreover, for ease of beam alignment, a four-axis adjustable stage is especially made for laser mounting.

Accuracy Considerations

As an instrument for spatial position measurement, the system must be more accurate than the inspected multi-axis machine itself. Error sources, therefore, must be identified and properly calibrated to improve the instrument's system accuracy.

Clearance Error of Tubes

As shown in Figure 4a, under improper fit of the linear bearing a small amount of clearance may generate side motion during the extension of the inner tube.

The angle of rotation can be estimated by $\tan\theta = 2C/L$, where C denotes clearance and L indicates bearing length. In this study, a copper spacer was designed to give interference fit with the end of the inner tube and precise fit with the outer tube. Under good lubrication, the copper spacer can freely slide along the outer tube as a slide bearing. Because in

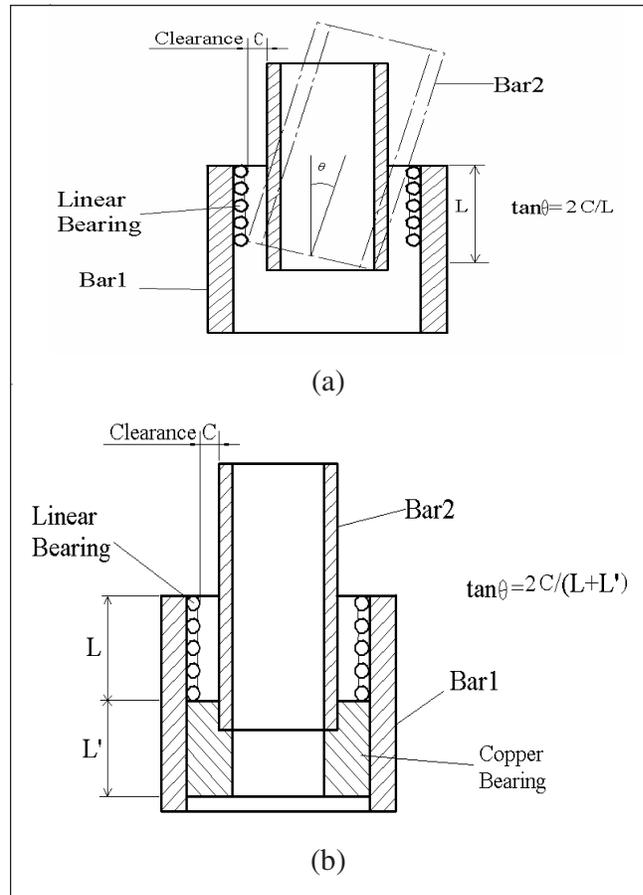


Figure 4
 Clearance Error: (a) caused by linear bearing,
 (b) corrected by a copper bearing.

practice the linear bearing and tubes have to be selected from standard items in the shop, a possible clearance even after minor machining still cannot be avoided. The copper spacer, however, can be self-made to assure minimum clearance. Therefore, even at the maximum extension condition, as shown in Figure 4b, the loose motion of the inner tube must be much smaller than before.

Assembly Errors

To modify the measurement inaccuracy, geometric assembly errors should be superimposed to Eq. (1). These include the axes perpendicularity and the axes offset with respect to the origin (O) of the reference frame XYZ . These errors are illustrated in Figures 5–7, respectively.

As shown in Figure 5, the perpendicularity error (α) of the θ -axis with respect to the Z axis can be checked by a CMM and computed as

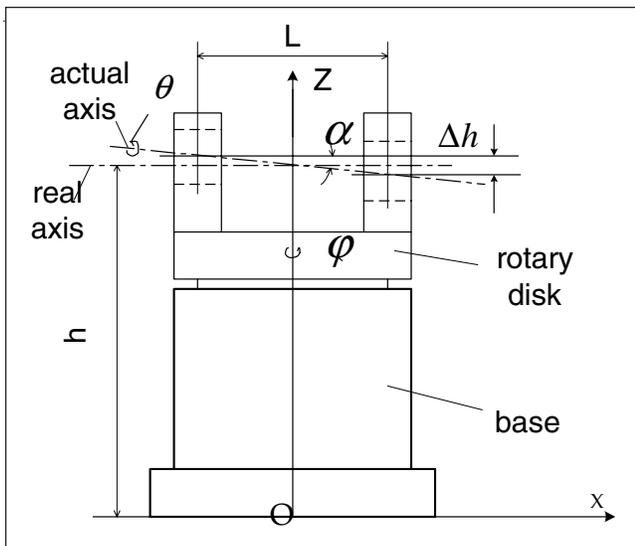


Figure 5
Squareness Error of θ -Axis to Z-Axis

$$\alpha = \arctan \frac{\Delta h}{L} \quad (2)$$

where Δh is the difference of the height of two bearing centers and L is the distance between two bearing supports. The measurement can be carried out before mounting the shaft and the encoders. The measured inner ring surface should be as close to the outside wall as possible. The length L is determined by the distance between the two outside walls of the bearing supports. Another way is to measure the wobble of the rotary disk. Placing a dial gauge at 100 mm radial position and rotating the disk a full circle, the height change of the disk surface could be found. Using Eq. (2), the perpendicularity error (α) is obtained.

From Figure 6, the perpendicularity error (β) of the bar with respect to the θ -axis also can be checked by the CMM. The origin O_1 indicates the intersection of the θ -axis and R -axis. From Figure 7a, in the X - Y plane there is an offset error (a, b) of origin O_1 with respect to origin O of the ϕ -axis. The (a, b) offset could be found by the following procedures:

1. Use a roundness measuring machine to measure the central circle of the rotary disk and find the offset (a_1, b_1) of center O_o with respect to the rotation center O (refer to Figure 5).
2. Use the CMM to find the offset (a_2, b_2) of the disk center O_o with respect to the origin O_1 .
3. Therefore, $a = a_2 - a_1, b = b_2 - b_1$.

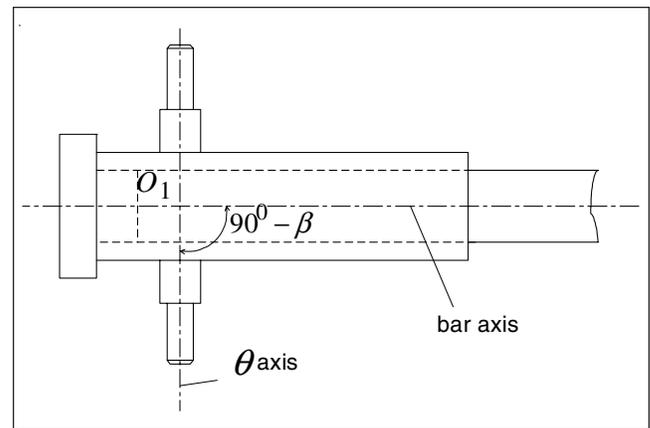


Figure 6
Squareness Error θ -Axis

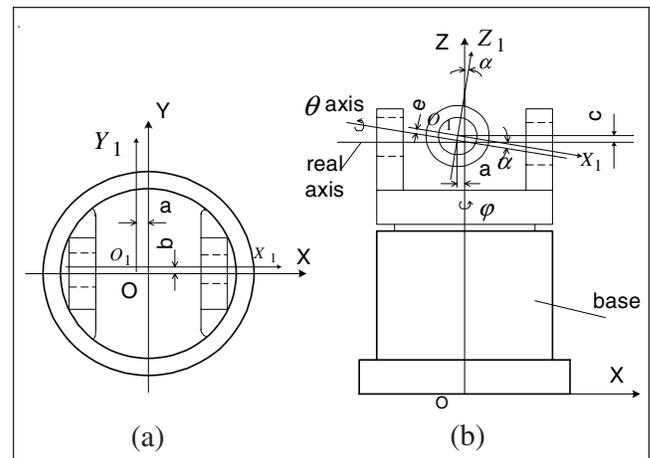


Figure 7
Eccentricity of Origin O_1

Then, in the Z -direction, the deviation c (see Figure 7b) can be calculated as

$$c = a \tan \alpha + e \cos \alpha \quad (3)$$

where e is the center offset of the bar axis with respect to the θ -axis along the Z_1 direction.

Experimental tests were conducted on the prototype 3D-LBB. All the assembly errors could thus be identified as listed in Table 1.

Because $a, b, c, \alpha,$ and β are constant assembly errors, these factors must be added to the system mechanism, and Eq. (1) has to be modified accordingly. To derive the actual measurement equations, two relative coordinate frames are of interest, as shown in Figure 8. The reference frame XYZ is fixed at the base center, with the Z -axis denoting the cylindrical base axis. A movable frame $X_1Y_1Z_1$ is assigned at the point O_1 , with X_1 parallel to the θ -axis and Y_1

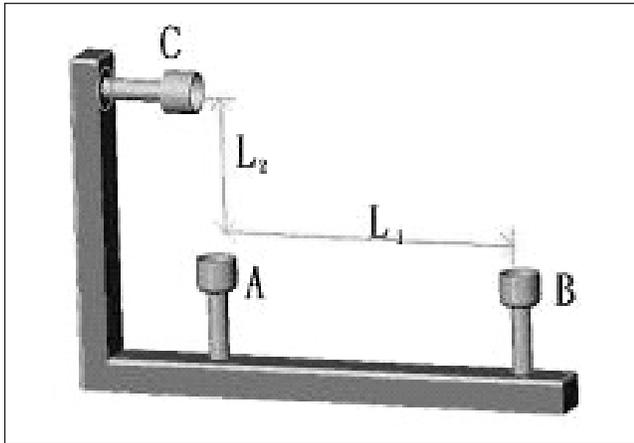


Figure 9
Artifact for 3D-LBB Initial Length Measurement

Substituting each coordinate into Eq. (6) and simplifying with trigonometric operations, the following two equations can be obtained.

$$L_1^2 = 2R_0^2 + (\Delta R_B)^2 + 2R_0 \Delta R_B - 2R_0 (R_0 + \Delta R_B) (\cos \Delta \phi_B + 1) \cos \Delta \theta_B \quad (7-1)$$

$$L_2^2 = 2R_0^2 + (\Delta R_C)^2 + 2R_0 \Delta R_C - 2R_0 (R_0 + \Delta R_C) (\cos \Delta \phi_C + 1) \cos \Delta \theta_C \quad (7-2)$$

There is an interesting finding that in these two equations there is only one variable R_0 . It means that only one standard distance is needed to find the initial bar length. The second standard distance can be used to double check the calculated R_0 , which was found to be 142 mm, as indicated earlier.

2. During the R -direction alignment step, first we let the precision ball of the 3D-LBB be dragged with a magnetic socket by the moving axis along the R direction. Second, we adjusted the gimbal base to allow for two unchanged encoder readings throughout the travel. Then, we reset the two encoder readings.
3. Then we positioned the artifact in front of the 3D-LBB and let point A be in line with the moving axis as close as possible. Now we could take readings of A, B, and C sockets and found R_0 .

In addition to the geometric errors by assembly and the elastic deformation as described in the above sections, there are also other systematic errors that affect the accuracy of measured R , ϕ , and θ data,

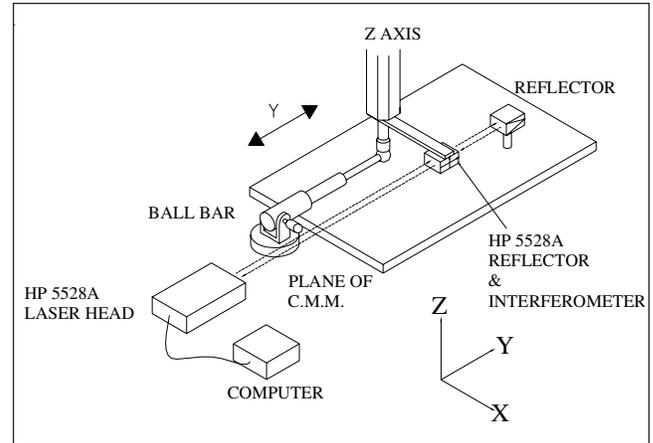


Figure 10
Setup for R Accuracy Calibration

such as friction, laser stability and misalignment, clearances of fits, and sensor errors. Therefore, the accuracy calibration of the developed 3D-LBB is necessary. In addition, with the error compensation scheme the system accuracy can be significantly enhanced.

Calibration of the R Axis

As shown in Figure 10, an HP 5528A laser interferometer was used to compare with the reading of the LDS (not shown in the figure). The 3D-LBB was mounted onto a side table of a table-type CMM. The standard ball of the 3D-LBB was fixed to the spindle end with a magnetic socket. The set of corner cube reflectors and the interferometer cube were mounted on an extension bar from the spindle end. A possible Abbe error induced by this setup will be due to the roll error of the moving spindle. In fact, this roll error is very small and can be neglected. Bidirectional motion with three runs each was carried out for calibration. Calibrated results are shown in Figure 11a. Because the error has an obvious tendency and repeatability, the R errors can be compensated by the best-fitting line. The slope of the error tendency is caused by the misalignment of the LDS laser beam with respect to the HP5528 laser beam. However, the maximum error at the far end is only about 1.5 μm , which can be reasonably compensated by a curve-fitting technique. The modified R reading is expressed by Eq. (8). As shown in Figure 11b, after compensation, positioning errors of the LDS can be maintained within $\pm 0.3 \mu\text{m}$.

$$R_{\text{mod}} = R_r - 4 \times 10^{-6} R_r - 0.0003 \quad (8)$$

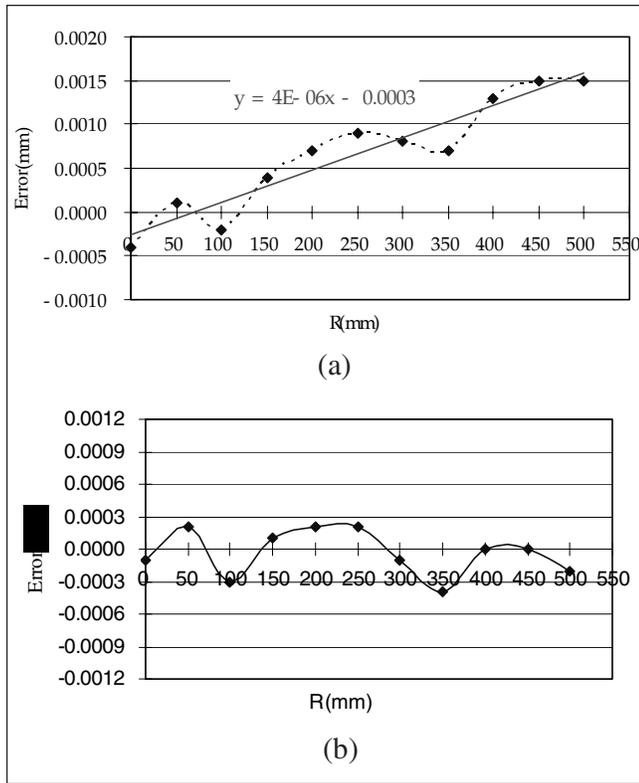


Figure 11
Calibrated R Linear Errors
(a) results, (b) residual errors after compensation

where R_{mod} is the modified R_r value, which is the direct reading from the LDS.

Calibration of the ψ Axis

In this experiment, the bar was carefully aligned parallel with the X - Y plane and directed to the Y -axis of a table-type precision CMM, as shown in Figure 12a. The setup was similar to the setup of linear calibration, the only change being that the 3D-LBB moves to the Y -direction. While the spindle moves in the X -direction and its position is recorded by the HP 5528A, the ϕ angle changes in a trigonometric relationship, as shown in Figure 12b and expressed by Eq. (9).

$$\phi_i = \arccos\left(\frac{R_0^2 + R_i^2 - X_i^2}{2R_0R_i}\right) \quad (9)$$

$$\Delta\phi_i = \phi_{ir} - \phi_i$$

where ϕ_i is the calculated nominal angle at the i th position and ϕ_{ir} is the actual readout from the vertical encoder.

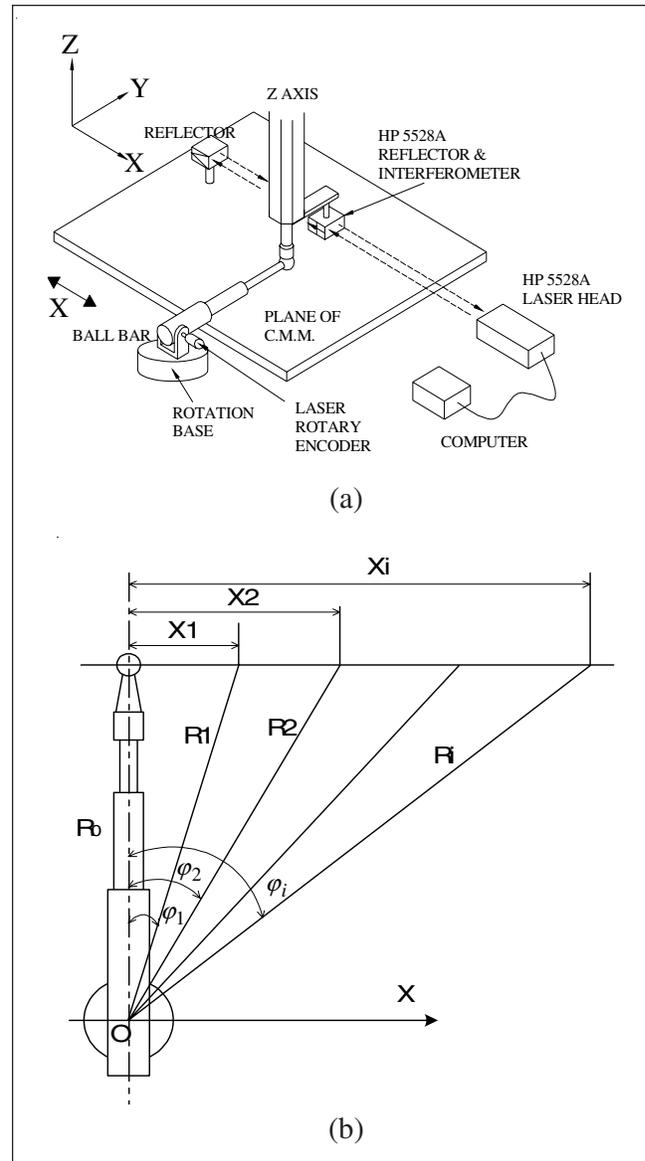


Figure 12
(a) Setup for ϕ calibration, (b) principle of calibration

The calibrated ϕ_i errors can be expressed by Eq. (10). After correction, the ϕ errors can be maintained within ± 1.5 arc-sec, as shown in Figure 13.

$$\phi_{\text{mod}} = \phi_r - (-4 \times 10^{-5} \phi_r - 23.818) \quad (10)$$

where ϕ_{mod} is defined as the modified value and ϕ_r is the readout from the vertical encoder.

Calibration of the θ Axis

For calibration of the θ axis, the setup and principle of calibration are similar to Figure 12 except

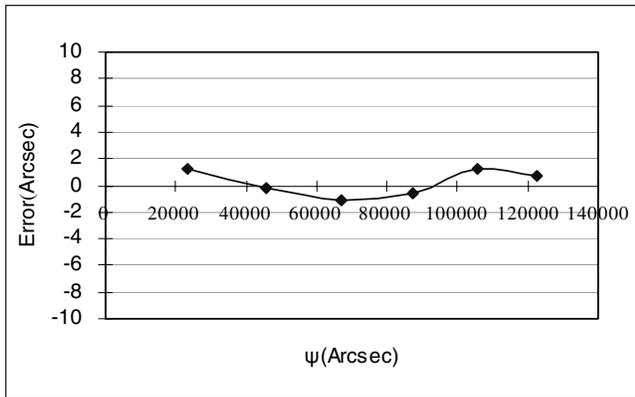


Figure 13
Calibrated ϕ Angular Errors

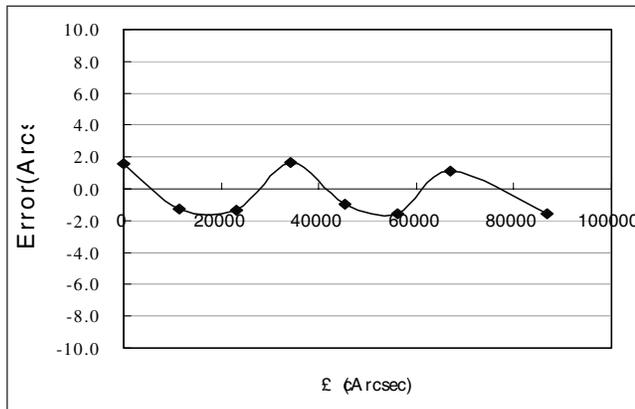


Figure 14
Calibrated θ Angular Errors

the laser beam is bent to the spindle direction. With proper alignment, the bar rotates only around the θ -axis. The errors can be found by comparing the θ readouts from the horizontal encoder with values of Z_i from HP and R_i from LDS and calculated using Eq. (11). Error correction is done by Eq. (12). Residual errors are about ± 1.6 arc-sec, as shown in Figure 14.

$$\theta_i = \arccos\left(\frac{R_0^2 + R_i^2 - Z_i^2}{2R_0R_i}\right) \quad (11)$$

$$\Delta\theta_i = \theta_{ir} - \theta_i$$

where θ_i is the calculated nominal angle and θ_{ir} is the readout from the horizontal encoder.

$$\theta_{\text{mod}} = \theta_r - (-0.0038 \times 10^{-5} \theta_r - 3.1053) \quad (12)$$

where θ_{mod} is the modified value and θ_r is the readout of the horizontal encoder.

Table 2
Accuracy and Repeatability of 3D-LBB

Coordinate Parameter	Range	Accuracy	Repeatability $\pm 3\sigma$
R	500 mm	$\pm 0.3 \mu\text{m}$	$0.21 \mu\text{m}$
ϕ	35°	± 1.5 in.	1.2 in.
θ	25°	± 1.6 in.	0.8 in.

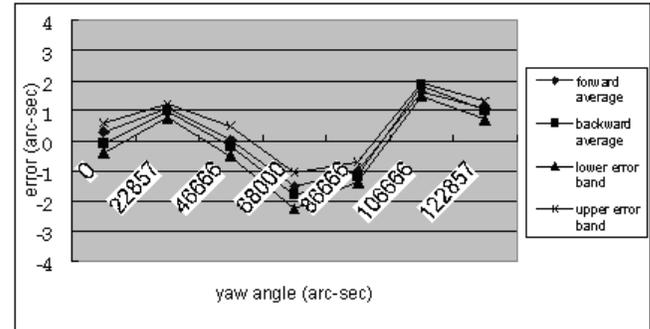


Figure 15
Calibration in Yaw Angle Rotation of 3D-LBB

Compensated 3D-LBB Errors

After correction of the errors, the measurement accuracy of this instrument is significantly improved. The compensated system accuracy is listed in Table 2. Repeatability tests were based on the results of bidirectional motion with three runs each for all of the above three calibration processes. With careful assembly and fastening processes, the 3D-LBB can perform good repeatability. One typical example is shown in Figure 15 for the ϕ accuracy calibration. The uncertainties of all calibrated errors in the ± 3 sigma band (99.7% certainty) are summarized in the last column of Table 2.

Applications

Volumetric Error Measurement of a Serial-Parallel Type Machine Tool

The experimental setup is shown in Figure 16. The base of the 3D laser ball bar is fixed on the X - Y table. The end ball is mounted at the spindle end by a magnetic socket with three points of contact. The machine tool is of a serial-parallel type consisting of a 3DOF parallel spindle platform with two angular orientations and one linear motion in the Z -axis and a conventional X - Y table, which carries the workpiece. The spindle is assembled on the platform, which is connected to three constant-length struts by means of ball joints, which are equally spaced at 120 de-

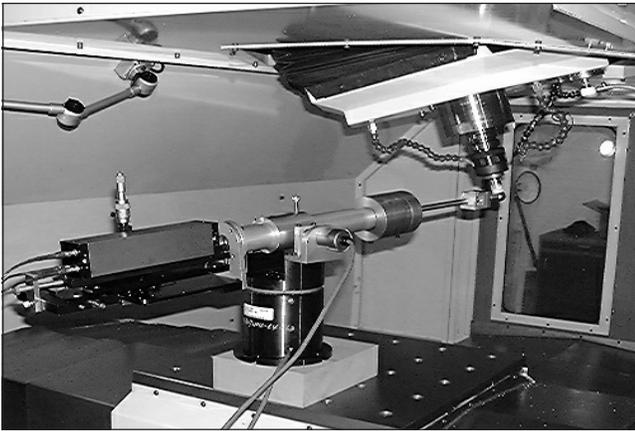


Figure 16

Setup for Accuracy Check of a Serial-Parallel Machine Tool

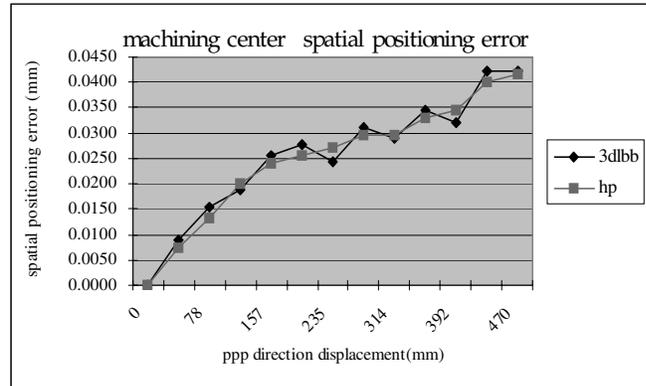


Figure 18

Comparison of Calibrated Results Between 3D-LBB and an HP 5528 Along a Diagonal Test of a Machine Tool

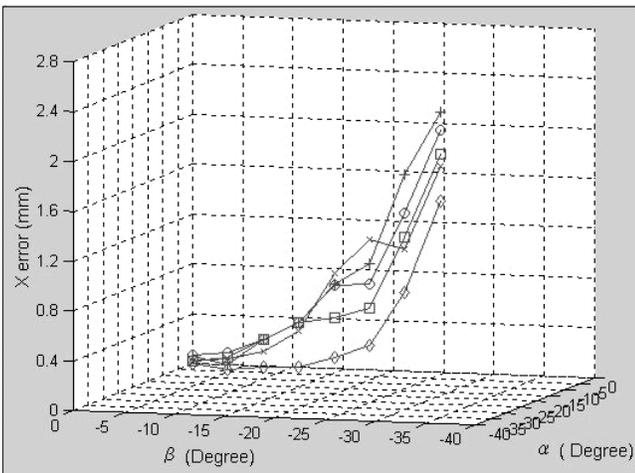


Figure 17

Diagonal Positioning Error Plot

grees. By giving commands to change two angular orientations of the spindle platform, the tool tip spatial positions could be measured by the 3D laser ball bar. Partial experimental results of volumetric errors are plotted in *Figure 17*.

Accuracy Calibration and Verification in Diagonal Path Measurement

A diagonal path with 12 constant intervals of a machining center was measured by the 3D-LBB and an HP interferometer conforming to the ASME B5.54 standard with machine coordinates from (0, 0, 0) to (312, 324, 128). Measured results are compared in *Figure 18*, from which it can be seen that this machine tool has significant volumetric errors, and the maximum difference between the 3D-LBB and HP5528 readouts is about 2.6 μm . This can verify the applicability of the developed 3D-LBB.

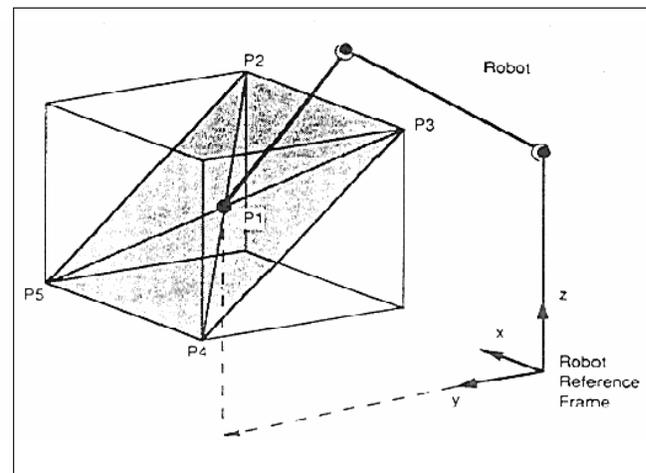


Figure 19

Spatial Path for Robot Calibration

Robot Spatial Position Error Measurement

According to the guideline for robot spatial path position error calibration (ISO 9283; 1990), the measuring sequence of a standard spatial paths P1 \rightarrow P2 \rightarrow P3 \rightarrow P4 \rightarrow P5 \rightarrow P1 is illustrated in *Figure 19*.

Experimental results are shown in *Figure 20*. The repeatability (6σ) of spatial position errors of the investigated robot is about 0.08 ~ 0.085 mm, which meets general requirements. The maximum spatial position error is about 1 mm, which implies that this robot is only suitable for rugged work.

Conclusions

A novel 3D-LBB system was developed for measuring the volumetric errors of multiaxis machines. This paper describes how possible errors due to as-

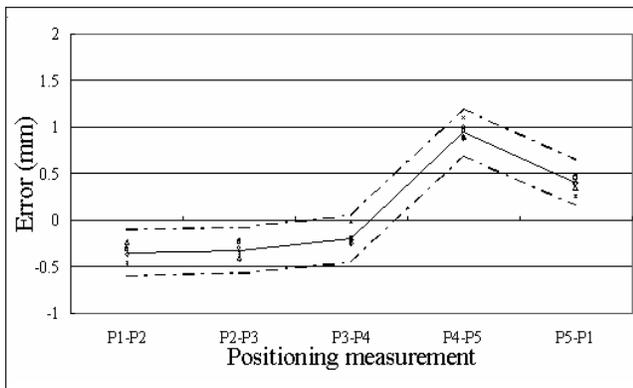


Figure 20
 Results of a Robot Calibration

sembly, elastic deformation, and calibration processes could be found and compensated. For the current prototype, its accuracy after compensation is found to be quite promising: $\delta_R = \pm 0.3 \mu\text{m}$, $\delta_\phi = \pm 1.5 \text{ arc-sec}$, and $\delta_\theta = \pm 1.6 \text{ arc-sec}$. The repeatability and verification tests are also reported, which showed quite satisfactory results. This paper proposes the methodology of design, assembly, and error correction of a 3D laser ball bar, which has more flexible and versatile functions than the currently used laser interferometer and 1-D LBB for the accuracy calibration of machine tools. In addition to the spatial position measurements, this instrument also can be used to check other kinds of errors in machine tool metrology, such as circular test, straightness, spindle drift, and so on.

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Authors' Biographies

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