Pose Calibration for 2D Laser Profiler Integrated in Five-Axis Machine Tools

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Abstract. Laser scanning is a fast and effective method to acquire the 3D surface profiles of part. To implement on-machine measurement (OMM), the 2D laser profiler could be integrated in five-axis machine tools and moves under the command of the computer numerical control (CNC) system. The 2D profile data and the corresponding machine coordinates are acquired and saved by the CNC system, and then converted to 3D point cloud using the kinematic model. Therefore, calibration of the position and orientation of the laser profiler with respect to the machine tool will directly influence the inspection accuracy. In this paper, a pose calibration method is proposed to identify the position and orientation of the laser sensor. A laser scanning system integrated in five-axis machine tool is developed. The position and orientation deviations between the local laser coordinate system (LCS) and tool coordinate system (TCS) are defined. Then, a designed calibration block is scanned, and its feature is reconstructed. Furthermore, the position and orientation of the laser profiler is identified by comparing the reconstructed features with the designed features. Finally, the position and orientation deviations parallel to five axes of the machine tool are compensated by coordinate offset, and the remaining orientation deviation is corrected by the kinematic model during converting measurement data to 3D point cloud. Experiment is carried out to validate the proposed method.

1. Introduction

Laser scanning is a non-contact measuring method with high speed and sufficient accuracy[1], which is widely used for microscopy[2], map building[3, 4], shape acquisition and quality assessment[5]. Bi [6] adopted a laser scanner mounted on the spindle to measure the deformed large skin. Liu [7] employed an iso-planar-based on-machine scanning method to obtain the shape of complex surface. Sharifzadeh [8] used laser scanners integrated in robot to detect the small abnormalities on large complex free-form surfaces. However, laser scanning is usually not as accurate as coordinate measurement machine (CMM) with a contact-type probe [9].

A lot of research is devoted to improving the accuracy of laser scanning. Ishiell [9] studied the effects of three geometrical parameters of sensor positioning, and built a global and local correction model to reduce the mean errors and standard deviations, respectively. Li [10] extended the depth-of-view of the portable 3D scanning system from the Scheimpflug condition by tilting the charge coupled device (CCD) plane, and improved the measurement accuracy via segmental calibration. Sun [11] proposed a vision measurement model and a corresponding calibration method for the laser displacement sensor to avoid linear approximation and be implemented conveniently. Genta [12] proposed a thorough approach based on a reference ball plate to calibrate the triangular laser scanner. Abu-Nabah [13]
presented a simplified method for laser vision sensor calibration using a rectangular notch calibration block with high precision. Most above calibration methods are proposed for scanner uncertainties, which could be calibrated and compensated by the manufacturer [9]. However, in practical applications, laser scanning system is implemented by mounting a commercial laser sensor at the end of a machine tool or robot. The profile information and the corresponding machine coordinates are sampled at the same time and then converted to 3D points through kinematic model [14]. During the installation of the laser sensor, assembly error is inevitable. Therefore, in addition to the performance of the laser sensor, its assembly error affects the scanning accuracy. The true installation position and posture of the sensor need to be accurately calibrated to improve measurement accuracy. However, there is a lack of methods for calibrating the pose of the laser scanner at present. This work proposes a pose calibration method for the 2D laser profiler integrated in five-axis machine tool. The laser scanning system is introduced briefly in Section 2. Then, Section 3 defines position and orientation deviations and proposes a pose calibration method based on a designed calibration block. Experiment is conducted in Section 4, and conclusions are drawn in Section 5.

2. Laser scanning system
The employed experiment platform is a dual-five-axis mirror milling system, which is composed of a five-axis milling head and a five-axis support head, as shown in Figure 1. The milling head consists of three translations (following \(X_1, Y_1\) and \(Z_1\)) and two rotations (following \(A_1, C_1\)), the support head also consists of three translations (following \(X_2, Y_2\) and \(Z_2\)) and two rotations (following \(A_2, B_2\)). A 2D laser profiler (Keyence LJ-V7200) mounted on the support head moves under the command of CNC system to implement on-machine scanning. The CNC system acquires the profile data from laser sensor and the corresponding machine coordinates from machine tool at the same time and saves it to the measurement file. The specifications of the adopted profiler are listed in Table 1.

![Figure 1. Experiment setup.](image)

| Height (Z)         | Parameters | Width (X)     | Parameters |
|-------------------|------------|---------------|------------|
| Reference distance| 200 mm     | Profile data count | 800 items |
| Measurement range | ±48 mm (F.S.=96 mm) | Measurement range | 62 mm    |
| Linearity         | ±0.1% of F.S. | Profile Data interval | 100 μm    |
| Repeatability     | 1 μm       | Repeatability  | 20 μm      |

3. Calibration method

3.1. Position and orientation deviation description
LCS \((O_LX_LY_LZ_L)\) is a local measurement coordinate system fixed with the reference point of the laser profiler, and TCS \((O_TX_TY_TZ_T)\) is fixed with the tip point of support head. Limited to the structure of support head and assembly errors of the laser profiler, LCS deviates from TCS, as shown in Figure 2(a). The positional deviations are the coordinates of LCS origin in TCS, defined as \((\delta x, \delta y, \delta z)\). The
orientation deviations are the posture differences between LCS and TCS, represented by \((\alpha, \beta, \gamma)\), as shown in Figure 2(b). \(\alpha\) is the angle between \(Z_{T2}\) and the projection of the \(Z_{L}\) axis in the \(Y_{T2}Z_{T2}\) plane. \(\beta\) is the angle between \(X_{T2}\) and the projection of the \(X_{L}\) axis in the \(Z_{T2}X_{T2}\) plane. \(\gamma\) is the angle between \(X_{T2}\) and the projection of the \(X_{L}\) axis in the \(X_{T2}Y_{T2}\) plane.

The target of the pose calibration for 2D laser profiler is to identify and correct \(\alpha, \beta, \gamma, \delta x, \delta y\) and \(\delta z\). The calibrated deviations \(\alpha, \beta, \delta x, \delta y\) and \(\delta z\), which are parallel to the axes of support head, could be adjusted by setting machine zero point of support head. After adjustment, the central axis of the laser plane \(Z_{L}\) and origin of LCS coincide with TCS, as shown in Figure 2(c). The remaining orientation deviation \(\gamma\) can be compensated when the measurement data is converted to point cloud. Assume that the measured height of the \(i\)-th measuring point \(P_i\) is \(h\) in the LCS, then the \(P_i\) can be represented as:

\[
L_P = \begin{bmatrix} t_x p_i, t_y p_i, t_z p_i \end{bmatrix}^T = \begin{bmatrix} \Delta d(i-400), 0, h \end{bmatrix}^T
\]

(1)

where \(\Delta d = 0.1\) mm is the profile data interval of the laser profiler. As illustrated in Figure 2(d), convert \(L_P\) to \(T_2 P_i\) considering orientation deviation \(\gamma\):

\[
T_2 P_i = \begin{bmatrix} t_x p_i, t_y p_i, t_z p_i \end{bmatrix}^T = \begin{bmatrix} \Delta d(i-400) \cos \gamma, \Delta d(i-400) \sin \gamma, h \end{bmatrix}^T
\]

(2)

\(T_2 P_i\) can be further converted to \(W P_i\) using the kinematic transformation model proposed in Ref. [15] to obtain 3D point cloud in the workpiece coordinate system.

3.2. Calibration model of \(\beta\)

When orientation deviation \(\beta\) is nonzero, the measured profile will deviate from the reference profile, which is parallel to \(X_2 Y_2\) plane, as shown in Figure 3(a). If \(B_2\) axis rotates, \(\beta\) changes accordingly. When the recognized \(\beta\) is zero, the angle of \(B_2\) currently is the calibration value of \(\beta\).

3.3. Calibration model of \(\alpha\)

As shown in Figure 3(b), \(O\) is the pivot of \(A_2\) axis, \(A\) is the laser source, \(B\) is the image point of the laser on the workpiece, \(C\) is the foot point of \(O\) on the reference plane, \(\angle COA = \sigma\). When \(A_2\) axis rotate \(\varphi\), \(A\) moves to \(A'\), \(B\) moves to \(B'\), and measured distance \(h\) changes accordingly. \(\varphi\) and \(h\) satisfies the following equation:

\[
h = \frac{l - n \cos(\sigma - \varphi)}{\cos(\alpha - \varphi)}
\]

(3)
\( l, n, \sigma \) and \( \alpha \) are the parameters to be determined. The curve about \( \varphi \) and \( h \) can be obtained through scanning a reference plane by rotating the \( A_2 \) axis. Fit the measured curve using the least square method to identify \( l, n, \sigma \) and \( \alpha \).

3.4. Calibration model of \( \gamma, \delta x, \delta y \) and \( \delta z \)
After correction of \( \alpha \) and \( \beta \), \( Z_L \) is parallel to \( Z_{T2} \), but laser plane may be not coincided with \( X_{T2}Z_{T2} \) plane. Remaining \( \gamma, \delta x, \delta y \) and \( \delta z \) can be calibrated by scanning a reference hole. When the laser profiler scanning the hole along \( Y_2 \) direction, the laser image line is not perpendicular to the scanning direction due to the orientation deviation \( \gamma \), as shown in Figure 3(c). The scanned point on the edge of the hole can be described as the following parametric equation:

\[
\begin{align*}
    x - x_0 &= r \cos \theta \\
    y - y_0 &= r \sin \theta
\end{align*}
\]

The corresponding recognized distance along the laser image line and along the scanning direction are

\[
\begin{align*}
    dx &= x' - x_0 = r \frac{\cos \theta}{\cos \gamma} \\
    dy &= y' - y_0 = r \sin \theta - r \cos \theta \tan \gamma
\end{align*}
\]

Eliminate \( \theta \), we get a new curve equation

\[
    r^2 = (x' - x_0)^2 + (y' - y_0)^2 + 2(x' - x_0)(y' - y_0)\sin \gamma
\]

The right schematic in figure 3(c) illustrates the curve described by Eq.(6), which is the recognized hole contour without compensation for \( \gamma \). The recognized contour is fitted using least squares to identify \( \gamma, x_0, y_0 \). Fit the plane where the hole is located and get its z coordinate \( z_0 \). Comparing \((x_0, y_0, z_0)\) to the center coordinates of reference hole yields \((\delta x, \delta y, \delta z)\).

![Figure 3. Calibration model: (a) Model of \( \beta \); (b) Model of \( \alpha \); (c) Model of \( \gamma, \delta x, \delta y \) and \( \delta z \).](image)

4. Experiment
A designed calibration block with a hole, as shown in Figure 4, is utilized to calibrate the pose of the laser profiler. The bottom of the central notch and the side wall of the hole are finished as the reference plane and hole. Its exact dimensions are measured by CMM and marked in Figure 4(a). The block is mounted on the spindle of the milling head by a shank, and its edge is adjusted to be parallel to the machine coordinate system via spindle positioning. Therefore, at the initial pose of the milling head, the reference plane is parallel to XY plane, and the centre coordinates of the reference hole is (0.043, -27.470, 0.000).

The calibration experiment is carried out in four steps:

**Step1: Calibration of \( \beta \)** Scan the reference plane by rotating \( B_2 \) axis while \( A_2 = 0^\circ \) and obtain the curve about \( \beta \) and \( B_2 \), as shown in Figure 5(a). When recognized \( \beta \) is \( 0^\circ \), \( B_2 \) is 0.277°. So \( \beta = 0.277^\circ \).
Step 2: Calibration of $\alpha$. Scan the reference plane by rotating $A_2$ axis while $B_2 = 0.277^\circ$ and obtain the curve about $h$ and $\phi$, as shown in Figure 5(b). Fit the curve using Eq.(3) and obtain $\alpha = -0.899^\circ$.

Step 3: Calibration of $\gamma, \delta x, \delta y$ and $\delta z$. Scan the reference hole along $Y_2$ direction while $A_2 = -0.899^\circ$ and $B_2 = 0.277^\circ$ and recognize the contour of the hole, as shown in Figure 5(c). Fit the measured edge using Eq.(6) and obtain $\gamma = 0.227^\circ$, $x_0 = -129.830mm$, $y_0 = -95.046mm$, $z_0 = 112.748mm$. Corresponding position deviations are $\delta x = 129.873mm$, $\delta y = 67.576mm$, $\delta z = -112.748mm$.

Step 4: Correction of deviations. Set $A_2 = -0.899^\circ$, $B_2 = 0.277^\circ$, $X_2 = 129.873mm$, $Y_2 = 67.576mm$, $Z_2 = -112.748mm$ as the new zero point of support head to correct $\alpha, \beta, \delta x, \delta y$ and $\delta z$. Use Eq.(2) to compensate for $\gamma$ during measurement data converting.

Figure 4. Calibration block: (a) Dimensions of block (unit: mm); (b) Photo of block.

Figure 5. Experiment results: (a) Calibration of $\beta$; (b) Calibration of $\alpha$; (c) Calibration of $\gamma, \delta x, \delta y, \delta z$.

The calibration results can be used to correct the assembly deviations. To verify the effectiveness of the proposed calibration method, the reference hole was scanned with and without correcting the deviations. The scanned hole contours are then recognized and then fitted to ellipses, and the lengths of semi-major and semi-minor axis are listed in Table 2. Due to orientation deviations, the uncorrected hole contour, which is the projection of a circle on the inclined plane, will appear elliptical. The difference between the semi-major and semi-minor axis characterizes the proximity of the recognized hole contour to the true hole contour, which is a circle. In other words, the smaller the difference, the higher the scanning and recognition accuracy. Obviously, the fitted ellipse with correction has a smaller difference, indicating that the measurement accuracy is improved after correction.
Table 2. Ellipse fitting results.

|                      | Semi-major axis (mm) | Semi-minor axis (mm) | Difference (mm) |
|----------------------|----------------------|----------------------|-----------------|
| With correction      | 10.13                | 10.12                | 0.01            |
| Without correction   | 10.15                | 10.09                | 0.06            |

5. Conclusion
This paper presents a pose calibration method for 2D laser profiler integrated in five-axis machine tool. Three angular deviations and three translational deviations are defined to represent the orientation and position of the laser profiler. Then, a calibration method is proposed to identify and correct the defined deviations using a designed calibration block. Experiment demonstrates the feasibility of the approach. The proposed calibration method makes full use of the large numbers of measured points through curve fitting, reduces the random error and improves measurement accuracy.

6. References
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