A new solution of measurement using 3D artefact to identify all location errors related to rotary axis of five-axis machine tool

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Abstract. In the manufacturing industry, computer numerical control (CNC) machine tool has been applied widely due to their high adaptability and precision in the machining of diversity shape, especially five-axis CNC machine tools. However, more error terms related to rotary axes, in which location errors are always considered as one of the most fundamental error sources, affect directly to machine tool performance. Thus, ensuring that a five-axis machine tool is machining within tolerance is a crucial demand in the market. This study investigates an efficient strategy using a specific 3D artifact to identify and characterize the location errors in rotary axes of a five-axis machine tool. The intended 3D artifact consists of a base plate, 2 standards ball with high roundness embedded on the top surface of the base. A Touch Trigger Probe will be utilized as the calibration instrument to capture the coordinate of 6 arbitrary contact points of the balls, then an optimization algorithm is applied to calculate the coordinate of the centers of the balls. By comparisons the relative position of the imaginary circles made of those centers with the ideal ones, all location errors will be measured individually.

1. Introduction
Machine tools with two rotary axes (A, C) to tilt and rotate a workpiece, in addition to three orthogonal translation axes, have been the most popular configuration of five-axis machine tool in the industry community. With two more rotary axes, the programmable tool orientation is very useful in the manufacturing of complicated workpiece with free-form surfaces. However, more movement components lead more kinds of error source effect directly to machine performance, both static and dynamic. In the past years, many studies have been proposed to find out the reliable solution for the identification and compensation of the geometric errors, especially location errors, caused by the two rotary axes. The results have shown that the rotary axes contribute up to 80% of the total tool positioning error [1]. On the other hand, the vibration of all machine components, especially the spindle, plays an important role in the ensuring the highest quality of the workpiece [2][3][4][5].

There have been many research works related to on-the-machine measurement for location errors of rotary axes. The methods included in ISO 230-1:2012 using 6D laser interferometer is always considered as the most common, efficient and low-cost time to measure all geometric error component. Recently, a new commercial product which can be applied along with a laser interferometer system to test the accuracy of a rotary axis has been proposed. The double ball bar (DBB) system is one of the best measurement instruments to calibrate dynamic errors of two simultaneously rotary axes [1][6].

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However, the ball bar system needs many different setups to measure individually all location errors and a competent user to operate it. Besides those direct measurement methods, many researchers have been spending more attention on developing in-direct measurement strategy, in which multi-axis motion of the machine under test. Indirect measurement using an artefact which can be machined or even in the original form (1D, 2D or 3D artefact such as ball arrays or ball plates [7][8][9] and then these artefacts will be measured by using Coordinate Measuring Machine. However, many factors such as machine parameters, CMM machine uncertainty and so on, can affect significantly to the result of the calibration process.

This study proposes a new scheme to calibrate all location errors of rotary axes by on-the-machine measurement of a 3D artifacts (precision balls) by using Touch Trigger Probe instead of CMM machine. As the matter of fact, it is limited to the center and the orientation of a rotary table, so a complete measurement procedure and a mathematical algorithm based on the idea of tracking the position of the center points of each precision balls

2. Machine configuration and location error budget

2.1. Machine configuration

This paper is considering an orthogonal five-axis machine tool configuration with a tilting rotary table (A- and C- rotate about the X- and Z- axes respectively). It is worth to notice that the idea of this research can be totally applied to any kind of machine configuration

2.2. Location error budget

As mentioned in [10] and ISO standard [11], location errors are identified as an error from the nominal position and orientation of this axis in the machine coordinate system. In fact, the location errors can be formed as the mounting errors during the assembly process. According to [7], only four location errors (two orientation errors and two position errors) are sufficient as expressed in Table 1:

| Table 1. Location errors of A and C axis |
|----------------------------------------|
| **C- Rotary Axis** | Position errors | Orientation errors |
| Linear offset in X direction \( [\delta_{Cx}] \) | Squareness error to X-axis \( [\alpha_{Cx}] \) |
| Linear offset in Y direction \( [\delta_{Cy}] \) | Squareness error to Y-axis \( [\alpha_{Cy}] \) |
| **A- Rotary axis** | Linear offset in Y direction \( [\delta_{Ay}] \) | Squareness error to Y-axis \( [\alpha_{Ay}] \) |
| Linear offset in Z direction \( [\delta_{Az}] \) | Squareness error to Z-axis \( [\alpha_{Az}] \) |

2.3. Error modelling and kinematic coordinate transformation

Since five-axis machine kinematic models can be found in many previous studies, thus this section only briefly reviews it. Positioning in the machine axes generates a tool position and orientation with respect to the workpiece coordinate system. To describe the relative position of two consecutive axes coordinate systems, a 4x4 homogeneous transformation matrix (HTM) will be widely used. Based on the structure of five-axis machine tool in Fig.1 and the kinematic chain in Fig.2, in which the origin of reference coordinate system \( r \) is fixed to the home position of Z-axis, the tool coordinate system will be expressed with respect to workpiece coordinate system as the following equation:

\[
 wT_t = (rT_w)^{-1} \cdot rT_t \tag{1}
\]

Then, by adding the estimated errors of the tool-chain and the workpiece chain, the total deviation of the tool in the global reference frame can be described.
3. Measurement procedure for location errors of rotary axis

3.1. Measuring instrument

The basic idea this indirect measuring method is the use of a precision 3D artifact (as shown in the Figure 2) in different positions in the working volume of the rotary axes. By comparing the error vectors or geometrical parameter formed from the operation process of rotary axes to their ideal ones, all location errors will be detected. The 3D artifact consists of a base plate (diameter \( d = 150 \text{mm} \)), 2 standards ball with highly geometrical precision embedded on the top surface of the base, Ball 1 (D=26mm) and Ball 2 (D=41mm) is placed as far as possible from the center for the reason of magnifying the deviation values. This device will be attached on the C-table.

![Figure 1. The kinematic chain of five-axis machine tool](image1)

![Figure 2. 3D artefact with three precision balls](image2)

3.2. Optimization algorithm for best fit sphere

As far as we know, the equation of the sphere is: 
\[
(x - x_o)^2 + (y - y_o)^2 + (z - z_o)^2 = r^2,
\]
then the minimizing function to obtain initial estimates for a sphere is: 
\[
f = r^2 - r_0^2.
\]
Expand this equation and represent the set of equations for 6 positions of the contact point between the probe and the balls in matrix form:

\[
A = \begin{bmatrix}
-2x_1 & -2y_1 & -2z_1 & 1 \\
-2x_2 & -2y_2 & -2z_2 & 1 \\
\vdots & \vdots & \vdots & \vdots \\
-2x_6 & -2y_6 & -2z_6 & 1
\end{bmatrix}
\times P = \begin{bmatrix}
x_o \\
y_o \\
z_o \\
\delta
\end{bmatrix}
+ B = \begin{bmatrix}
x_1^2 + y_1^2 + z_1^2 \\
x_2^2 + y_2^2 + z_2^2 \\
\vdots \\
x_6^2 + y_6^2 + z_6^2
\end{bmatrix}
= \begin{bmatrix}
f_1 \\
f_2 \\
\vdots \\
f_6
\end{bmatrix}

(2)

Where: \( \delta = (x_0 + y_0 + z_0) - r_0 \). The variable \( \delta \) is introduced to make the equation linear. To get the best fit sphere, it means \( f_i = 0 \). Because matrix \( A \) couldn’t be squared so \( P \) need to be satisfied the following equation: 
\[
A^TPA = A^T(-B).
\]
The estimated value of \( r \) (\( x_o, y_o, z_o \) and \( \delta \)) will be calculated by solving this equation.
After obtaining the initial estimates for the center and radius, the Gauss-Newton method is used to get the final values. The Jacobian matrix $J$ is built up and by solving the linear square equation: $J \times P = -d$, in which $radius$ is as shown: $P = [P_x, P_y, P_z, P_r]^T$ The more approximate value of the center and radius is as shown: $P = [x_0, y_0, z_0, r_0]$.

$$J = \begin{bmatrix}
\frac{\partial d_1}{\partial x_0} & \frac{\partial d_1}{\partial y_0} & \frac{\partial d_1}{\partial r_0} & \frac{\partial d_1}{\partial x_1} & \frac{\partial d_1}{\partial y_1} & \frac{\partial d_1}{\partial r_1} & \frac{\partial d_1}{\partial x_2} & \frac{\partial d_1}{\partial y_2} & \frac{\partial d_1}{\partial r_2} & \frac{\partial d_2}{\partial x_0} & \frac{\partial d_2}{\partial y_0} & \frac{\partial d_2}{\partial r_0} & \frac{\partial d_2}{\partial x_1} & \frac{\partial d_2}{\partial y_1} & \frac{\partial d_2}{\partial r_1} & \frac{\partial d_2}{\partial x_2} & \frac{\partial d_2}{\partial y_2} & \frac{\partial d_2}{\partial r_2} & \frac{\partial d_n}{\partial x_0} & \frac{\partial d_n}{\partial y_0} & \frac{\partial d_n}{\partial r_0} & \frac{\partial d_n}{\partial x_1} & \frac{\partial d_n}{\partial y_1} & \frac{\partial d_n}{\partial r_1} & \frac{\partial d_n}{\partial x_2} & \frac{\partial d_n}{\partial y_2} & \frac{\partial d_n}{\partial r_2} & \frac{\partial d_n}{\partial x_n} & \frac{\partial d_n}{\partial y_n} & \frac{\partial d_n}{\partial r_n} \\
\end{bmatrix}
\Rightarrow \begin{cases}
x_0 = x_o + p_x o \\
y_0 = y_o + p_y o \\
z_0 = z_o + p_z o \\
r_0 = r_o + p_r 
\end{cases}$$

(3)

4. Measurement procedure

4.1. Position errors
- $\delta_{CX}$ and $\delta_{CY}$:

The measuring process goes through these following steps:

**Step 1:** Measure the center position of the C- Table in the machine coordinate system then set it as the origin of the reference coordinate system (C-axis as well)

**Step 2:** Operate the C-table to rotate 30 degrees in 12 times (360 degrees in total) and detect the centers of Ball 1 and 2 for each time of rotation by using the algorithm discussed in previous sections.

**Step 3:** Two imaginary circles which are the best fit circles made up by two sets of center points from Step 2 will be built up.

**Step 4:** Projecting the error vector connecting two centers of imaginary circles from step 3, which is the actual axis of C-axis, on the $X_cOY_c$ and figure out the intersection points. Then, the position errors of C-axis ($\delta_{CX}$ and $\delta_{CY}$) will be the distance from the intersection point to $OX_c$ and $OY_c$, respectively.

- $\delta_{AY}$ and $\delta_{AZ}$:

For the A-axis, the same procedure will be gone through. However, the A-axis will be commanded to rotate 15 degrees in 6 times (90 degrees in total) and 6 center points of each Ball 1 and Ball 2 will be taken into the account. As shown in the Fig. 4, the offset between the actual A-axis and the origin of C-axis in Y-direction and Z-direction is identified. That leads to the position errors of A-axis is calculated from these equations:

$$\begin{cases}
\delta_{AY} = Y_{ac} - Y_{aw}, \text{ where } d_2 \text{ and } Y_{ac} \text{ are the machine parameters} \\
\delta_{AZ} = Z_{ac} - d_2
\end{cases}$$

(4)

The scheme of measuring process for position errors of A and C-axis is described in Figure 3.

![Figure 3. Measurement scheme for position errors of C-axis](image)
4.2. Orientation errors
The error vectors will be projected onto two orthogonal planes corresponding to C- and A- coordinate system to identify the tilting angles which are also the orientation errors.

5. Experimental case study
The present error calibration scheme is applied to a commercial five-axis milling machining center of the mentioned configuration which is MIKRON UCP 600 VARIO. A Touch-Trigger Probe, OMP40-2 by Renishaw, is mounted in the spindle head. Three standard steel balls using in Ball Bearing is employed by Probe to detect the contact of the probe ball. Table 2 shows the results of experiment In this section, 5 pairs of A and C angle is used to check the improvement of the machine accuracy after measurement and compensation process. The angle of rotation movement should be chosen wisely to avoid any kind of unwanted collision between the artifacts, Probe and other machine components. To compensate for the calibrated location errors from Table 2, a compensation algorithm, based on the idea that the tool orientation is only related to the movement of rotary axes and the purpose of simplifying the calculation process, will be applied. Table 3 shows the enhancement of the machine accuracy after compensation.

From the results shown in Table 3, it can be seen clearly that the accuracy of the machine tool has been improved over 50% in every single pair of the rotation angle of A- and C- axis. This also shows that the main contribution of the tool-tip orientation inaccuracy is the location errors of the rotary table.

| Rotation Angle [°] | Linear Axes | Linear Deviation [mm] | Improving rate | Tilting Angle [°] | Improving rate |
|-------------------|-------------|-----------------------|----------------|------------------|----------------|
|                   | Uncompensated | Compensated          |                | Uncompensated/Compensated |                |
| A = -15            | X            | -0.0681               | -0.0286        | 58.01%           |                |
| C = 0              | Y            | 1.5602                | 0.1124         | 92.8%            | 0.687          | 0.182          | 73.51%       |
|                   | Z            | -0.4058               | -0.195         | 51.95%           |                |
| A = 180            | Y            | 1.1835                | 0.3308         | 72.05%           | 1.04           | 0.0017        | 99.84%       |
| C = -15            | X            | -0.1275               | -0.0525        | 58.83%           |                |
|                   | Z            | -0.6781               | -0.1842        | 72.84%           |                |
| A = -30            | X            | 0.2285                | -0.089         | 61.06%           |                |
| C = 30             | Y            | 0.9536                | -0.2153        | 77.43%           | 1.56           | 0.35          | 77.57%       |
|                   | Z            | -0.5459               | 0.0532         | 92.26%           |                |
| A = -45            | X            | 0.509                 | 0.139          | 72.7%            |                |
| C = 60             | Y            | 1.692                 | 0.5213         | 69.2%            | 0.823          | 0.287         | 65.13%       |
|                   | Z            | -0.2324               | -0.089         | 61.71%           |                |
| A = -60            | X            | -0.859                | 0.359          | 58.21%           |                |
| C = 90             | Y            | 2.301                 | 0.926          | 59.76%           | 2.013          | 0.801         | 60.21%       |
|                   | Z            | 0.704                 | -0.254         | 63.93%           |                |

Finally, due to the inherent nature of the measurement method, the results do not include any working load. Hence, the assessment of the accuracy might not reflect the actual performance of the machine tool. It is possible that during machining there might be a cancellation of some of the geometric errors.
of the machine because of the effects of the cutting process.

6. Conclusion
The new method proves the efficiency in enhancing the accuracy of five-axis machine tool by detecting all location errors of rotary axes. It has following advantages: (1) All eight location errors regarding rotary axes can be directly identified, (2) the influence of location errors of rotary axes will be emphasized by neglecting the geometric errors of all linear axes, (3) the proposed method is characterized by easy setup. More importantly, the method can be extended to other configurations of five-axis machine tool and considered as a form of regular acceptance test of machine accuracy.

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Acknowledgments
This work was supported by The University of Da Nang – University of Science and Technology, code number of project: T2019-02-07