Title:
Calculation of Five-Axis Machine Tool Location Errors

Authors:
Jorge Adan Cubas Brizuela, cubas89@gmail.com, National Taipei University of Technology
Syh-Shiuh Yeh, ssyeh@ntut.edu.tw, National Taipei University of Technology

Keywords:
Location Error, Five-Axis Machine Tool, Touch-Trigger Probe, Calibration Sphere

DOI: 10.14733/cadconfP.2022.150-154

Introduction:
The accuracy of five-axis computer numerical control (CNC) machine tools is the most significant factor during cutting processes. However, such accuracy can be easily compromised, primarily due to the location errors of the machine. Therefore, the correction of the location errors becomes crucial for improving the machine performance and the manufacturing accuracy of the products. Touch-trigger probes have been extensively used for many years in the on-machine measurements of the dimensional accuracy of machining tools and parts, due to their simplicity and ease of use. Therefore, the location errors can be calculated and identified using touch-trigger probes and probing systems. For instance, Huang et al. [1] developed an error measurement and identification method for the rotary axes by using a touch-trigger probe and a test piece installed on the five-axis CNC machine tool. Jiang et al. [3] developed a model-based algorithm for decoupling the squareness errors induced by motions of the linear and rotary axes. Then, they proposed a probing procedure to identify the location errors of the five-axis CNC machine tool as the moving distance of the linear axes increased, but without using additional auxiliary equipment. Existing approaches have demonstrated the feasibility of using a set of touch-trigger probes and a test piece for the measurement of the geometric errors of five-axis CNC machine tools. Nevertheless, the measurement and calculation results were significantly affected by the operational methods and inherent characteristics of touch-trigger probes [2,4].

The objective of this study is to design and implement an off-line data acquisition and processing method for precisely calculating the location errors particular to five-axis CNC machine tools, while mitigating the adverse influences caused by the use of touch-trigger probes. This study is conducted in three stages: the data acquisition protocol, data pre-filtering and error calculation, and data filtering from the calculation results. In particular, the filtering approaches in the data processing stage improve the calculation results. The statistical characteristics of the measurement data points, and all the possible combinations are further considered to reduce the adverse influence of the measurement errors on the calculation results. The location errors of a five-axis CNC machine tool were calculated off-line using the approaches developed in this study. These calculated location errors were used to set the error compensation parameters used in the adopted CNC controller in order to realize the compensation of location errors. To further validate the data acquisition and processing method developed in this study, the calculated location errors were compared with the results obtained using the procedures that have been adopted extensively by commercial manufacturers of five-axis CNC machine tools. The cutting tests performed on an AC-type five-axis CNC machine tool indicated a significant decrease in location errors by applying error compensation to the calculated results.

Hardware Description:
This study was conducted by using a five-axis AC-type CNC machine tool, which utilized the FANUC controller series 31i-Model B5, as shown in Fig. 1. The calibration sphere used in the experiment had a diameter of 30 mm, which was actually measured as 29.9996 mm. The touch-trigger probe was the main tool used during the procedure, and was designed as the data input source of the calculation system. Through several moving tests, a feed rate of 10 mm/min was used to move the touch-trigger probe to minimize measurement errors. The laptop computer with Intel Core i7-4800MQ, 2.7-GHz CPU, and 64-bit Microsoft Windows 8.1 operating system was utilized to implement the whole system developed in this study; moreover, the Matlab R2014a software was used for the calculations and simulations in this study.

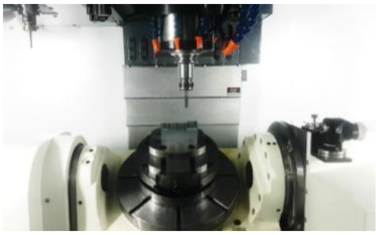

Fig. 1: Working space of the five-axis CNC machine tool employed in this study.

Data Acquisition:
In this study, three phases were established for data acquisition, as follows:
(A) Device calibration phase:
- The calibration sphere was fixed either by the magnetic base or by being screwed in place with the C-axis at the zero position.
- The length between the rotary table of the machine (C-axis) and the spindle at its zero Z position were measured, and the value was saved for further use.
- The spindle (mounted in the linear Z-axis) was set to zero, and the rotary axes were sent to the home-position. Then, the touch-trigger probe was mounted in place.

(B) Data acquisition phase:
- The calibration sphere was measured by contacting the stylus of the touch-trigger probe at five different points on the calibration sphere, and the sensed coordinates were recorded to calculate the sphere position.
- The positions of the calibration sphere were arranged from 0° to 360° with 10° increment while the rotary C-axis rotating, and therefore there are 36 sphere positions for the C-axis. It is noticed that the rotary A-axis was kept at 0° when the rotary C-axis is rotating.
- Similarly, for the rotary A-axis, the positions of the calibration sphere were arranged from -90° to +30° with 10° increment. There are 13 sphere positions for the A-axis and the rotary C-axis must be kept at 0° when the rotary A-axis is rotating.

(C) Data arrangement phase:
- The data obtained in each position was constructed based on the five points located at positions Xc+, Xc-, Yc+, Yc-, and Zc- of the sphere where the letter “c” represents the contact point between the probe and the calibration sphere, while the variables X, Y, and Z represent the direction of contact. The sign “-” represents the up to down movement of the probe, for each one of the contact points with coordinates X, Y, and Z. This protocol was designed to calculate an accurate center for the calibration sphere at each of the 49 positions with distributions: 36 positions for the C-axis and 13 positions for the A-axis.
- The five-point set was arranged into four different combinations with distributions: {Xc+, Xc-, Yc+, Zc-}, {Xc+, Xc-, Yc-, Zc-}, {Xc+, Yc+, Yc-, Zc-}, and {Xc-, Yc+, Yc-, Zc-}, where each arrangement maintained the Zc- point of the sphere. This avoided an error in the Z axis, which commonly occurs when the other four points are in the X-Y plane. Each combination of points was obtained while disregarding one of the Xc+, Xc-, Yc+, and Yc- contact points each time. As

an example, to gain a better understanding into this matter, the first set of points will be Xc+, Xc-, Yc+, Zc-, the second set will be Xc+, Xc-, Yc-, Zc-, the third set will be Xc+, Yc+, Yc-, Zc-, and the final set will be Xc-, Yc+, Yc-, and Zc-.

- After each set was calculated, the four obtained centers were combined and averaged, and the resultant value was taken as the center of that position. In this way there are 36 centers for the C-axis, with one center in each position, and 13 centers for the A-axis. These centers were later used to create a plane in which any three centers of each axis were contained. This can be used to calculate the center between the three center points, and also can be used to create a vector normal to the plane. Moreover, this normal vector was perpendicular to the plane between the three center points but was not normal to the machine's zero-plane origin. This means that there is an angle difference between this vector and the machine's zero-plane normal vector, which can be applied to calculate the deviation of the machine. It is clear that this value could affect the accuracy of the machine.

Calculation:

When the centers and the normal vectors of rotary axes C and A were calculated, the data required to calculate the machine location errors can also be obtained. By ISO definition, these errors consist of the rotary axes position, rotary axes orientation, and zero position or offset. According to ISO 230-7, the machine errors for the rotary axis are as presented in Tab. 1. In this case, for the rotary axis C, where XOC is the X position of C, YOC is the Y position of C, AOC is the squareness of C to Y, and BOC is the squareness of C to X, Fig. 2. illustrates this relationship with more clarity. In Fig. 2., the location errors of the C axis are illustrated more clearly, where XOC is the X value of the coordinate where vector $\vec{N}$ crossed the plane XY, and YOC is the Y value of the coordinate where vector $\vec{N}$ crossed the plane XY. AOC is the angle between the projection of vector $\vec{N}$ in the YZ plane and the Z axis of the machine. The BOC error is the angle between the projection of vector $\vec{N}$ in the XZ plane and the Z axis of the machine, and the angle deviation is the angle between vector $\vec{N}$ and the Z axis of the machine.

C - axis	A - axis	B - axis
XOC	YOA	XOB
YOC	ZOA	ZOB
AOC	BOA	AOB
BOC	COA	COB

Tab. 1: Location error nomenclature.

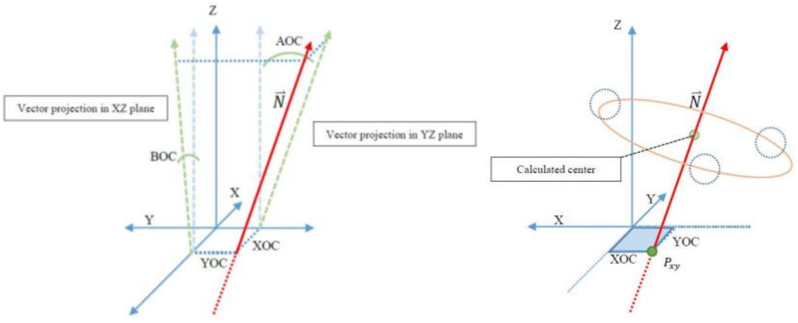

Fig. 2: Location errors in C-axis.

Fig. 2. also illustrates the relationships among the calculated center, the normal vector, and the machine coordinate frame. The XOC and YOC errors can be calculated by Eqn. (4.1). Here, P_{xy} is the intersection point between vector $\vec{N}$ and the XY plane, and Cxy is the center of the calculated circle.

Proceedings of CAD'22, Beijing, China, July 11-13, 2022, 150-154

Cxy(z) denotes the Z-component of the calculated center Cxy and $\vec{N}(z)$ denotes the Z-component of the vector $\vec{N}$. The X and Y coordinates of point P_{xy} correspond to the XOC and YOC values. In the same way, the errors of the titling axis were calculated after calculating the centers of each position of the sphere.

$$P_{xy} = Cxy - \left(\frac{Cxy(z)}{\vec{N}(z)}\right) \cdot \vec{N} \tag{4.1}$$

The computer program to calculate the location errors was developed in four different stages. Stage one consisted of declaring the global variables and the input of calculation data. In this stage, the sphere position was also plotted by using the center of each sphere as a reference. This plotted diagram provided a better idea about the set of points by representing them graphically, and aided during the debugging stage if there was a problem with the dataset prior to the calculation. The second stage consisted of the first error calculation, which was strictly aimed at the location errors in the C-axis, which were defined based on ISO 230-7. Because 36 data points were measured on the C-axis and 13 data points were measured on the A-axis in this study, the numbers of combinations were 7,140 and 286 for the C-axis and A-axis, respectively. The operations in this stage entailed iterations based on the number of combinations calculated previously. Each iteration calculated the errors for a set of three points, which means that each iteration obtained the axis center, total radius from the axis to the plotted circle, $\vec{N}$ vector perpendicular to the plane where the circle was contained, location errors for the XOC, YOC, AOC, and BOC for C-axis, respectively, and the angle deviation. The third stage consisted of calculating the errors of the AC-type CNC machine tool. The calculation for the A-axis was executed by following the same structure, but with a different reference to the nomenclature presented in Tab. 1. with regard to the description of each axis. The fourth and last stage consisted of the part of the program managing the calculated data, which were processed to obtain a more accurate result. This was achieved by eliminating some of the calculated errors exhibiting erroneous behavior according to the selection process, since they may had compromised the accuracy of the performed calculations. The selection process was based on the normal distribution method, which was used in order to calculate the probability distribution.

Validation:

To validate the developed method and ensure that it is at least comparable to already existing approaches, a real test had to be carried out. Such a test was developed by a machining tool company, and consisted of cutting the surface of a square shape work-piece divided into nine different sections. In this test, each section is machined by using a combination of angles for the rotary axes of the five-axis CNC machine tool. The first section was cut in the center at A = 0 and C = 0. Then, this section was taken as the reference, and the rest of the sections were measured and compared to the first section by using a micrometer. Thereby, the closer the height of each section was, the better was the accuracy of the machine. The experiment was executed on an aluminum material by using a round-tip milling tool. The test was carried out with a spindle speed of 6,000 rpm and feed rate 600 mm/min. In Fig. 3., it shows that how the work piece was divided, the sequence of the machined sections, and the angles used in each section. First, the test was conducted by using the parameters calculated by the commercialized measurement software. Then, the piece was measured, and the same setup was used in the second test, but with the values updated based on the calculation results of this study. To make the results more comprehensible, the final result of both tests can be seen in Fig. 4. Here, all measurements and compensation processes were performed under the similar temperature (around 28°C) and air humidity (relative humidity around 75%) for a comparison fair. For the test conducted with the values from the machine, the maximum value of the errors was -15 μm and occurred at sections 5, 8, and 9. The average value of errors (AVG), maximum value of absolute errors, and root-mean-square value of errors (RMS) were -9.8889 μm, 15 μm, and 10.9697 μm, respectively. On the other hand, the height errors were significantly reduced by applying the values obtained from the calculation proposed in this study. The maximum value of the errors was -3 μm and occurred at section 8, where the A-axis was located at -30° and the C-axis was located at 270°. The AVG value was -0.1111 μm, and was much smaller than that of the first test. A 98.88% rate of improvement was achieved. The RMS value was 1.7321 μm, and was also much smaller than that of the first test. An

84.21% rate of improvement was achieved, and this demonstrated the precise calculation of location errors and the feasibility of the programming process proposed in this study.

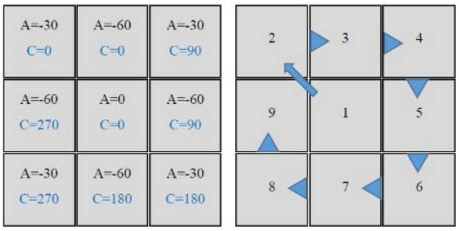

Fig. 3: Rotary axes parameters and machining path.

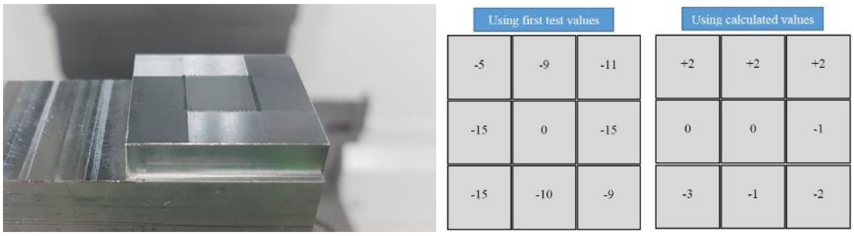

Fig. 4: Workpiece after cutting test.

Conclusions:

The five-axis CNC machine tool generally has 43 errors (including component errors and location errors) that significantly depend on the manufacturing and assembly processes of the machine tool. This study focused on the design of the calculation and programming processes to significantly improve the calculation results for the measurement of the geometric errors of a five-axis CNC machine tool using the acquired data points that could be contaminated during the touch-trigger probe measurement processes. This study considers the statistical characteristics of the measurement data points and all possible combinations to reduce the effects of measurement errors on the calculation results. The cutting test that is generally used by manufacturers to evaluate the motion performances of a five-axis CNC machine tool, successfully validated the proposed approaches with the statistical analysis developed in this study.

Acknowledgements:

This research was supported in part by the Ministry of Science and Technology, Taiwan, under Contract MOST110-2221-E-027-116.

References:

[1] Huang, N.; Zhang, S.; Bi, Q.; Wang, Y.: Identification of Geometric Errors of Rotary Axes on 5-Axis Machine Tools by On-Machine Measurement, International Journal of Advanced Manufacturing Technology, 84(1-4), 2016, 505-512. https://doi.org/10.1007/s00170-015-7713-y

[2] Jankowski, M.; Wozniak, A.: Mechanical Model of Errors of Probes for Numerical Controlled Machine Tools, Measurement: Journal of the International Measurement Confederation, 77, 2016, 317-326. https://doi.org/10.1016/j.measurement.2015.09.023

[3] Jiang, Z.; Bao, S.; Zhou, X.; Tang, X.; Zheng, S.: Identification of Location Errors by a Touch-Trigger Probe on Five-Axis Machine Tools with a Tilting Head, International Journal of Advanced Manufacturing Technology, 81(1-4), 2015, 149-158. https://doi.org/10.1007/s00170-015-7189-9

[4] Wozniak, A.; Jankowski, M.: Variable Speed Compensation Method of Errors of Probes for CNC Machine Tools, Precision Engineering, 49, 2017, 316-321. https://doi.org/10.1016/j.precisioneng.2017.03.001