

## Selection method of CNC machine tools based on big data cloud database

Qing Liu<sup>1</sup>, Dun Lyu<sup>1</sup>, Wanhua Zhao<sup>1</sup>

<sup>1</sup>School of Mechanical Engineering, Xi'an Jiaotong University

[liuqing67@stu.xjtu.edu.cn](mailto:liuqing67@stu.xjtu.edu.cn)

### Abstract

Parts from design models to actual entities generally are achieved by machining. And the machining accuracy rely on the choice of CNC machine tool. However, it is hard to predict whether the choice of machine tool is reasonable and whether it can complete the machining efficiently on the premise of satisfying the accuracy requirement. In this study a method based on a machine tools big data was proposed to select the machine tools. A machine tool big data cloud database was built to collect and upload the data through identification experiment of candidate machine tool. The actual position prediction method of the feed shaft for five-axis machining and the solving method of the contour error for the part were established respectively. The actual position of the feed shaft for five-axis machining is predicted by using the big data cloud database to establish the transfer function of each axis for the machine tool, and the actual position of each axis is predicted by inputting the interpolation instruction of each axis into the transfer function. The solving method of the contour error for the part is established by using the big data cloud database to synthesize the interpolation instruction and predicted actual position of each axis, and then to calculate the contour error of the part. The new method proposed herein can choose the optimal CNC machine tool with high efficiency and accuracy.

Keywords: big data cloud database, CNC machine tool, actual position prediction, contour error

### 1. Introduction

At present, the global manufacturing industry is accelerating to the era of digitization and intelligence, and the impact of intelligent manufacturing on the manufacturing industry is growing rapidly. CNC machine tools as the basis of industrial manufacturing have an irreplaceable position. Combining CNC machine tools with intelligent manufacturing to improve the accuracy of CNC machine tools has become the goal of the tireless efforts of machine tool designers and manufacturers in the new era<sup>[1]</sup>.

Machining accuracy and processing efficiency are the main indicators for measuring the performance of CNC machine tools. However, the processing of complex curved parts is difficult, and the machining accuracy and efficiency are difficult to unify. If the machining accuracy is to be ensured, it is often necessary to reduce the feed rate and sacrifice the machining efficiency. If the machining efficiency is to be improved, a higher accuracy machine tool is required, which leads to higher processing cost. In order to overcome the shortcomings mentioned above, an intelligent selection method of CNC machine tools with optimal machining accuracy and efficiency was proposed. The purpose of this method is to combine the big data cloud database to predict the tool path accuracy before processing, and select the optimal CNC machine tool to improve the machining accuracy, processing efficiency and reduce the processing cost.

### 2. Establishing the machine tools big data database for accuracy prediction

In order to choose the optimal CNC machine tool in the factory, even the whole society, on the one hand, it is necessary to treat the candidate machine tool for identification experiments to obtain the transfer function of each axis to get

the actual displacement of each axis by simulation. On the other hand, it is necessary to combine the part displacement instruction into instruction continuous path and the actual displacement of each axis into actual continuous path to predict the accuracy of the parts. Thus, high accuracy machine tools can be selected before processing<sup>[2-4]</sup>.

Therefore, the cloud database stores not only a large amount of data required for the system identification, but also a large amount of data required for the accuracy prediction.

#### 2.1. Obtaining the machine tools status data

##### 2.1.1. Obtaining the data used for system identification

The excitation displacement instruction is generated by the NC system interpolation of the excitation code which are used for the identification of the servo feed system. The excitation displacement instruction is mainly used for the identification experiment of the candidate machine tool. As the input interpolation instruction of the candidate machine tool, the excitation displacement instruction is used to fully excite the characteristics of machine tool to obtain the transfer function of each axis.

The method for obtaining the system identification data is as follows. The excitation code is generated by using the inverse M sequence and input into the NC system to obtain the excitation displacement instruction after the NC system interpolation. After the excitation displacement instruction passes through the servo feed system, the generated grating feedback displacement, encoder feedback speed, actuator end displacement and sampling frequency are collected.

##### 2.1.2. Obtaining the transfer function of each axis

The identification experiment is performed by using the excitation displacement instruction, actuator end displacement/grating feedback displacement/encoder feedback speed, sampling frequency etc. to obtain the transfer function of each axis for the candidate machine tool.

The input-output relationship of established transfer function is as follows,

$$G(z^{-1}) = \frac{B(z^{-1})}{A(z^{-1})} = \frac{\sum_{i=0}^{n_b} b_i z^{-i}}{1 + \sum_{j=1}^{n_a} a_j z^{-j}} \quad (1)$$

Where,  $B(z^{-1})$  is actuator end displacement/grating feedback displacement/encoder feedback speed value.  $A(z^{-1})$  is excitation displacement instruction value.  $b_i$  and  $a_j$  are the coefficients of the discrete transfer function numerator and denominator, respectively.  $n_a$  and  $n_b$  are the order of the discrete transfer function numerator and denominator, respectively. And,  $b_i$ ,  $a_j$ ,  $n_a$ ,  $n_b$  are obtained by identification.

The identification method of numerator order  $n_a$  and denominator order  $n_b$  for discrete transfer function is search method, in which the discrete transfer function of different order is identified by setting the range of order-valued definition, and the order value with the least estimation error is selected as the order parameter identification result.

The identification method of numerator coefficient  $b_i$  and denominator coefficient  $a_j$  of the discrete transfer function is the least squares method<sup>[5]</sup>.

### 2.1.3. Obtaining the data used for accuracy prediction

First, the geometry of the selected complex surface part is designed by CAD, and it is converted into part NC codes by CAM. Then, the part NC codes are input into the NC system and the part displacement instructions are gotten after interpolation. The final step is to collect part NC code, part displacement instruction and sampling frequency.

## 2.2. Establishing the machine tools database

The excitation displacement instruction is generated by the NC system interpolation of the excitation code which are used for the identification of the servo feed system. The excitation displacement instruction is mainly used for the identification experiment of the candidate machine tool. As the input interpolation instruction of the candidate machine tool, the excitation displacement instruction is used to fully excite the characteristics of machine tool to obtain the transfer function of each axis.

The data of machine tools database set up in this paper include: part NC code, part displacement instruction, excitation code, excitation displacement instruction, grating feedback displacement, encoder feedback speed, actuator end displacement, each axis transfer function, sampling frequency, machine tool number, machine tool type, machine tool axis number, and date.

These data are divided into two types: identification data and accuracy prediction data. Then a database form is established.

In the identification data form, the data such as date, machine tool number, machine tool type, machine tool axis number, excitation code, excitation displacement instruction, actuator end displacement, grating feedback displacement, encoder feedback speed, and transfer function are the form header.

In the accuracy prediction data form, the data such as date, machine tool number, machine tool type, machine tool axis number, sampling frequency, part NC code, and part displacement instruction are the form header. As shown in table 1 and table 2.

Table 1 Identification Database Form

Identification Database Form				
Date	Machine Tool Number	Machine Tool Type	Machine Tool Axis Number	Excitation Code
	No. i			
Excitation Displacement Instruction	Actuator End Displacement	Grating Feedback Displacement	Encoder Feedback Speed	Transfer Function

Table 2 Accuracy Prediction Database Form

Accuracy Prediction Database Form			
Date	Machine Tool Number	Machine Tool Type	Machine Tool Axis Number
	No. i		
Sampling Frequency	Part NC Code	Part Displacement Instruction	

## 3. The tool path accuracy prediction method using machine tools state data

### 3.1. Describing the structure of machine tool

The relationship between the various parts of the machine tool can be described by topology. Taking an A-C double-turn five-axis milling machine composite vertical machining as an example, the topological structure diagram is set up as shown in Fig. 1.

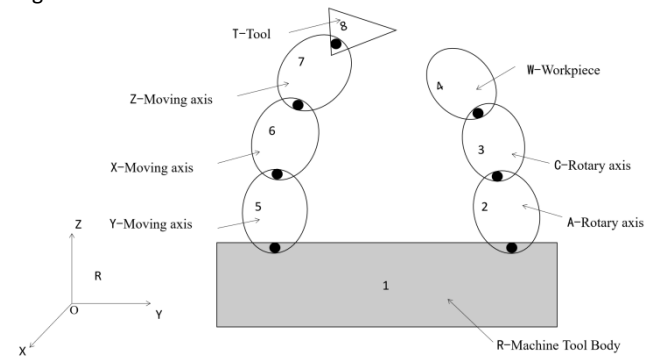


Figure 1. The topological structure diagram of the A-C double-turn machine tool.

### 3.2. Establishing the feature transformation of moving body

According to the topology structure diagram established in the previous section, the independent coordinate systems for machine tool each part are established as shown in Fig. 2.

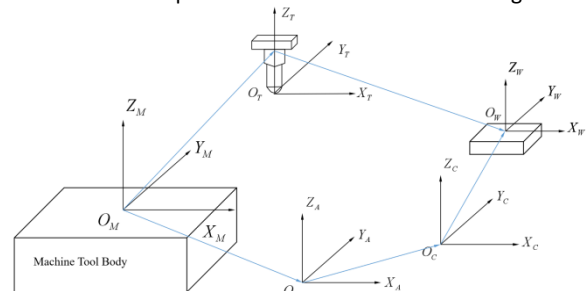


Figure 2. Coordinate system of A-C double-turn machine tool each part.

The research on the position change of each adjacent moving body can be converted into the study of each moving body

coordinate system, which is described by the mathematical method of 4x4 order feature transformation matrix<sup>[6]</sup>.

The X-axis, Y-axis and Z-axis translational motion feature transformation matrix are as follows

$$T_X = \begin{bmatrix} 1 & 0 & 0 & x_{ij} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} T_Y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & y_{ij} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} T_Z = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & z_{ij} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

The X-axis, Y-axis and Z-axis rotational motion feature transformation matrix are as follows

$$R_A = R(X, \theta_A) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \theta_A & -\sin \theta_A & 0 \\ 0 & \sin \theta_A & \cos \theta_A & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$R_B = R(Y, \theta_B) = \begin{bmatrix} \cos \theta_B & 0 & \sin \theta_B & 0 \\ 0 & 1 & 0 & 0 \\ -\sin \theta_B & 0 & \cos \theta_B & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_C = R(Z, \theta_C) = \begin{bmatrix} \cos \theta_C & -\sin \theta_C & 0 & 0 \\ \sin \theta_C & \cos \theta_C & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

If the origin of the coordinates in the tool coordinate system is set at the end face of the spindle, the effect of the tool length on the coordinate transformation needs to be considered. Setting the length of the tool is  $L_{\text{tool}}$ , the feature transformation matrix from the end face of the spindle to the tool center point is  $T_{\text{tool}}$ .

$$T_{\text{tool}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_{\text{tool}} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

### 3.3. Combing into the continuous path of machine tools

Since the coordinate system of the candidate part is the work piece coordinate system, and the data collected in the actual machining is the actual position of the tool center point, the acquired data needs to be converted from the tool coordinate system to the work piece coordinate system.

Taking an A-C double-turn five-axis milling machine composite vertical machining as an example, the feature transformation matrix can be obtained as follows

$$T_{\text{tw}}(X, Y, Z, A, C) = {}^w T_c T_c^w R_C^c T R_C^A T R_A^A T R_A^Y T Y^X T X^Z T Z^{\text{tool}} \quad (5)$$

$$= \begin{bmatrix} \cos \theta_C & -\cos \theta_A \sin \theta_C & \sin \theta_A \sin \theta_C & F_x \\ \sin \theta_C & \cos \theta_A \cos \theta_C & -\sin \theta_A \cos \theta_C & F_y \\ 0 & \sin \theta_A & \cos \theta_A & F_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where

$$\begin{cases} F_x = (Z + L_{tz}) \sin \theta_A \sin \theta_C - Y \cos \theta_A \sin \theta_C - L_{acy} \sin \theta_C \sin \theta_C \\ \quad + X \cos \theta_C + L_{ac} \sin \theta_C - L_{cwx} \cos \theta_C + L_{awx} \\ F_y = (-L_{tz} - Z) \sin \theta_A \sin \theta_C + Y \cos \theta_A \cos \theta_C \\ \quad + L_{acy} \cos \theta_C + X \sin \theta_C + L_{acx} \sin \theta_C + L_{cwy} \\ F_z = (Z + L_{tz}) \cos \theta_A + Y \sin \theta_A + L_{acz} + L_{cwx} \end{cases} \quad (6)$$

In the work piece coordinate system, the homogeneous coordinates of the tool center point and the tool axis direction are as follows

$${}^w P = (x \ y \ z \ 1)^T \quad {}^w V = (i \ j \ k \ 0)^T \quad (7)$$

In the tool coordinate system, the homogeneous coordinates of the tool center point and the tool axis direction are as follows

$${}^T P = (0 \ 0 \ 0 \ 1)^T \quad {}^T V = (0 \ 0 \ 1 \ 0)^T \quad (8)$$

so

$$[{}^w V \ {}^w P] = T_{\text{tw}}(X, Y, Z, A, C) [{}^T V \ {}^T P] \quad (9)$$

The forward kinematics transformation of A-C double-turn machine tool is as follow

$$\begin{cases} x = F_x \\ y = F_y \\ z = F_z \end{cases} \quad \begin{cases} i = \sin A \sin C \\ j = -\sin A \cos C \\ k = \cos A \end{cases} \quad (10)$$

So far, the data such as actuator end displacement, grating feedback displacement, encoder feedback speed have been transformed from tool coordinate system to work piece coordinate system. Then, sampling frequency, part displacement instruction and other data should be download from the cloud database. And the final step is combining the displacement instruction of the parts into instruction continuous path and the actual displacement of each axis into actual continuous path by using MATLAB emulation program.

### 3.4. Calculating the continuous path error of machine tools

The machine tool continuous path error refers to the normal path error between the actual continuous path and the instruction continuous path. The continuous path error is solved according to the tracking error and the end error by using the spatial geometric vector.

Taking a five-axis CNC machine tool as an example, the point milling method is used, as shown in Fig. 3.  $p_r = [p_{rx}, p_{ry}, p_{rz}]$  is the instruction tool center point,  $p_a = [p_{ax}, p_{ay}, p_{az}]$  is the actual tool center point;  $p_c = [p_{cx}, p_{cy}, p_{cz}]$  is the point closest to the actual continuous path point on the instruction continuous path and is the calculation reference point of the contour error. The vector  $\overline{p_c(i)}p_a(i)$  is defined as the tracking error vector  $\overline{p_c(i)}, \varepsilon(i)$  is the approximate path error vector, that is, the five-axis continuous normal path error, as shown in Fig.4<sup>[7-10]</sup>.

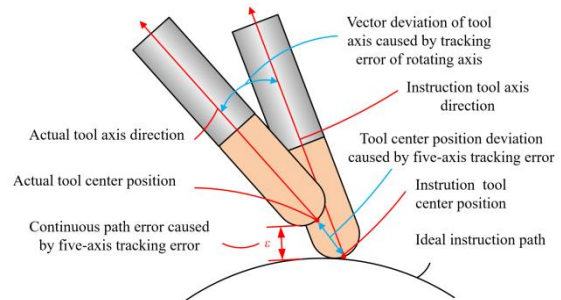


Figure 3. Continuous error caused by five-axis tracking error.

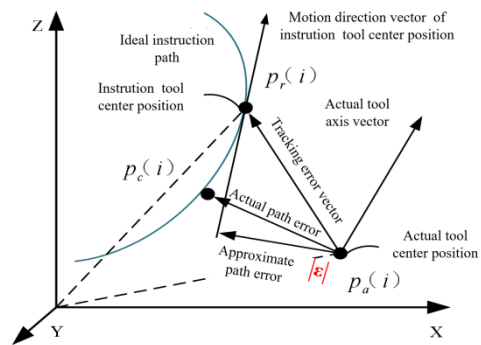


Figure 4. Five-axis continuous normal path error.

#### 4. The intelligent optimization method for cnc machine tools

The flow chart of the intelligent method for machine tools is shown as Fig. 5.

Firstly, the machine tools big data cloud database is built including the data used for identification and accuracy prediction. Secondly, the candidate machine tool is used for system identification experiment. The part displacement instruction is input to each axis transfer function read from the database, and the output is the actual displacement of each axis for machine tool. Finally, the machine tool continuous path accuracy prediction is performed. The actual displacements of each axis combine into actual continuous path, and the part displacement instruction combine into instruction continuous path to calculate normal path error between the actual continuous path and the instruction continuous path.

#### 5. Conclusion

The CNC machine tool and intelligent manufacturing are combined in this paper, and the methods of system identification, multi-body system motion feature analysis and moving volume feature transformation matrix are combined on the basis of data cloud database to select CNC machine tools which accord with machining accuracy and efficiency before machining.

This method is a general method, choosing the best machine tools in the factory and the whole society, and can make full use of the performance of the machine tool and ensure the high efficiency and high accuracy machining of the parts, realizing the unification of machining accuracy.

#### References

- [1] BOHEZ E L J . Five-axis milling machine tool kinematic chain design and analysis[J]. International Journal of Machine Tools and Manufacture, 2002, 42(4):505-520.
- [2] LI Jie, XIE Fugui, LIU Xinjun, et al. Analysis on the research status of volumetric positioning accuracy improvement methods for five-axis NC machine tools [J]. Chinese Journal of Mechanical Engineering, 2017, 53(7): 113-128.
- [3] GUO Shijie, JIANG Gedong, MEI Xuesong. Motion error measurement and identification of rotary axis of five-axis machine tool [J]. Transactions of the Chinese Society for Agricultural Machinery, 2019, 50(2): 402-410, 426.
- [4] LÜ Dun, LI Runze, LIU Hui, et al. A control strategy of tracking errors for numerical control machine tools at high speed and acceleration feeding [J]. Journal of Xi'an Jiaotong University, 2018, 52(12): 25-31.
- [5] PANG Zhonghua, CUI Hong. MATLAB simulation of system identification and adaptive control[M]. Beijing: Beijing University of Aeronautics and Astronautics, 2009.8. ISBN 978-7-81124-769-5. P27-30.
- [6] DENAVIT J, HARTENBERG R S. A kinematic notation for lower-pair mechanisms based on metrics [J]. Journal of Applied Mechanics, 1955, 22(2): 215-221.
- [7] YANG J X, ALTINTAS Y. A generalized on-line estimation and control of five-axis contouring errors of CNC machine tools [J]. International Journal of Machine Tools and Manufacture, 2015, 88: 9-23.
- [8] ERKORKMAZ K, YEUNG C H, ALTINTAS Y. Virtual CNC system: part II High speed contouring application [J]. International Journal of Machine Tools and Manufacture, 2006, 46(10): 1124-1138.
- [9] ERKORKMAZ K, ALTINTAS Y. High speed contouring control algorithm for CNC machine tools[C]// Proceedings of ASME Dynamic Systems and Control Division. USA: ASME ,1998: 463-469.
- [10] ERKORKMAZ K, YEUNG C H, ALTINTAS Y. Virtual CNC system: part II High speed contouring application [J]. International Journal of Machine Tools and Manufacture, 2006, 46(10): 1124-1138.

