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Research paper

# Prediction of machining accuracy and surface quality for CNC machine tools using data driven approach☆

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A B S T R A C T

CNC machine tool is universal machinery in industry, and each product has the different quality requirements during machining process. Therefore, the performance of machine tool is very important for machining capabilities. The milling accuracy and surface quality are usually regarded as the indicators of product quality, and these indicators are affected by CAD/CAM, machining parameters of CNC controller, servo loop, and feed drive system, etc. In this paper, we propose a data driven method to predict machining quality of product by ANFIS model, which the inputs are CNC machining parameters and the outputs are two performance indexes (milling accuracy and surface quality). The corresponding fuzzy rules can be extracted from the ANFIS for user to understand the relationship between CNC parameters and performance indexes. Finally, simulation and experimental results illustrate that the two indexes can be predicted effectively for different machining parameters. Therefore, this predicted system can help user to achieve the required product quality and machining productivity.



## 1. Introduction

In our life, many implements were manufactured by CNC machine tools, and Machinery is a foundation of industry, which can be regarded as the development level of country. The automobile, aerospace materials, mold, screw and precision components are based on mechanical manufacturing. The machining products have strict quality threshold for military product, aerospace materials and semiconductor, etc. With requirements of high product quality and machining productivity, high-speed and high precision is main trend for CNC machine tool in the future. Therefore, it is an important topic that how to improve the machining capabilities of machine tool and more intelligent [1–12].

In general, each product has different machining requirement; the milling accuracy and surface quality are usually regarded as performance index of product quality during machining process. However, the machining flow, shown in Fig. 1, includes design of CAD/CAM, machining parameters of CNC controller, servo control, feed drive system and mechanical property [13–22]. The machining performance indexes will be affected by these operations. Fig. 2 shows the dynamic model of feed drive system. Fig. 3 shows the control architecture for servo loop and feed system. From these two figures, we can find that the feed drive system of machine tools includes the PID controller, motor torque, rotary inertia, stiffness of lead screw, table mass, etc. It is obvious that the adjustment of PID controller in servo loop and the design of mechanical body will affect the motion for each axis. For example, the inappropriate PID parameters will cause the resonance of machinery or servo lag. The asymmetric body design and the unsuitable components will cause the geometric errors for axial movement.

For machining processes, users should ask the experts (or according experiences) to choose the better CNC machining parameters for different requirements of product. However, these experiences have not been concluded for expert rules. Therefore, in this paper, our objective is to know the effects of CNC machining parameters on machining accuracy and surface quality, which includes jerk, acceleration and feedrate, etc. Therefore, the predicted system is developed by data driven approach. Data-driven methods from machine learning and data mining have traditionally been used for analyzing static data sets that are not updated very frequently. This means that we mainly use data to directly to do predictions or by generalizing to a model from the data.

In this study, we propose an intelligent predicted system for milling accuracy and surface quality of machining operation by using data driven approach [23–25], and the predicted system is based on adaptive neuro-fuzzy inference systems (ANFIS) [26–33]. The experimental data are collected for calculating contouring error and tracking error corresponds to milling accuracy and surface

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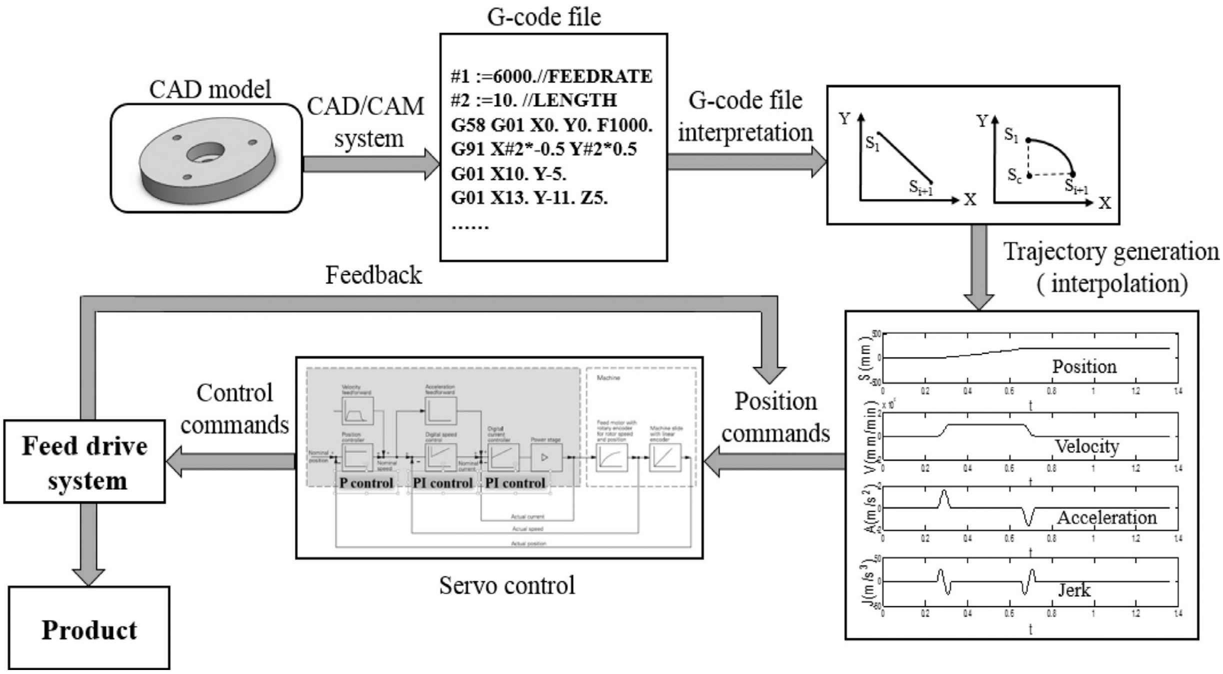



**Fig. 1.** Illustration of machining flow.

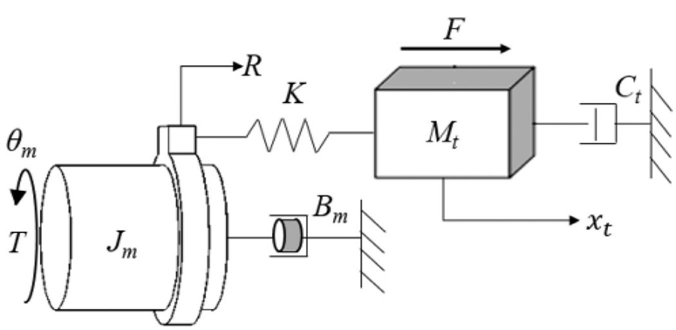


**Fig. 2.** Freebody diagram of feed drive system.

quality, and the ANFIS model is established by these data set. The inputs and outputs of ANFIS model are CNC machining parameters and two performance indexes, respectively. Finally, the results illustrate that milling accuracy and surface quality can be predicted effectively for different machining parameters.

This rest of this paper is introduced as follows. Section 2 introduces the CNC machining parameters, milling accuracy, surface quality, and major specification of the used machine tool. Section 3 introduces adaptive neuro-fuzzy inference systems. The proposed method for prediction of milling accuracy and surface quality using data driven approach is introduced in Section 4. In addition, the predicted results of and fuzzy rules are also introduced here. Finally, the conclusion is given.

## 2. CNC machining parameters and machining performance indexes

### 2.1. CNC machining parameters

The machining is a very complicated process, the quality of product depends on the design of mold, controllers, servo loop, feed drive system, mechanical structure [13–21], etc. The CNC controller plays the role of the brain for machining tools, which are high value-added products, and the machining parameters of CNC controller are the one of key factor for machining capabilities. In this study, we choose the milling accuracy and surface quality as the main performance indexes of product. Over several parameters are provided by CNC machining tool and each controller of manufacturer has different definition for machining parameters.

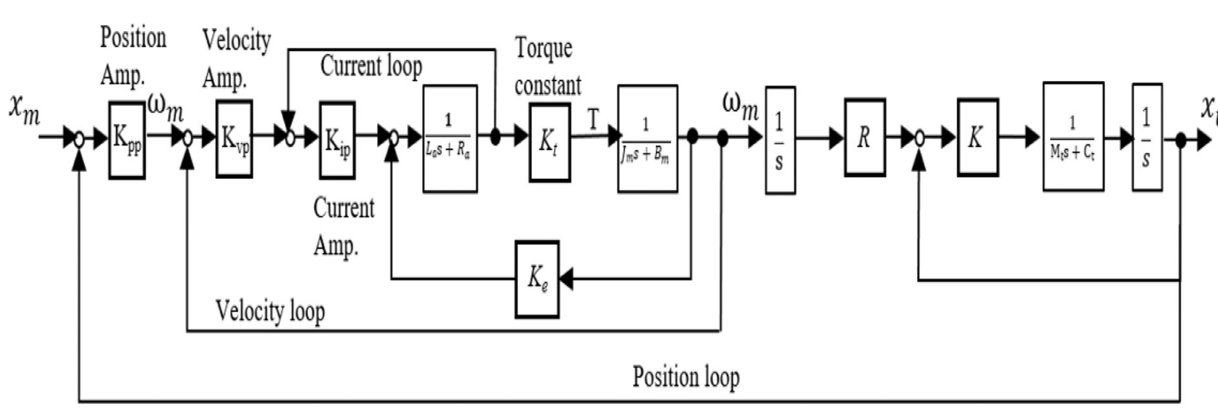



**Fig. 3.** The control architecture for servo loop and feed system.

**Table 1**
The definition of CNC controller parameters.

| Parameters | Definition |
|---|---|
| $J_{max}$ [m/s$^3$] | maximum permissible jerk |
| $A_{max}$ [m/s$^2$] | maximum permissible acceleration |
| $F_{max}$ [mm/min] | maximum permissible feedrate |
| $J_{c,max}$ [m/s$^3$] | maximum permissible jerk at corners or tangential transitions |
| $A_{r,max}$ [m/s$^2$] | maximum radial acceleration on circles and curved paths |

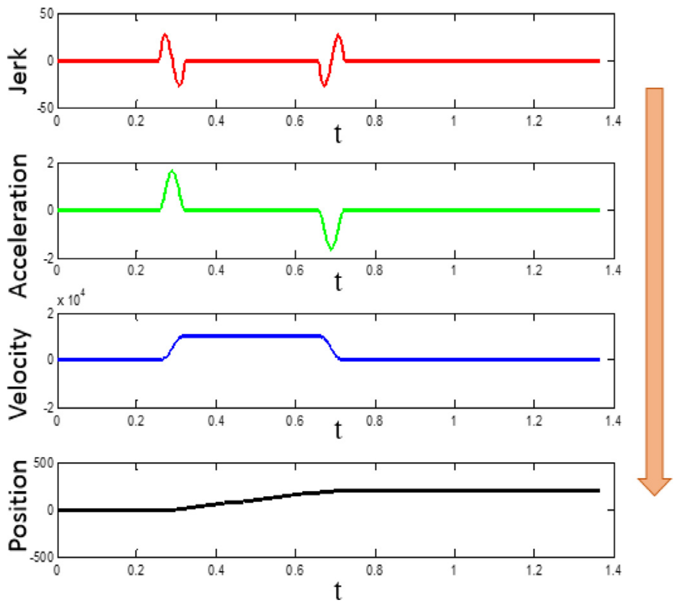



**Fig. 4.** Planning profile of jerk, acceleration, velocity, and position.

Therefore, we find firstly the main parameters for the effect of performance indexes via analysis of experimental data, the machining parameters include jerk, acceleration, feedrate, jerk of corner and centripetal acceleration. The type of CNC controller is with type of TNC640 by HEIDENHAIN [22]. The definitions of the selected machining parameters are introduced in Table 1.

As shown in Fig. 1, the tool paths are generated by interpolator process and CNC machining parameters would affect the planning of trajectory and velocity [33–36]. These result different quality of machining product. Thus the selection of machining parameters is a very important factor for two-performance index. In general, CNC controllers use jerk control to generate tool path. In other words, the order of planning is jerk, acceleration/deceleration, velocity and position as shown in Fig. 4. In this study, there are five key parameters, which affect the milling accuracy and surface quality, where $J_{max}$: maximum jerk, $A_{max}$: maximum acceleration, $F_{max}$: maximum feedrate, $J_{c,max}$: maximum jerk of corner and $A_{r,max}$: maximum centripetal acceleration. The parameters $J_{max}$, $A_{max}$, and $F_{max}$ control the profile planning of jerk, acceleration and velocity. The parameter $J_{c,max}$ control the velocity of tool path at corner, for example, a fast velocity through corner of trajectory when giving a high value. The parameter $A_{r,max}$ control the velocity of circle and curved paths, velocity, and be known according to formula of centripetal acceleration ($V = \sqrt{A \times R}$), where $V$ is the tangential velocity of circle, $A$ is the centripetal acceleration and $R$ is the radius of circle.

### 2.2. Milling accuracy and surface quality

Every product all has different requirements during machining process, some workpieces need smooth surface, the other need high precision. Therefore, this paper proposes an approach to establish an intelligent predicted system based on CNC machining parameters. Herein, the main predicted objectives are the milling accuracy and surface quality.

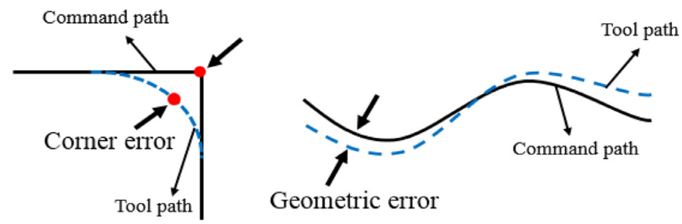



**Fig. 5.** The illustration of corner error and geometric error.

#### 2.2.1. Milling accuracy

The estimation method for milling accuracy is contouring error, which includes the corner error and geometric error as shown in Fig. 5. The corner error is the smallest distance between the real tool path (by linear scale) and the vertex of ideal corner path. The geometric error is the distance between the ideal path and real tool path. This means that the greater value of contouring error corresponds to the worse milling accuracy.

The milling accuracy is affected by our selected CNC machining parameters; we here discuss the influence of five machining parameters for milling accuracy. In this study, we design the rhombus path, one of five parameters was changed and the others were fixed during machining process. The experimental data were collected by linear scale for calculating the contouring error. The effect trend of each machining parameter for milling accuracy is obtained after analyzing these data. The experimental flow is shown in Fig. 6. In general, the control system of the machine tool adopts closed loop; the position detector is installed on the machine table and the actual position error is fed back to the control system. The resonance of mechanical body, stick slip and axial motion will cause the machining error that these dynamic characteristics are all included in the position control loop. Therefore, we use linear scale to collect the data because it can help us obtain the information for motion characteristics of machine tool. Table 2 shows the variations of each machining parameter ($J_{max}$, $A_{max}$, $F_{max}$, $J_{c,max}$ and $A_{r,max}$) and the corresponding contouring error. Fig. 7 shows the trend of contouring error for variations of each machining parameter. In Fig. 7, it can be seen that the contouring error increases with increasing the values of the parameters ($J_{max}$, $A_{max}$, $F_{max}$, $J_{c,max}$ and $A_{r,max}$), herein, we can know that the milling accuracy decreases with increasing five machining parameters.

#### 2.2.2. Surface quality

The estimation method for surface quality is tracking error [37], and the calculation method is that subtract command from real position. This error was generated by deformation of mechanical structure and servo delay. The greater tracking error value, the worse surface quality. Table 2 also shows the variations of each machining parameter and the values of tracking error. Fig. 8 shows the trend of tracking error for variations of each machining parameter. In Fig. 8, it can be seen that the tracking error increases with increasing the values of the parameters ($J_{max}$, $A_{max}$, $F_{max}$, $J_{c,max}$ and $A_{r,max}$), herein, we can know that the surface quality decreases with increasing five machining parameters.

### 2.3. Specifications of CNC machine tool

In this study, the five-axis machine tool (Microcut-MCU-5X) was used to collect experimental data. Fig. 9 and Table 3 show the real machinery and major specifications, respectively. The type of controller is TNC640, which is published by HEIDENHAIN [23].

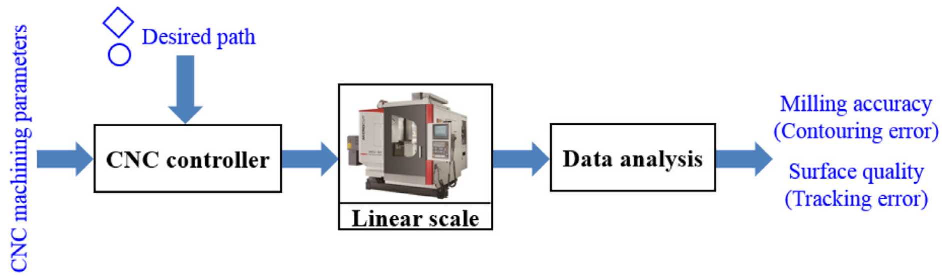



**Fig. 6.** The flowchart for the collection of experimental data.

By using HEIDENHAIN TNSCOPE software to connect the CNC controller, we can collect the corresponding position, velocity, acceleration, and jerk of each axis, etc.

## 3. ANFIS-based prediction system

In this study, we propose an intelligent predicted system for milling accuracy and surface quality of machining operation by using data driven approach, and the predicted system is established by the adaptive neuro-fuzzy inference system (ANFIS). The experimental data are collected for calculating contouring error and tracking error corresponds to milling accuracy and surface quality, and the ANFIS model is established by the data set.

### *3.1. Adaptive neuro-fuzzy inference systems*

The ANFIS was proposed by Jang [26] and the major structure is fuzzy inference systems, which uses descriptive statements (fuzzy if-then rules) to simulate human knowledge and inference logic. In other words, the experience and knowledge of expert can become fuzzy rules by fuzzy systems. ANFIS contains fuzzy inference systems and neural network (supervised learning network), herein, it has the better abilities for solving non-linear and unknown questions. The systems also have the abilities of self-learning and self-organization that the antecedent parameters and consequent parameters can be adjusted. The adjusting flow of parameters is shown in Fig. 10. The antecedent and consequent parameters are adjusted by recursive least square and gradient descent method, respectively. The main objective is to establish the projection relationship of input and output for ANFIS, herein, it was usually utilized in predicted model [27,28,30,31]. The network structure for our ANFIS model is shown in Fig. 11.

**Layer 1.** The neuron nodes perform the fuzzy membership grade of the inputs in this layer. The membership functions usually select Gaussian function, and the output is given by

$$O_{ji}^{(1)} = \mu_j(x_i) = \exp\left[-\frac{(x_i - m_{ji})^2}{\sigma_{ji}^2}\right], i = 1, 2 \ldots, 5, j = 1, 2 \quad (1)$$

where $x_i$ are the inputs which include $J_{max}$, $A_{max}$, $F_{max}$, $J_{c,max}$ and $A_{r,max}$, $m_{ji}$ and $\sigma_{ji}$ are the membership function parameters of Gaussian (antecedent parameters), $O_{ji}^{(1)}$ are the outputs of Layer 1.

**Layer 2.** This layer is to calculate the firing strength of the corresponding neuron node and the *t*-norm product operation is adopted, the output is given by

$$O_p^{(2)} = w_p = \prod_{i=1}^{5} \mu_{ji}(x_i), \ p = 1, 2, \ldots, 32 \quad (2)$$

**Layer 3.** This layer performs the normalization operation of each firing strength, it can be represented as

$$O_p^{(3)} = \overline{w}_p = \frac{w_p}{\sum_{p=1}^{32} w_p} \quad (3)$$

**Layer 4.** The outputs of this layer are the product of normalization results and Sugeno model, which are represented as

$$O_p^{(4)} = \overline{w}_p f_p = \overline{w}_p \left(\sum_{i=0}^{5} r_{pi} x_i + r_{p0}\right), x_0 = 1 \quad (4)$$

where $r_{pi}$ and $r_{p0}$ are the consequent parameters.

**Layer 5.** In the last layer, the result is the sum of Layer 4 outputs, it is given by

$$O^{(5)} = \sum_{p=1}^{32} \overline{w}_p f_p = \frac{\sum_{p=1}^{32} w_p f_p}{\sum_{p=1}^{32} w_p}. \quad (5)$$

### *3.2. Prediction results for milling accuracy and surface quality*

In this study, the prediction system of machining performance index is established by using the ANFISs and collected data. Fig. 12 shows the flowchart of establishing prediction system. The inputs are the parameters $J_{max}$, $A_{max}$, $F_{max}$, $J_{c,max}$, and $A_{r,max}$, the outputs are the milling accuracy and surface quality, respectively. Fig. 13 shows the structure of prediction system. First, the training data of ANFIS are obtained by real CNC machining tool (Microcut-MCU-5X). The experimental machining trajectory is rhombus, the positions of X-axis and Y-axis were collected by linear scale for different CNC machining parameters. These data were analyzed to obtain contouring error (milling accuracy) and tracking error (surface quality) which are the performance indexes. Fig. 6 shows the flowchart for the collection of the experimental data and Table 4 shows the range of machining parameters. Finally, the ANFIS model was trained by these sampling data. There are five input variables and each one has two fuzzy term sets in this network, herein, thirty-two fuzzy rules are created after training. The corresponding fuzzy sets are **High** (**H**) and **Low** (**L**). And the fuzzy rules help us to understand the relationships and effects between CNC machining parameters and milling accuracy and surface quality. The thirty-two fuzzy rules for ANFIS-milling accuracy and ANFIS-surface quality are show in Appendix A.

The 113 experimental data are collected, and these data are utilized to establish the prediction system. 90% of them are as the training data and the others as testing data. Fig. 14 shows the RMSE trajectories of training results. Fig. 15 shows the actual and predicted comparisons of testing data for two performance indexes. Table 5 shows the prediction results of testing data for milling accuracy and surface quality. The shape of membership function for ANFIS model before and after training are shown in Figs. 16 and 17. By these results, we can see that the final RMSE is 0.000681 for milling accuracy predictions and the final RMSE is

**Table 2**
Effect trend of machining parameter ($J_{max}$, $A_{max}$, $F_{max}$, $J_{c,max}$ and $A_{r,max}$).

(a) Results for $J_{max}$.

| Parameters | Data1 | Data2 | Data3 | Data4 | Data5 | Data6 |
|---|---|---|---|---|---|---|
| $J_{max}$ [m/s^3] | 5 | 10 | 15 | 20 | 25 | 30 |
| $A_{max}$ [m/s^2] | 10 | 10 | 10 | 10 | 10 | 10 |
| $F_{max}$ [mm/min] | 6000 | 6000 | 6000 | 6000 | 6000 | 6000 |
| $J_{c,max}$ [m/s^3] | 80 | 80 | 80 | 80 | 80 | 80 |
| $A_{r,max}$ [m/s^2] | 10 | 10 | 10 | 10 | 10 | 10 |
| Contouring error [mm] | 0.029588 | 0.030409 | 0.030276 | 0.032018 | 0.032395 | 0.034428 |
| Tracking error [mm] | 2.565669 | 2.56748 | 2.567467 | 2.568306 | 2.56875 | 2.569609 |

(b) Results for $A_{max}$.

| Parameters | Data1 | Data2 | Data3 | Data4 | Data5 | Data6 |
|---|---|---|---|---|---|---|
| $J_{max}$ [m/s^3] | 80 | 80 | 80 | 80 | 80 | 80 |
| $A_{max}$ [m/s^2] | 0.01 | 0.05 | 0.1 | 0.3 | 0.5 | 0.7 |
| $F_{max}$ [mm/min] | 6000 | 6000 | 6000 | 6000 | 6000 | 6000 |
| $J_{c,max}$ [m/s^3] | 80 | 80 | 80 | 80 | 80 | 80 |
| $A_{r,max}$ [m/s^2] | 10 | 10 | 10 | 10 | 10 | 10 |
| Contouring error [mm] | 0.000561 | 0.00178 | 0.003292 | 0.009782 | 0.01642 | 0.023115 |
| Tracking error [mm] | 0.435429 | 0.974597 | 1.380339 | 2.302305 | 2.56606 | 2.567175 |

(c) Results for $F_{max}$.

| Parameters | Data1 | Data2 | Data3 | Data4 | Data5 | Data6 |
|---|---|---|---|---|---|---|
| $J_{max}$ [m/s^3] | 80 | 80 | 80 | 80 | 80 | 80 |
| $A_{max}$ [m/s^2] | 10 | 10 | 10 | 10 | 10 | 10 |
| $F_{max}$ [mm/min] | 1000 | 2000 | 3000 | 4000 | 5000 | 6000 |
| $J_{c,max}$ [m/s^3] | 80 | 80 | 80 | 80 | 80 | 80 |
| $A_{r,max}$ [m/s^2] | 10 | 10 | 10 | 10 | 10 | 10 |
| Contouring error [mm] | 0.027868 | 0.026969 | 0.030303 | 0.037484 | 0.044414 | 0.04857 |
| Tracking error [mm] | 0.44483 | 0.872783 | 1.293773 | 1.720461 | 2.14704 | 2.57554 |

(d) Results for $J_{c,max}$.

| Parameters | Data1 | Data2 | Data3 | Data4 | Data5 | Data6 |
|---|---|---|---|---|---|---|
| $J_{max}$ [m/s^3] | 80 | 80 | 80 | 80 | 80 | 80 |
| $A_{max}$ [m/s^2] | 10 | 10 | 10 | 10 | 10 | 10 |
| $F_{max}$ [mm/min] | 6000 | 6000 | 6000 | 6000 | 6000 | 6000 |
| $J_{c,max}$ [m/s^3] | 5 | 10 | 20 | 30 | 40 | 50 |
| $A_{r,max}$ [m/s^2] | 10 | 10 | 10 | 10 | 10 | 10 |
| Contouring error [mm] | 0.023418 | 0.026806 | 0.030143 | 0.032387 | 0.036837 | 0.038728 |
| Tracking error [mm] | 2.573657 | 2.573608 | 2.573695 | 2.574113 | 2.574355 | 2.574518 |

(e) Results for $A_{r,max}$.

| parameters | Data1 | Data2 | Data3 | Data4 | Data5 | Data6 |
|---|---|---|---|---|---|---|
| $J_{max}$ [m/s^3] | 80 | 80 | 80 | 80 | 80 | 80 |
| $A_{max}$ [m/s^2] | 10 | 10 | 10 | 10 | 10 | 10 |
| $F_{max}$ [mm/min] | 6000 | 6000 | 6000 | 6000 | 6000 | 6000 |
| $J_{c,max}$ [m/s^3] | 80 | 80 | 80 | 80 | 80 | 80 |
| $A_{r,max}$ [m/s^2] | 0.1 | 0.3 | 0.5 | 0.7 | 1 | 2 |
| Contouring error [mm] | 0.026569 | 0.032241 | 0.037136 | 0.042139 | 0.048458 | 0.048538 |
| Tracking error [mm] | 2.573217 | 2.573565 | 2.574195 | 2.574754 | 2.575304 | 2.575346 |

**Table 3**
Major specifications of machine tool (Microcut-MCU-5X).

| | |
|---|---|
| X/Y/Z Axis Travel [mm] | 600/600/500 |
| Tilting Axis A [degree] | +120/−120 |
| Rotary C [degree] | 360 |
| Rapid Traverse X/Y/Z [mm/min] | 36000/36000/36000 |
| Max. Speed A/C [rpm] | 16.6/90 |
| Spindle Speed Range [rpm] | 12000 (std)/15000 (opt) |
| Type of Position Control | Full-closed control |

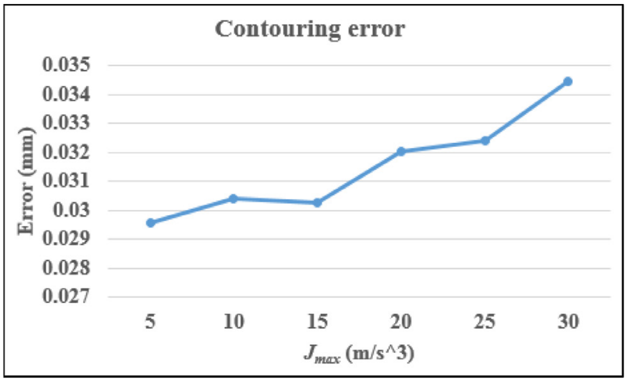
**Table 4**
CNC machining parameters range.

| Parameters | Maximum | Minimum |
|---|---|---|
| $J_{max}$ [m/s^3] | 25 | 4 |
| $A_{max}$ [m/s^2] | 1.2 | 0.4 |
| $F_{max}$ [mm/min] | 100 | 6000 |
| $J_{c,max}$ [m/s^3] | 65 | 2 |
| $A_{r,max}$ [m/s^2] | 1 | 0.005 |

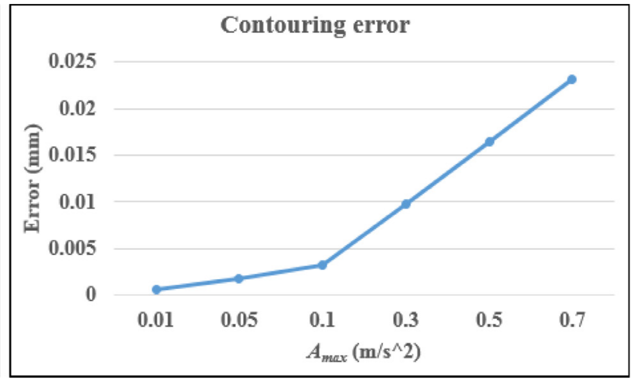
0.001046 for surface quality predictions in training data. The corresponding RMSE of testing data are 0.000911 and 0.002062. In Table 5, we can obviously see that the predicted error is less than 9% and 5% for milling accuracy and surface quality, respectively. This system is verified that it has the excellent prediction ability according to these results. Therefore, it can accurately predict the performance indexes for different CNC machining parameters.

## 4. Conclusions

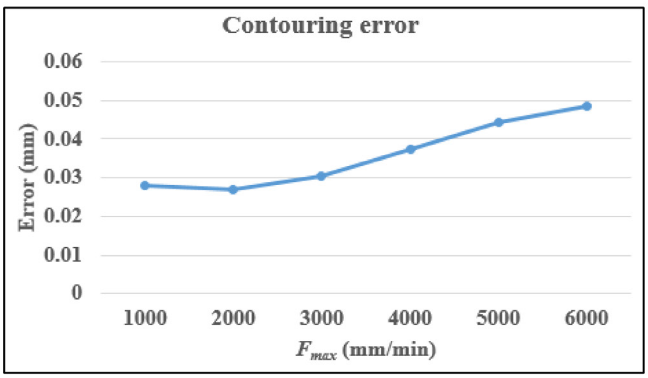
During the machining process, the main objectives are to improve the product quality and productivity, herein, we proposes an intelligent prediction system of milling accuracy and surface quality for CNC machining parameters based on ANFIS. The experimental data were collected by machining tool to calculate the contouring error (milling accuracy) and tracking error (surface quality). The ANFIS model is established by these data. The



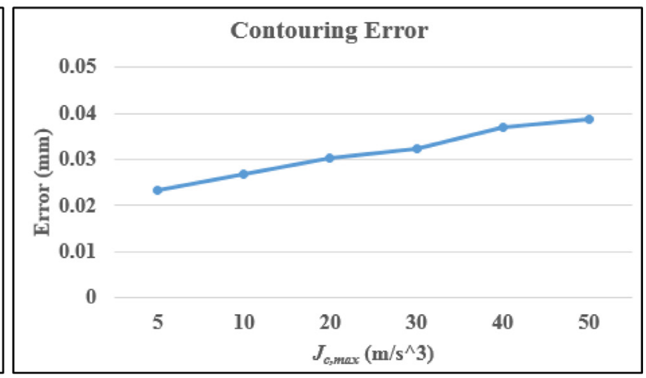

(a) The trend of contouring error for parameter $J_{max}$.



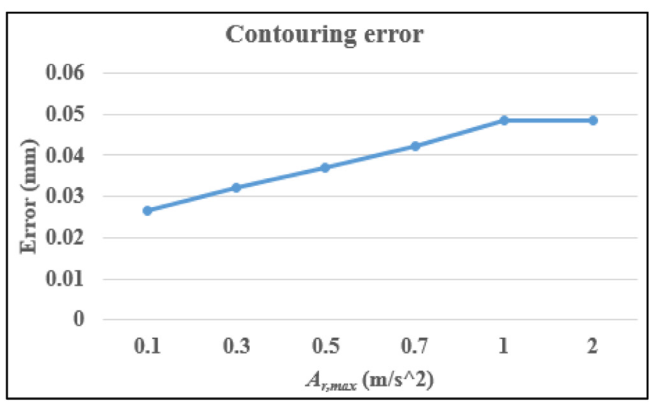

(b) The trend of contouring error for parameter $A_{max}$.




(c) The trend of contouring error for parameter $F_{max}$.




(d) The trend of contouring error for parameter $J_{c,max}$.




(e) The trend of contouring error for parameter $A_{r,max}$.

**Fig. 7.** The trend of contouring error for variations of each machining parameter.

fuzzy rules also help us to understand the effects and relationships between CNC machining parameters and two performance indexes. According to the simulation results, we can obviously find that the prediction errors are small, thus, the system that can effectively predict performance indexes was verified. As above described, the prediction system can provide the accurate evaluations of milling accuracy and surface quality for the different CNC machining parameters. Therefore, the users can judge the feasibility of the CNC machining parameters for the products. In addition, the cutting depth and spindle speed also affect the machining performance indexes, but our ANFIS model needs hundreds of data to train. Compared with our selected CNC machining parameters, if our model joins these two factors, it will waste massive costs and time on machining process. Therefore, we will consider these two parameters in the future after we optimize our ANFIS model.

## Appendix A

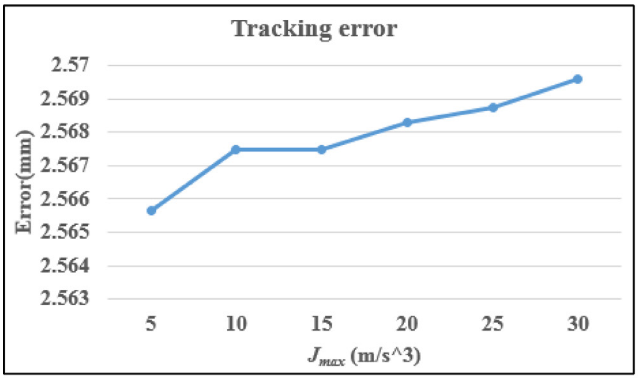
### A1. Fuzzy rules of ANFIS-milling accuracy

$R^1$: IF $A_{max}$ is **L** and $J_{max}$ is **L** and $F_{max}$ is **L** and $A_{r,max}$ is **L** and $J_{c,max}$ is **L** THEN *Milling Accuracy* is [283.3, 2.792, 7.319, 2.815, 2.937, 2.812]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-9}$.

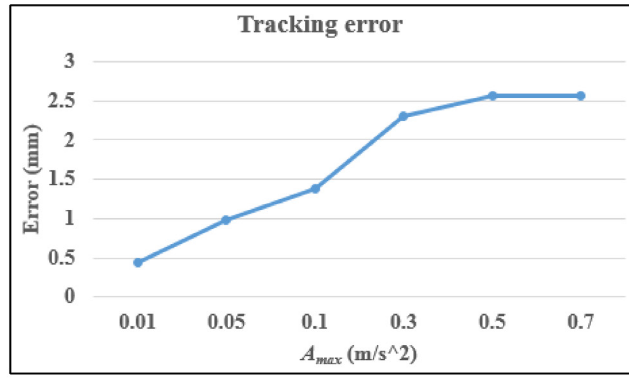
$R^2$: IF $A_{max}$ is **L** and $J_{max}$ is **L** and $F_{max}$ is **L** and $A_{r,max}$ is **L** and $J_{c,max}$ is **H** THEN *Milling Accuracy* is [53.3, 0.5249, 1.377, 0.5293e, 0.5289e, 0.5287]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-7}$.

$R^3$: IF $A_{max}$ is **L** and $J_{max}$ is **L** and $F_{max}$ is **L** and $A_{r,max}$ is **H** and $J_{c,max}$ is **L** THEN *Milling Accuracy* is [139.6, 1.378, 3.609, 1.382, 1.45, 1.388]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-8}$.

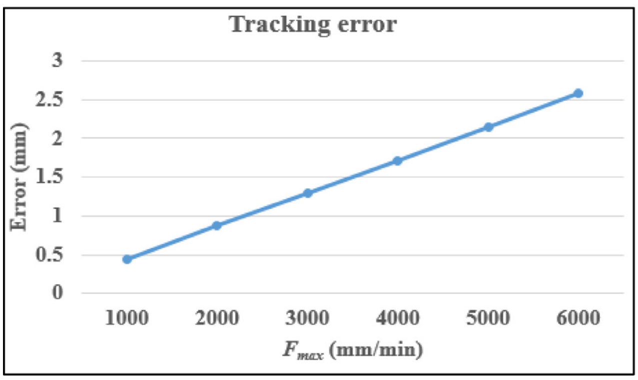
$R^4$: IF $A_{max}$ is **L** and $J_{max}$ is **L** and $F_{max}$ is **L** and $A_{r,max}$ is **H** and $J_{c,max}$ is **H** THEN *Milling Accuracy* is [262.6, 2.591, 6.788, 2.598, 2.611, 2.61]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-7}$.



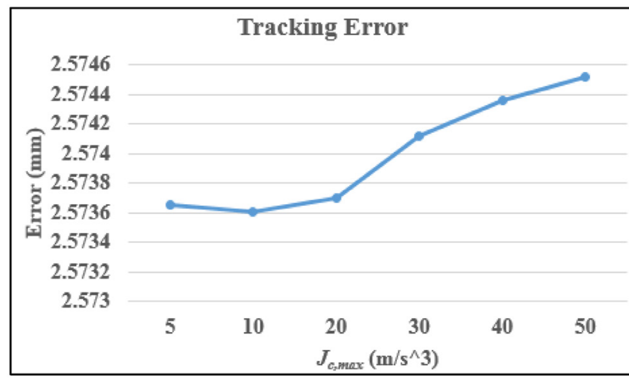

(a) The trend of tracking error for parameter $J_{max}$.



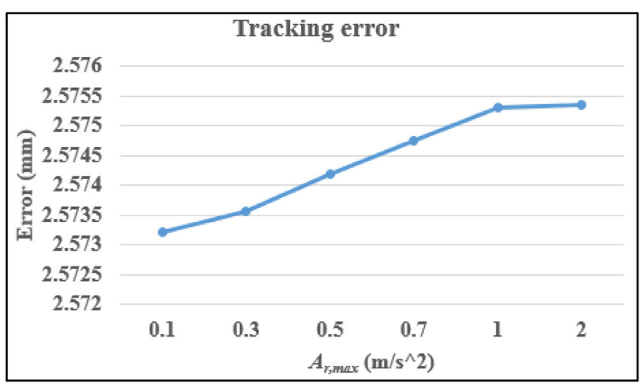

(b) The trend of tracking error for parameter $A_{max}$.




(c) The trend of tracking error for parameter $F_{max}$.




(d) The trend of tracking error for parameter $J_{c,max}$.




(e) The trend of tracking error for parameter $A_{r,max}$.

**Fig. 8.** The trend of tracking errors for variations of each machining parameter.

$\boldsymbol{R}^5$: IF $A_{max}$ is **L** and $J_{max}$ is **L** and $F_{max}$ is **H** and $A_{r,max}$ is **L** and $J_{c,max}$ is **L** THEN *Milling Accuracy* is [239.7, 2.475, 2.487, 2.495, 2.597, 2.492]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-7}$.

$\boldsymbol{R}^6$: IF $A_{max}$ is **L** and $J_{max}$ is **L** and $F_{max}$ is **H** and $A_{r,max}$ is **L** and $J_{c,max}$ is **H** THEN *Milling Accuracy* is [451.1, 4.654, 4.676, 4.69, 4.687, 4.685]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-6}$.

$\boldsymbol{R}^7$: IF $A_{max}$ is **L** and $J_{max}$ is **L** and $F_{max}$ is **H** and $A_{r,max}$ is **H** and $J_{c,max}$ is **L** THEN *Milling Accuracy* is [118.1, 1.222, 1.228, 1.225, 1.282, 1.23]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-6}$.

$\boldsymbol{R}^8$: IF $A_{max}$ is **L** and $J_{max}$ is **L** and $F_{max}$ is **H** and $A_{r,max}$ is **H** and $J_{c,max}$ is **H** THEN *Milling Accuracy* is [222.3, 2.297, 2.308, 2.303, 2.314, 2.313]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-5}$.

$\boldsymbol{R}^9$: IF $A_{max}$ is **L** and $J_{max}$ is **H** and $F_{max}$ is **L** and $A_{r,max}$ is **L** and $J_{c,max}$ is **L** THEN *Milling Accuracy* is [553.9, 5.451, 14.27, 5.466, 5.703, 5.459]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-8}$.

$\boldsymbol{R}^{10}$: IF $A_{max}$ is **L** and $J_{max}$ is **H** and $F_{max}$ is **L** and $A_{r,max}$ is **L** and $J_{c,max}$ is **H** THEN *Milling Accuracy* is [104.2, 1.025, 2.685, 1.028, 1.027, 1.026]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-6}$.

$\boldsymbol{R}^{11}$: IF $A_{max}$ is **L** and $J_{max}$ is **H** and $F_{max}$ is **L** and $A_{r,max}$ is **H** and $J_{c,max}$ is **L** THEN *Milling Accuracy* is [272.9, 2.691, 7.038, 2.683, 2.815, 2.695]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-7}$.

$\boldsymbol{R}^{12}$: IF $A_{max}$ is **L** and $J_{max}$ is **H** and $F_{max}$ is **L** and $A_{r,max}$ is **H** and $J_{c,max}$ is **H** THEN *Milling Accuracy* is [513.5, 5.059, 13.24, 5.044, 5.069, 5.066]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-6}$.

$\boldsymbol{R}^{13}$: IF $A_{max}$ is **L** and $J_{max}$ is **H** and $F_{max}$ is **H** and $A_{r,max}$ is **L** and $J_{c,max}$ is **L** THEN *Milling Accuracy* is [8.917, 0.8853, 8.906, 11.93, 12.01, 11.56].$[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-4}$.

$\boldsymbol{R}^{14}$: IF $A_{max}$ is **L** and $J_{max}$ is **H** and $F_{max}$ is **H** and $A_{r,max}$ is **L** and $J_{c,max}$ is **H** THEN *Milling Accuracy* is [882.1, 9.085, 9.081, 9.109, 9.103, 9.098]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-5}$.

**Table 5**
The prediction results of testing data.

| *Prediction results of milling accuracy* | | | | |
|---|---|---|---|---|
| Testing data no. | Actual (mm) | Prediction (mm) | Predicted errors (mm) | Error (%) |
| 1 | 0.027910825 | 0.027309854 | 0.000600971 | 2.15 |
| 2 | 0.004767216 | 0.004385669 | 0.000381547 | 8.00 |
| 3 | 0.024879595 | 0.025135376 | 0.000255781 | 1.03 |
| 4 | 0.027133843 | 0.027058269 | 7.55736E-05 | 0.28 |
| 5 | 0.024170055 | 0.024256161 | 8.61061E-05 | 0.36 |
| 6 | 0.027427133 | 0.027394048 | 3.30854E-05 | 0.12 |
| 7 | 0.017149782 | 0.017617908 | 0.000468126 | 2.73 |
| 8 | 0.02969802 | 0.027750182 | 0.001947838 | 6.56 |
| 9 | 0.028590645 | 0.028112751 | 0.000477894 | 1.67 |
| 10 | 0.028885361 | 0.02716372 | 0.001721641 | 5.96 |
| 11 | 0.005740485 | 0.006196271 | 0.000455786 | 7.94 |
| Average | | | 0.000591304 | 3.35 |
| *Prediction results of surface quality* | | | | |
| Testing data no. | Actual (mm) | Prediction (mm) | Predicted errors (mm) | Error (%) |
| 1 | 2.384487453 | 2.385280064 | 0.000792611 | 0.033 |
| 2 | 2.299349198 | 2.300453535 | 0.001104337 | 0.048 |
| 3 | 2.553224031 | 2.55335 | 0.000125969 | 0.005 |
| 4 | 2.553856802 | 2.554550253 | 0.000693451 | 0.027 |
| 5 | 2.555647801 | 2.555132702 | 0.000515099 | 0.02 |
| 6 | 0.046337985 | 0.048495695 | 0.00215771 | 4.656 |
| 7 | 2.554590541 | 2.554828572 | 0.000238031 | 0.009 |
| 8 | 2.554349652 | 2.554316435 | 3.32174E-05 | 0.001 |
| 9 | 1.19861822 | 1.196706643 | 0.001911577 | 0.159 |
| 10 | 2.554944529 | 2.554890435 | 5.40939E-05 | 0.002 |
| 11 | 2.553285298 | 2.553165329 | 0.000119969 | 0.005 |
| Average | | | 0.000704188 | 0.452 |


**Fig. 9.** Five-axis machine tool (Microcut-MCU-5X).

$\boldsymbol{R}^{15}$: IF $A_{max}$ is **L** and $J_{max}$ is **H** and $F_{max}$ is **H** and $A_{r,max}$ is **H** and $J_{c,max}$ is **L** THEN *Milling Accuracy* is [231, 2.385, 2.384, 2.379, 2.49, 2.389]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-5}$.

$\boldsymbol{R}^{16}$: IF $A_{max}$ is **L** and $J_{max}$ is **H** and $F_{max}$ is **H** and $A_{r,max}$ is **H** and $J_{c,max}$ is **H** THEN *Milling Accuracy* is [43.46, 0. 4485, 0. 4483, 0. 4472, 0. 4493, 0. 4491]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-3}$.

$\boldsymbol{R}^{17}$: IF $A_{max}$ is **H** and $J_{max}$ is **L** and $F_{max}$ is **L** and $A_{r,max}$ is **L** and $J_{c,max}$ is **L** THEN *Milling Accuracy* is [−4.139, −4.669, 157.3, −3.839, 0.501, −3.96]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-6}$.

$\boldsymbol{R}^{18}$: IF $A_{max}$ is **H** and $J_{max}$ is **L** and $F_{max}$ is **L** and $A_{r,max}$ is **L** and $J_{c,max}$ is **H** THEN *Milling Accuracy* is [−7.945, −8.941, 0. 295.8, −7.381, −7.511, −7.608]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-5}$.

$\boldsymbol{R}^{19}$: IF $A_{max}$ is **H** and $J_{max}$ is **L** and $F_{max}$ is **L** and $A_{r,max}$ is **H** and $J_{c,max}$ is **L** THEN *Milling Accuracy* is [−1.95, −2.211, 0. 77.59, −2.078, 0.3366, −1.862]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-5}$.

$\boldsymbol{R}^{20}$: IF $A_{max}$ is **H** and $J_{max}$ is **L** and $F_{max}$ is **L** and $A_{r,max}$ is **H** and $J_{c,max}$ is **H** THEN *Milling Accuracy* is [−3.746, −4.237, 145.9, −3.988, −3.533, −3.58]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-4}$.

$\boldsymbol{R}^{21}$: IF $A_{max}$ is **H** and $J_{max}$ is **L** and $F_{max}$ is **H** and $A_{r,max}$ is **L** and $J_{c,max}$ is **L** THEN *Milling Accuracy* is [5.41, 0.9291, 5.246, 7.944, 44.66, 6.924]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-5}$.

$\boldsymbol{R}^{22}$: IF $A_{max}$ is **H** and $J_{max}$ is **L** and $F_{max}$ is **H** and $A_{r,max}$ is **L** and $J_{c,max}$ is **H** THEN *Milling Accuracy* is [8.917, 0.8853, 8.906, 11.93, 12.01, 11.56].$[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-4}$.

$\boldsymbol{R}^{23}$: IF $A_{max}$ is **H** and $J_{max}$ is **L** and $F_{max}$ is **H** and $A_{r,max}$ is **H** and $J_{c,max}$ is **L** THEN *Milling Accuracy* is [3.425, 1.217, 3.344, 2.337, 22.77, 4.171]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-4}$.

$\boldsymbol{R}^{24}$: IF $A_{max}$ is **H** and $J_{max}$ is **L** and $F_{max}$ is **H** and $A_{r,max}$ is **H** and $J_{c,max}$ is **H** THEN *Milling Accuracy* is [5.789, 1.634, 5.637, 3.743, 7.595, 7.193]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-3}$.

$\boldsymbol{R}^{25}$: IF $A_{max}$ is **H** and $J_{max}$ is **H** and $F_{max}$ is **L** and $A_{r,max}$ is **L** and $J_{c,max}$ is **L** THEN *Milling Accuracy* is [−9.518, −9.464, 306.1, −8.932, −0.4439, −9.167]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-5}$.

$\boldsymbol{R}^{26}$: IF $A_{max}$ is **H** and $J_{max}$ is **H** and $F_{max}$ is **L** and $A_{r,max}$ is **L** and $J_{c,max}$ is **H** THEN *Milling Accuracy* is [−1.821, −1.811, 57.57, −1.711, −1.737, −1.756]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-3}$.

$\boldsymbol{R}^{27}$: IF $A_{max}$ is **H** and $J_{max}$ is **H** and $F_{max}$ is **L** and $A_{r,max}$ is **H** and $J_{c,max}$ is **L** THEN *Milling Accuracy* is [−4.514, −4.488, 151, −4.766, −0.04332, −4.342]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-4}$.

$\boldsymbol{R}^{28}$: IF $A_{max}$ is **H** and $J_{max}$ is **H** and $F_{max}$ is **L** and $A_{r,max}$ is **H** and $J_{c,max}$ is **H** THEN *Milling Accuracy* is [−8.645, −8.596, 284, −9.118, −8.228, −8.321]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-3}$.

$\boldsymbol{R}^{29}$: IF $A_{max}$ is **H** and $J_{max}$ is **H** and $F_{max}$ is **H** and $A_{r,max}$ is **L** and $J_{c,max}$ is **L** THEN *Milling Accuracy* is [−1.465, −1.015, −1.786, 3.491, 75.3, 1.497]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-4}$.

$\boldsymbol{R}^{30}$: IF $A_{max}$ is **H** and $J_{max}$ is **H** and $F_{max}$ is **H** and $A_{r,max}$ is **L** and $J_{c,max}$ is **H** THEN *Milling Accuracy* is [−5.38, −4.535, −5.405, 1.056, 1.215, 0.2566].$[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-3}$.

$\boldsymbol{R}^{31}$: IF $A_{max}$ is **H** and $J_{max}$ is **H** and $F_{max}$ is **H** and $A_{r,max}$ is **H** and $J_{c,max}$ is **L** THEN *Milling Accuracy* is [7.62, 9.839, 6.04, −13.64, 385.9, 22.21]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-4}$.

Please cite this article as: H.-W. Chiu, C.-H. Lee, Prediction of machining accuracy and surface quality for CNC machine tools using data driven approach, Advances in Engineering Software (2017), http://dx.doi.org/10.1016/j.advengsoft.2017.07.008

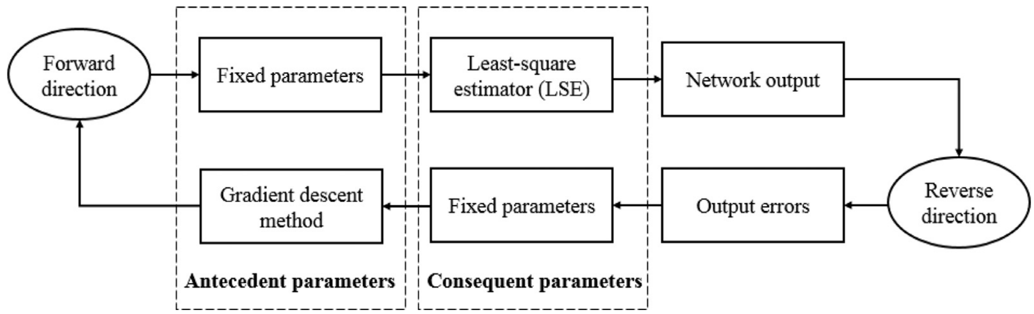



**Fig. 10.** The adjusting flow of antecedent parameters and consequent parameters.

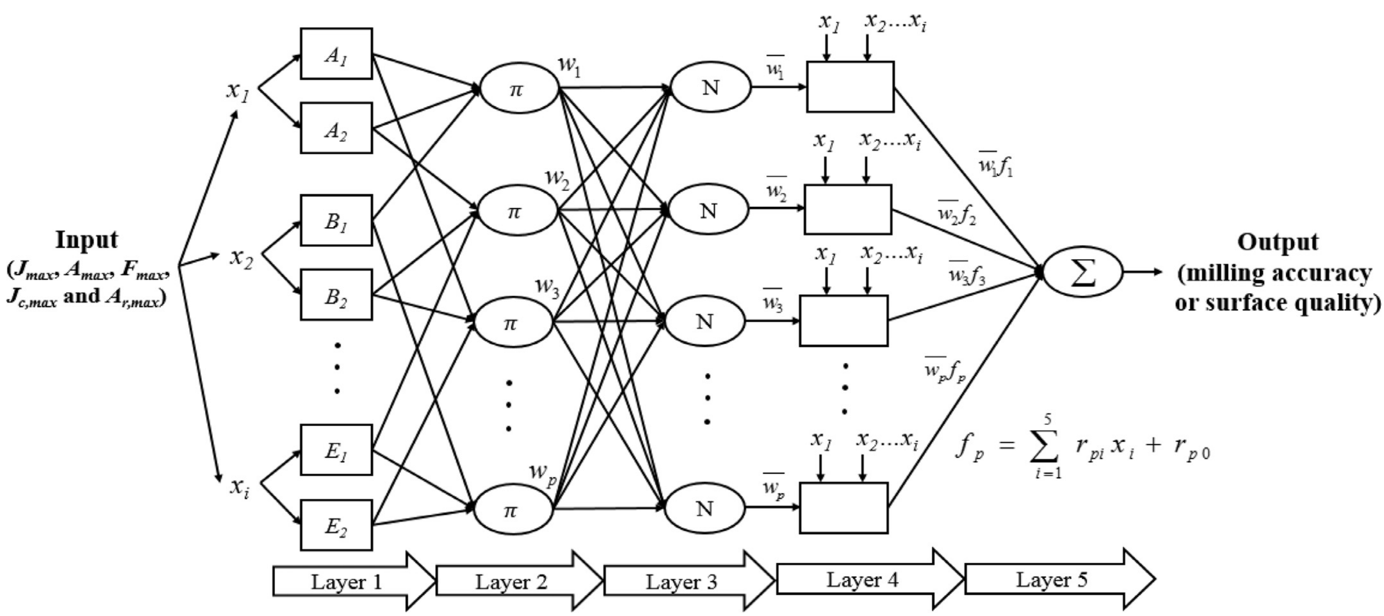



**Fig. 11.** The network structure for our ANFIS model.

$\boldsymbol{R}^{32}$: IF $A_{max}$ is **H** and $J_{max}$ is **H** and $F_{max}$ is **H** and $A_{r,max}$ is **H** and $J_{c,max}$ is **H** THEN *Milling Accuracy* is [1.532, 5.708, −1.441, −38.47, 36.85, 28.99]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-3}$.

### A2. Fuzzy rules of ANFIS-surface quality

$\boldsymbol{R}^{1}$: IF $A_{max}$ is **L** and $J_{max}$ is **L** and $F_{max}$ is **L** and $A_{r,max}$ is **L** and $J_{c,max}$ is **L** THEN *Surface Quality* is [4.001, 14.09, 4.001, 4.001, 4.001, 4.001]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-9}$.

$\boldsymbol{R}^{2}$: IF $A_{max}$ is **L** and $J_{max}$ is **L** and $F_{max}$ is **L** and $A_{r,max}$ is **L** and $J_{c,max}$ is **H** THEN *Surface Quality* is [6.334, 22.31, 6.334, 6.334, 6.334, 6.334]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-7}$.

$\boldsymbol{R}^{3}$: IF $A_{max}$ is **L** and $J_{max}$ is **L** and $F_{max}$ is **L** and $A_{r,max}$ is **H** and $J_{c,max}$ is **L** THEN *Surface Quality* is [4.844, 17.06, 4.844, 4.844, 4.844, 4.844]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-7}$.

$\boldsymbol{R}^{4}$: IF $A_{max}$ is **L** and $J_{max}$ is **L** and $F_{max}$ is **L** and $A_{r,max}$ is **H** and $J_{c,max}$ is **H** THEN *Surface Quality* is [7.668e, 27.01, 7.668, 7.668, 7.668, 7.668]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-5}$.

$\boldsymbol{R}^{5}$: IF $A_{max}$ is **L** and $J_{max}$ is **L** and $F_{max}$ is **H** and $A_{r,max}$ is **L** and $J_{c,max}$ is **L** THEN *Surface Quality* is [7.15, 25.18e, 7.15, 7.15, 7.15, 7.15]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-8}$.

$\boldsymbol{R}^{6}$: IF $A_{max}$ is **L** and $J_{max}$ is **L** and $F_{max}$ is **H** and $A_{r,max}$ is **L** and $J_{c,max}$ is **H** THEN *Surface Quality* is [1.13, 3.986, 1.132, 1.132, 1.132, 1.132]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-5}$.

$\boldsymbol{R}^{7}$: IF $A_{max}$ is **L** and $J_{max}$ is **L** and $F_{max}$ is **H** and $A_{r,max}$ is **H** and $J_{c,max}$ is **L** THEN *Surface Quality* is [8.656, 30.49, 8.656, 8.656, 8.656, 8.656]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-6}$.

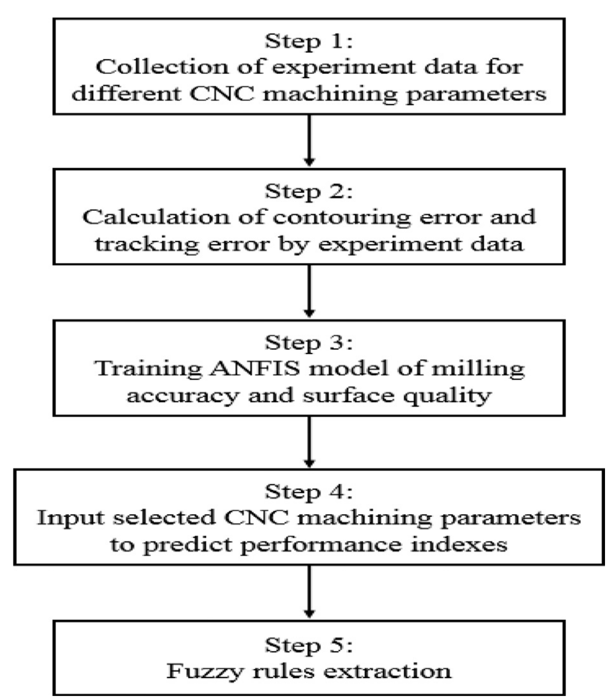



**Fig. 12.** The flowchart of our prediction system.

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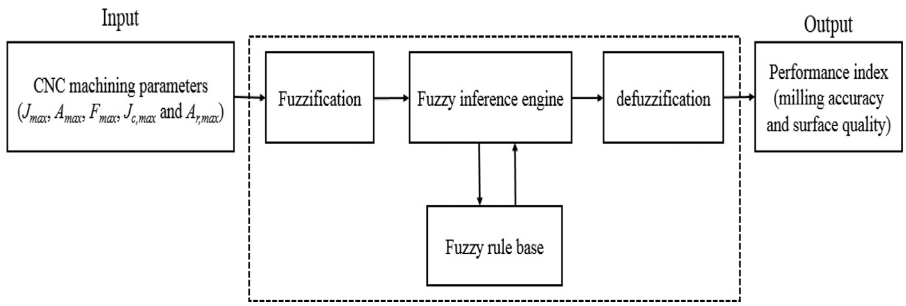
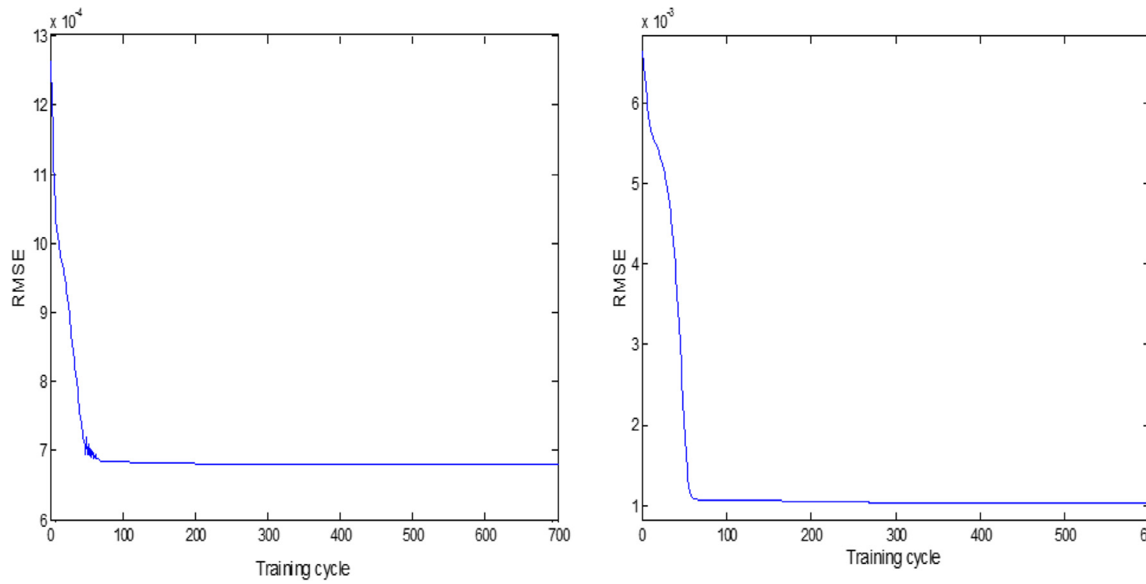
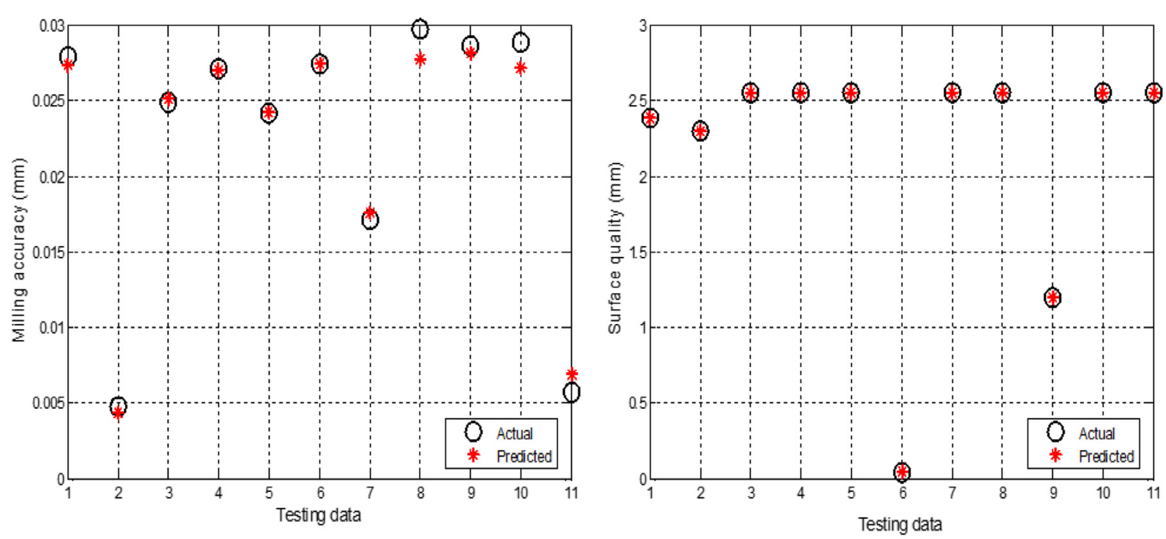



**Fig. 13.** The structure of prediction system.




(a) The RMSE trajectories of milling accuracy. (b) The RMSE trajectories of surface quality.

**Fig. 14.** The RMSE trajectories of training results.




(a) Actual versus predicted milling accuracy. (b) Actual versus predicted surface quality.

**Fig. 15.** The actual and predicted comparisons of testing data for two performance indexes.

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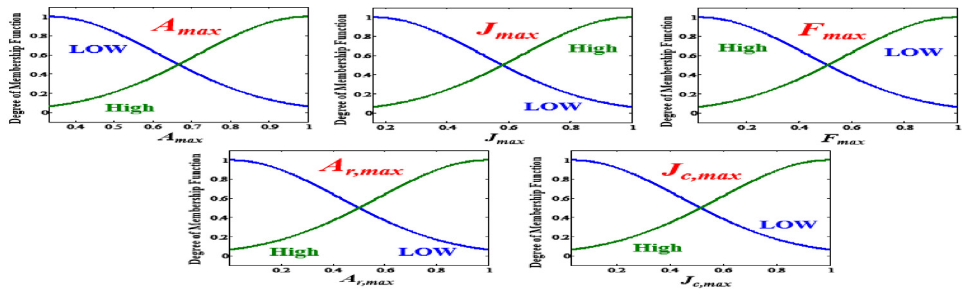
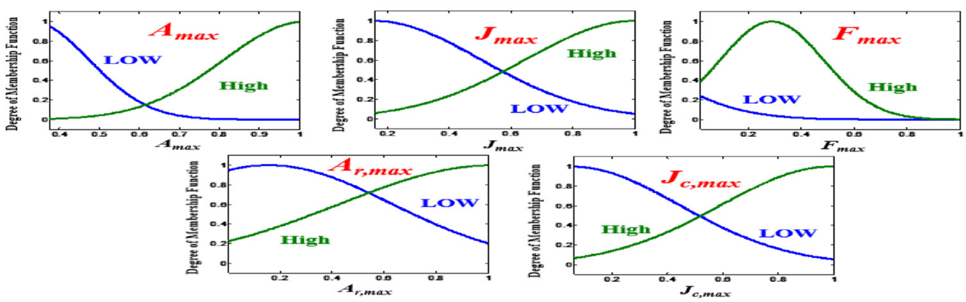
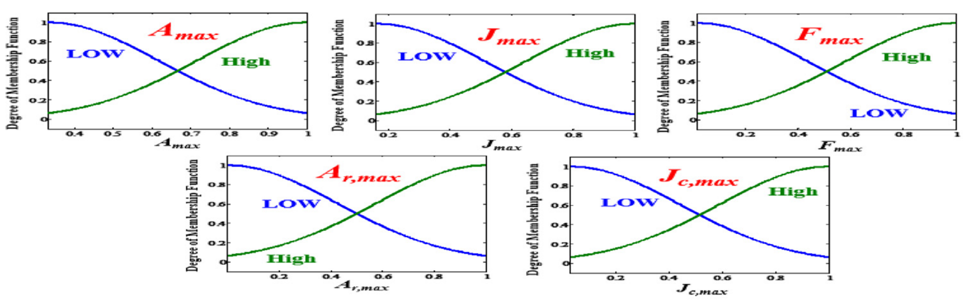



(a) Before training

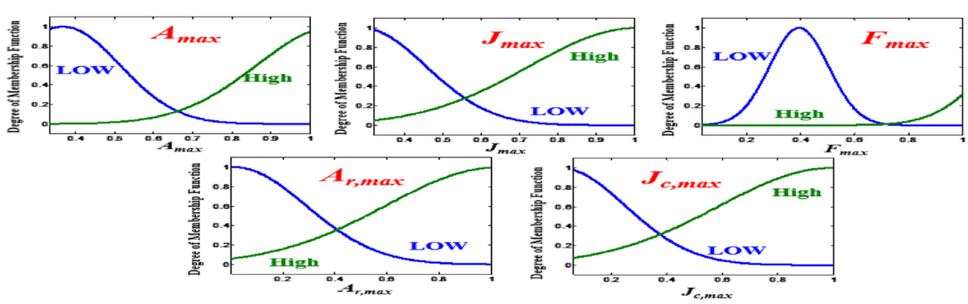



(b) After training

**Fig. 16.** The shape of membership function for ANFIS-milling accuracy before and after training.




(a) Before training




(b) After training

**Fig. 17.** The shape of membership function for ANFIS-surface quality before and after training.

$\boldsymbol{R}^8$: IF $A_{max}$ is **L** and $J_{max}$ is **L** and $F_{max}$ is **H** and $A_{r,max}$ is **H** and $J_{c,max}$ is **H** THEN *Surface Quality* is [1.37, 4.826, 1.37, 1.37, 1.37, 1.37]. [1 $A_{max}$, $J_{max}$, $F_{max}$, $A_{r,max}$, $J_{c,max}$]$^T \times 10^{-3}$.

$\boldsymbol{R}^9$: IF $A_{max}$ is **L** and $J_{max}$ is **H** and $F_{max}$ is **L** and $A_{r,max}$ is **L** and $J_{c,max}$ is **L** THEN *Surface Quality* is [1.306, 2.874, 3.271, 2.313, 2.14, 2.874]. [1 $A_{max}$, $J_{max}$, $F_{max}$, $A_{r,max}$, $J_{c,max}$]$^T \times 10^{-6}$.

$\boldsymbol{R}^{10}$: IF $A_{max}$ is **L** and $J_{max}$ is **H** and $F_{max}$ is **L** and $A_{r,max}$ is **L** and $J_{c,max}$ is **H** THEN *Surface Quality* is [9.103, 33.92, 40.21, 25.04, 33.92, 33.92]. [1 $A_{max}$, $J_{max}$, $F_{max}$, $A_{r,max}$, $J_{c,max}$]$^T \times 10^{-5}$.

$\boldsymbol{R}^{11}$: IF $A_{max}$ is **L** and $J_{max}$ is **H** and $F_{max}$ is **L** and $A_{r,max}$ is **H** and $J_{c,max}$ is **L** THEN *Surface Quality* is [9.071, 28.05, 32.86, 28.05, 19.17, 28.05]. [1 $A_{max}$, $J_{max}$, $F_{max}$, $A_{r,max}$, $J_{c,max}$]$^T \times 10^{-5}$.

$\boldsymbol{R}^{12}$: IF $A_{max}$ is **L** and $J_{max}$ is **H** and $F_{max}$ is **L** and $A_{r,max}$ is **H** and $J_{c,max}$ is **H** THEN *Surface Quality* is [3.485, 303.9, 380.1, 303.9, 303.9, 303.9]. [1 $A_{max}$, $J_{max}$, $F_{max}$, $A_{r,max}$, $J_{c,max}$]$^T \times 10^{-4}$.

$\boldsymbol{R}^{13}$: IF $A_{max}$ is **L** and $J_{max}$ is **H** and $F_{max}$ is **H** and $A_{r,max}$ is **L** and $J_{c,max}$ is **L** THEN *Surface Quality* is [2.333, 5.135, 5.174, 4.133, 3.824, 5.135]. [1 $A_{max}$, $J_{max}$, $F_{max}$, $A_{r,max}$, $J_{c,max}$]$^T \times 10^{-5}$.

$\boldsymbol{R}^{14}$: IF $A_{max}$ is **L** and $J_{max}$ is **H** and $F_{max}$ is **H** and $A_{r,max}$ is **L** and $J_{c,max}$ is **H** THEN *Surface Quality* is [1.626, 6.06, 6.123, 0.004.474, 6.06, 6.06]. [1 $A_{max}$, $J_{max}$, $F_{max}$, $A_{r,max}$, $J_{c,max}$]$^T \times 10^{-3}$.

$\boldsymbol{R}^{15}$: IF $A_{max}$ is **L** and $J_{max}$ is **H** and $F_{max}$ is **H** and $A_{r,max}$ is **H** and $J_{c,max}$ is **L** THEN *Surface Quality* is [1.62, 5.012, 5.06, 5.012, 3.425, 5.012]. [1 $A_{max}$, $J_{max}$, $F_{max}$, $A_{r,max}$, $J_{c,max}$]$^T \times 10^{-3}$.

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$\boldsymbol{R}^{16}$: IF $A_{max}$ is **L** and $J_{max}$ is **H** and $F_{max}$ is **H** and $A_{r,max}$ is **H** and $J_{c,max}$ is **H** THEN *Surface Quality* is [0.06154, 5.43, 5.506, 5.43, 5.43, 5.43]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-1}$.

$\boldsymbol{R}^{17}$: IF $A_{max}$ is **H** and $J_{max}$ is **L** and $F_{max}$ is **L** and $A_{r,max}$ is **L** and $J_{c,max}$ is **L** THEN *Surface Quality* is [1.367, 4.814, 1.367, 1.367, 1.367 1.367]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-6}$.

$\boldsymbol{R}^{18}$: IF $A_{max}$ is **H** and $J_{max}$ is **L** and $F_{max}$ is **L** and $A_{r,max}$ is **L** and $J_{c,max}$ is **H** THEN *Surface Quality* is [2.163, 7.619, 2.163, 2.163, 2.163, 2.163]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-4}$.

$\boldsymbol{R}^{19}$: IF $A_{max}$ is **H** and $J_{max}$ is **L** and $F_{max}$ is **L** and $A_{r,max}$ is **H** and $J_{c,max}$ is **L** THEN *Surface Quality* is [1.654, 5.828, 1.654, 1.654, 1.654, 1.654]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-4}$.

$\boldsymbol{R}^{20}$: IF $A_{max}$ is **H** and $J_{max}$ is **L** and $F_{max}$ is **L** and $A_{r,max}$ is **H** and $J_{c,max}$ is **H** THEN *Surface Quality* is [2.619, 9.225, 2.619, 2.619, 2.619, 2.619]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-2}$.

$\boldsymbol{R}^{21}$: IF $A_{max}$ is **H** and $J_{max}$ is **L** and $F_{max}$ is **H** and $A_{r,max}$ is **L** and $J_{c,max}$ is **L** THEN *Surface Quality* is [2.442, 8.601, 2.442, 2.442, 2.442, 2.442]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-5}$.

$\boldsymbol{R}^{22}$: IF $A_{max}$ is **H** and $J_{max}$ is **L** and $F_{max}$ is **H** and $A_{r,max}$ is **L** and $J_{c,max}$ is **H** THEN *Surface Quality* is [3.865, 13.61, 3.865, 3.865, 3.865, 3.865]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-3}$.

$\boldsymbol{R}^{23}$: IF $A_{max}$ is **H** and $J_{max}$ is **L** and $F_{max}$ is **H** and $A_{r,max}$ is **H** and $J_{c,max}$ is **L** THEN *Surface Quality* is [2.956, 10.41, 2.956, 2.956, 2.956, 2.956]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-3}$.

$\boldsymbol{R}^{24}$: IF $A_{max}$ is **H** and $J_{max}$ is **L** and $F_{max}$ is **H** and $A_{r,max}$ is **H** and $J_{c,max}$ is **H** THEN *Surface Quality* is [4.679, 16.48, 4.679, 4.679, 4.679, 4.679]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-1}$.

$\boldsymbol{R}^{25}$: IF $A_{max}$ is **H** and $J_{max}$ is **H** and $F_{max}$ is **L** and $A_{r,max}$ is **L** and $J_{c,max}$ is **L** THEN *Surface Quality* is [4.399, 4.399, 5.757, 2.484, 1.894, 4.399]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-4}$.

$\boldsymbol{R}^{26}$: IF $A_{max}$ is **H** and $J_{max}$ is **H** and $F_{max}$ is **L** and $A_{r,max}$ is **L** and $J_{c,max}$ is **H** THEN *Surface Quality* is [3.011, 3.012, 5.161, −0.01941, 3.012, 3.011]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-2}$.

$\boldsymbol{R}^{27}$: IF $A_{max}$ is **H** and $J_{max}$ is **H** and $F_{max}$ is **L** and $A_{r,max}$ is **H** and $J_{c,max}$ is **L** THEN *Surface Quality* is [3.023, 3.023, 4.667, 3.023, −0.01035, 3.023]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-2}$.

$\boldsymbol{R}^{28}$: IF $A_{max}$ is **H** and $J_{max}$ is **H** and $F_{max}$ is **L** and $A_{r,max}$ is **H** and $J_{c,max}$ is **H** THEN *Surface Quality* is [0.8181, 0.9906, 260.3, 0.9724, 1.063, 0.7979]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-3}$.

$\boldsymbol{R}^{29}$: IF $A_{max}$ is **H** and $J_{max}$ is **H** and $F_{max}$ is **H** and $A_{r,max}$ is **L** and $J_{c,max}$ is **L** THEN *Surface Quality* is [7.859, 7.859, 7.995, 4.438, 3.382, 7.859]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-3}$.

$\boldsymbol{R}^{30}$: IF $A_{max}$ is **H** and $J_{max}$ is **H** and $F_{max}$ is **H** and $A_{r,max}$ is **L** and $J_{c,max}$ is **H** THEN *Surface Quality* is [5.379, 5.379, 5.594, −0.03673, 5.379, 5.379]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-1}$.

$\boldsymbol{R}^{31}$: IF $A_{max}$ is **H** and $J_{max}$ is **H** and $F_{max}$ is **H** and $A_{r,max}$ is **H** and $J_{c,max}$ is **L** THEN *Surface Quality* is [0.54, 5.401, 5.565, 5.401, −0.02006, 5.4]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-1}$.

$\boldsymbol{R}^{32}$: IF $A_{max}$ is **H** and $J_{max}$ is **H** and $F_{max}$ is **H** and $A_{r,max}$ is **H** and $J_{c,max}$ is **H** THEN *Surface Quality* is [−1.015, −0.7065, 259.3, −0.739, −0.5765, −1.051]. $[1\ A_{max}, J_{max}, F_{max}, A_{r,max}, J_{c,max}]^T \times 10^{-2}$.

## References

[1] Parenti P, Bianchi G, Cau N, Albertelli P, Monno M. A mechatronic study on a model-based compensation of inertial vibration in a high-speed machine tool. J Mach Eng 2001;11(4):91–104.
[2] Altintas Y, Brecher C, Weck M, Witt S. Virtual machine tool. CIRP Ann 2005;54(2):115–38.
[3] Erkorkmaz K, Altintas Y, Yeung CH. Virtual computer numerical control system. CIRP Ann 2006;55(1):399–402.
[4] Yeung CH, Altintas Y, Erkorkmaz K. Virtual CNC system. Part I. system architecture. Int J Mach Tools Manufacture 2006;46(10):1107–23 I.
[5] Yeung CH, Altintas Y, Erkorkmaz K. Virtual CNC system. Part II. high speed contouring application. Int J Mach Tools Manufacture 2006;46(10):1124–38 I.
[6] Kao YC, Chen MS. An intelligent virtual multi-axis machine tool remote service system. IEEE/ASME Int Conf Adv Intell Mechatronics 2012:632–7.
[7] Erkorkmaz K, Altintas Y. High speed CNC system design, Part I: jerk limited trajectory generation and quintic spline interpolation. Int J Mach Tools Manufacture 2001;41(9):1323–45 I.
[8] Tsai MS, Nien HW, Yau HT. Development of integrated acceleration-deceleration look-ahead interpolation technique for multi-blocks NURBS curves. Int J Adv Manufacturing Technol 2011;56(5):601–18 I.
[9] Koren Y. Cross-coupled biaxial computer control for manufacturing system. *J Dyn Syst, Meas Control* 1980;102(4):265–72.
[10] Kima MS, Chung SC. A systematic approach to design high-performance feed drive systems. Int J Mach Tools Manufacture 2005;45:1421–35.
[11] Kamalzadeh A. Precision control of high speed ball screw drives Doctor thesis of Department Mechanical Engineering, Waterloo University; 2008.
[12] Yeh SS, Hus PL. Analysis and design of integrated control for multi-axis motion systems. IEEE Trans Control Syst Technol 2003;11(3):375–82.
[13] Altintas Y, Verl A, Brecher C, Uriarte L, Pritschow G. Machine tool feed drives. CIRP Ann 2011;60(2):779–96 I.
[14] Ding G, Zhu S, Yahya E, Jiang L, Ma S, Yan K. Prediction of machining accuracy based on a geometric error model in five-axis peripheral milling Process. Pro.of Inst Mech Eng, Part B 2014;228(10):1226–36.
[15] Srinivasan K, Tsao TC. Machine tool feed drives and their control-a survey of the state of the art. J Manufacturung Sci Eng 1997;119:743–8.
[16] Tang W, Yan G, Xu X, Yu D, Wang Z, Chu H. A research on NC machining cutting parameters optimization. In: *International conferenceon information sciences, machinery, materials and energy* (ICISMME); 2015. p. 1791–7.
[17] Suzuki Y, Matsubara A, Kakino Y, Ibaraki S, Lee K. A study on the tuning of CNC parameters to improve contour precision for NC machine tools. J Japan Soc Precision Eng 2003;69(8):1119–23.
[18] Gu J, Agapiou JS, Kurgin S. CNC machine tool work offset error compensation method. J Manufacturing Syst 2015;37:576–85 part 2.
[19] Khoshdarregi MR, Altintas Y. Contour error control of CNC machine tools with vibration avoidance. CIRP Ann - Manufacturing Technol 2012;61:335–8.
[20] Koren Y, Lo CC. Variable-gain cross-coupling controller for contouring. Ann CIRP 1991;104:371–4.
[21] Čuš F, Župerl U. Surface roughness control simulation of turning processes. J Mech Eng 2015;61:245–53.
[22] Heidenhain. Technical manual iTNC640 HSCI; 2015.
[23] Jain AK, Benyounis KY, Olabi AG. Optimization of different welding processes using statistical and numerical approaches – a reference guide. Adv Eng Software 2008;39(6):483–96.
[24] Lad K. Data driven models for prognostics of high speed milling cutters. Int J Performability Eng 2016;12(1):3–12.
[25] Yan W, Tang D, LinA Y. Data-driven soft sensor modeling method based on deep learning and its application. IEEE Trans Ind Electron 2017;64(5):237–4245 I.
[26] Jang J-SR. ANFIS: adaptive-network-based fuzzy inference system. IEEE Trans Syst, Man Cybern 1993;23:665–85.
[27] Yuan Z, Wang LN, Ji X. Prediction of concrete compressive strength: research on hybrid models genetic based algorithms and ANFIS. Adv Eng Software 2014;67:156–63.
[28] Terzi S. Modeling for pavement roughness using the ANFIS approach. Adv Eng Software 2013;57:59–64.
[29] Liang JH, Lee CH. Efficient collision-free path-planning of multiple mobile robots system using efficient artificial bee colony algorithm. Adv Eng Software 2015;79:47–56.
[30] Tseng TL, Konada U, Kwon Y. A novel approach to predict surface roughness in machining operations using fuzzy set theory. J Comput Des Eng 2016;3:1–13.
[31] Maher I, Eltaib MEH, Sarhan AAD, El-Zahry RM. Cutting force-based adaptive neuro-fuzzy approach for accurate surface roughness prediction in end milling operation for intelligent machining. Int J Adv Manufacturing Technol 2015;76(5):1459–67 I.
[32] Salimi1 A, Zadshakoyan M, Özdemir A, Seidi E. Designing an intelligent system to predict drill wear by using of motor current and fuzzy logic method. Acta Sci Technol 2013;35:669–76.
[33] Sannwan KS, Saxena S, Kant G. Optimization of machining parameters to minimize surface roughness using integrated ANN-GA approach. Procedia CIRP 2015;29:305–10.
[34] Han X, Wang B, Wang W. The research of open CNC system circular interpolation track based on kinetics and kinematics. In: International conference on measuring technology and mechatronics automation; 2013. p. 1216–18.
[35] Tsai MC, Cheng MY, Lin KF, Tsai NC. On acceleration/deceleration before interpolation for CNC motion control. In: IEEE conference on mechatronics; 2005. p. 382–7.
[36] Kim DI, Song JI, Kim S. Dependence of machining accuracy on acceleration/deceleration and interpolation methods in CNC machine tools. IEEE Proc Ind Appl Soc Annu Meeting 1994;3:1898–905.
[37] Chou KH. Machine tools applications and design. Hang Lu Com; 2014. (In Chinese).