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# A New Approach of Error Compensation on NC Machining based on Memetic Computation

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***Abstract***

*This paper is a study of the application of Memetic computation integrating and coordinating intelligence algorithms to solve the problems of error compensation for a high-precision numeral control machining system. The primary focus is on development of integrated intelligent computation approach to set up an error compensation system of a numeral control machine tool based on a dynamic feedback neural network. Optimization of error measurement points of a numeral control machine tool is realized by way of application of error variable attribute reduction on rough set theory. A principal component analysis is used for data compression and feature extraction to reduce the input dimension of a dynamic feedback neural network. A dynamic feedback neural network is trained on ant colony algorithm so that network can converge to get a global optimum. Positioning error caused in thermal deformation compensation capabilities were tested using industry standard equipment and procedures. The results obtained shows that this approach can effectively improve compensation precision and real time of error compensation on machine tools.*

***Keywords:*** *memetic computation, dynamic feedback neural network, rough set theory, principal component analysis, ant colony algorithm*



## 1. Introduction

There is a general push to reduce the dimensional errors of the machined parts in a modern high-precision industrial machining so that can constantly produce better and better machine parts by numeral control (NC) machining system. Generation of dimensional errors of the machined parts in machining procedure is caused by geometric errors, kinematic errors, force deformation error, thermal deformation error, and the other errors [1-4]. This is a kind of comprehensive errors in dynamically machining process; especially it is of errors with non-linear characteristics. It calls for us to set up a kind of model of comprehensive errors for a NC machining system. It needs to present a kind of method of dynamic error compensation.

Errors in dynamically machining process needs to be measured in a large scale. There are too many error measuring points on the layout of the workload which make the adjacent point outputs have greater relevance. The influence significance of error variables needs to be studied so that optimizes the numbers of error measurement points of machine tools.

Error compensation simplification representation of a NC machining system needs to do data compression and feature extraction so that reduce the input dimension of an error compensation control system. All of them call for development of integrated intelligent computation approach to implement a real-time error compensation system [5-7].

The use of sophisticated computational intelligence approaches for solving complex problems in science and engineering has increased steadily over the last 20 years. Within this growing trend, which relies heavily on state-of-the-art optimization and design strategies, the methodology known as Memetic computation [8-12] is, perhaps, one of the recent most successful stories. Memetic computation is a broad subject which studies complex and dynamic computing structures composed of interacting modules (memes) whose evolution dynamics is inspired by the diffusion of ideas. Memes are simple strategies whose harmonic coordination allows the solution of various problems. Memetic computation offers the possibility of flexibly designing domain-specific optimization algorithms by integrating and coordinating algorithmic

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components capable of dealing with difficulties specifically related to the decision space and fitness landscape of a given problem.

In this paper, we will present a new approach of error compensation on NC machining based on Memetic computation integrating and coordinating intelligence algorithm. At first, will set up a kind of model of comprehensive errors for a NC machining system and develop a kind of dynamic feedback neural network to set up a dynamic real-time error compensation system. Optimization measurement of error point compensation on machine tools will be discussed. A new approach of reducing redundancy condition attributes will be put forward based on an information consistency relationship of equivalent classification based on rough sets and principal component analysis. Optimization of training of a dynamic feedback neural network will be proposed on ant colony algorithm.

## 2. A Model of Comprehensive Errors for a NC Machining System

A large portion of the dimensional errors for a NC machining parts are caused by geometric errors, kinematic errors, force deformation error, thermal deformation error, and the other errors. Geometric error is extant in a machine on account of its basic design, the inaccuracies built-in during assembly and as a result of the components used on the machine. Kinematic errors are concerned with the relative motion errors of several moving machine components that need to move in accordance with precise functional requirements. Force deformation error is caused by including cutting force, artifacts, and fixtures, clamping force of gravity, gravity machine parts itself etc. Thermal deformation error is caused by temperature variables in machining procedure. The other errors are caused by machine controller shaft servo matching, NC interpolation error, back backlash, machine tool wear, vibration, and so on.

Geometric errors, kinematic errors, thermal errors and the other errors yield a kind of integrated comprehensive space error or volume error of 3D accuracy of a machine tool in the three-dimensional Cartesian coordinate system in X, Y, Z three coordinates of all effective working stroke. Since space error between any two points is more easily measured and is relatively stable, we can take into account all of these integrated comprehensive errors in 3D accuracy of a machine tool. According to 6 degrees of movement of an object in 3D space, 6 item errors of machine parts in the guide moves are 3 movement errors in line position and 3 rotational errors in rotation of all direction. 3D error for each space vector superposition of results can be defined 21 item errors as following: A line positioning error of movement in X axis direction is respectively $\delta_x(x)$, $\delta_y(x)$, $\delta_z(x)$; rolling error, runout error, pitch error of movement in X axis direction is respectively $\varepsilon_x(x)$, $\varepsilon_y(x)$, $\varepsilon_z(x)$.

A line positioning error of movement in Y axis direction is respectively $\delta_x(y)$, $\delta_y(y)$, $\delta_z(y)$; rolling error, runout error, pitch error of movement in Y axis direction is respectively $\varepsilon_x(y)$, $\varepsilon_y(y)$, $\varepsilon_z(y)$.

A line positioning error of movement in Z axis direction is respectively $\delta_x(z)$, $\delta_y(z)$, $\delta_z(z)$; rolling error, runout error, pitch error of movement in Z axis direction is respectively $\varepsilon_x(z)$, $\varepsilon_y(z)$, $\varepsilon_z(z)$.

A vertical error of between X axis and Y axis, between X axis and Z axis, between Y axis and Z axis is respectively $S_{xy}$, $S_{zx}$, $S_{yz}$.

In a coordinate system $O_1$: if $x_1, y_1, z_1$ is shifted at X axis,Y axis, Z axis direction respectively, then is rotated at θx, θy, θz. It is transformed a new coordinate system $O_2$ with $x_2, y_2, z_2$ ,a homogeneous coordinate transformation matrix is expressed as Equation (1).

**T=Trans (x)×Trans (y)×Trans (z) ×Rot (θx) ×Rot (θy)×Rot (θz)** =

$$\begin{bmatrix} \cos\theta_y\cos\theta_z & -\cos\theta_y\sin\theta_z & \sin\theta_y & x \\ \sin\theta_x\sin\theta_y\cos\theta_z+\cos\theta_x\sin\theta_z & -\sin\theta_x\sin\theta_y\sin\theta_z+\cos\theta_x\cos\theta_z & -\sin\theta_x\cos\theta_y & y \\ -\cos\theta_x\sin\theta_y\cos\theta_z+\sin\theta_x\sin\theta_z & \cos\theta_x\sin\theta_y\sin\theta_z+\sin\theta_x\cos\theta_z & \cos\theta_x\cos\theta_y & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Calculation of all of these integrated comprehensive errors in 3D can be realized as following: The tip coordinate of workpiece to be machined is expressed in the Cartesian coordinate system and conversed to the reference coordinate system and the spindle coordinate system in accordance with the principle of the homogeneous coordinate transformation. A coordinate system vector diagram and transformation is shown as Figure 1 and Figure 2.

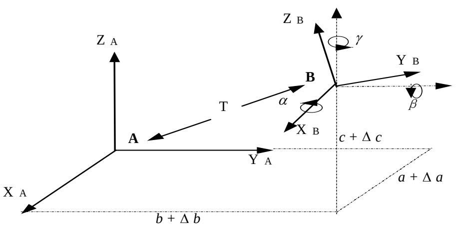


Figure 1. A Coordinate System Vector Diagram

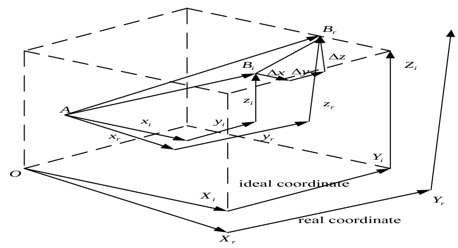


Figure 2. A Coordinate System

According to the point of tip and the workpiece cut is at the same point in space, set up the transform equation of two parts. Finally, an integrated total movement error mathematical model can be got. A geometry error and motion error vector diagram of a machine tool is shown as Figure 3.

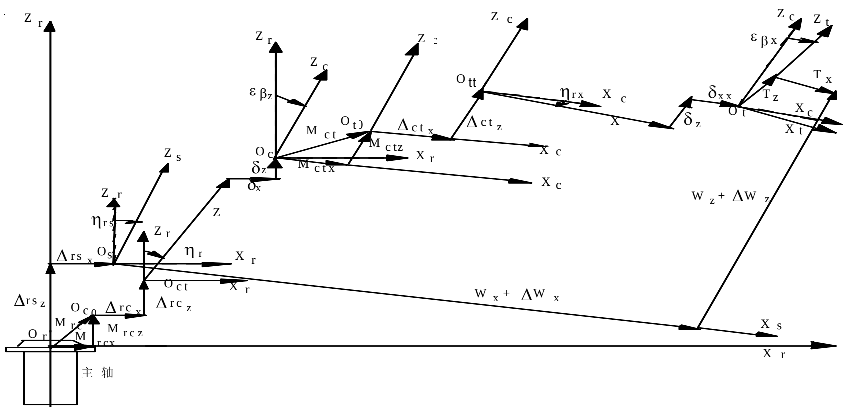


Figure 3. A Machine Tool Geometry Error And Motion Error Vector Diagram

## 3. An Error Compensation System for a NC Machining System

Since geometric errors, kinematic errors, thermal errors and the other errors yields a dynamic non-linear comprehensive errors. In the continuing effort to improve the performance of error compensation on a NC machining tool, some of control routines have been developed such as empirical formula, FEM, experimental methods, regression analysis, and so on [5-7]. But much of the work has gone into making error compensation on machine tools are not good in interpolation, real-time, and precision.

With the advent of open architecture control systems, which allow for the integration of external control routines into the basic function of the control system, there is now interest in more advanced and flexible error compensation routines. This article will develop an integrated intelligent computation approach to get an error compensation system which is embedded a dynamic feedback neural network in a NC machining system. An error compensation system in a NC machining system is shown as in Figure 4.

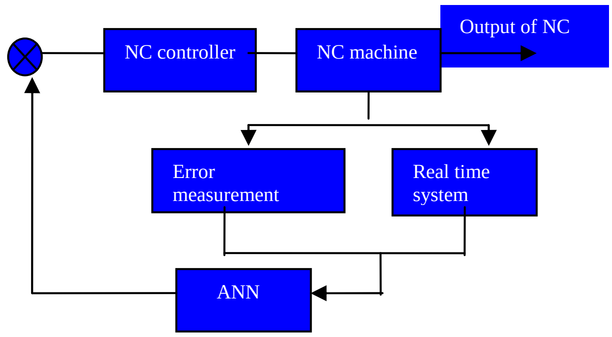

Figure 4. An Error Compensation System in A Nc Machining System

An error compensation in a NC machining system is realized by a position/velocity (P/V) control unit of a NC machine tool which embeds a dynamic feedback neural network (ANN) with integrated intelligent computation. A dynamic feedback neural network calculates increment values of position/velocity of a machine tool based on error measuring changes. The actual sampling values are compared with the values calculated based on neural network of an error compensation system to give the location tracking real-time error. The output of a dynamic feedback neural network is used as the input of computer control unit so that real-time error forecasted can be interpolated at each sampling period due to dimensional error of the axis. A programmable logic controller (PLC) gives a signal of error compensation to control increment values of position/velocity of main-axis of a machine tool. Error compensation on a NC machining system is completed in real time based on Memetic computation. A real-time position/velocity control system of a NC machining system is shown as in Figure 5.

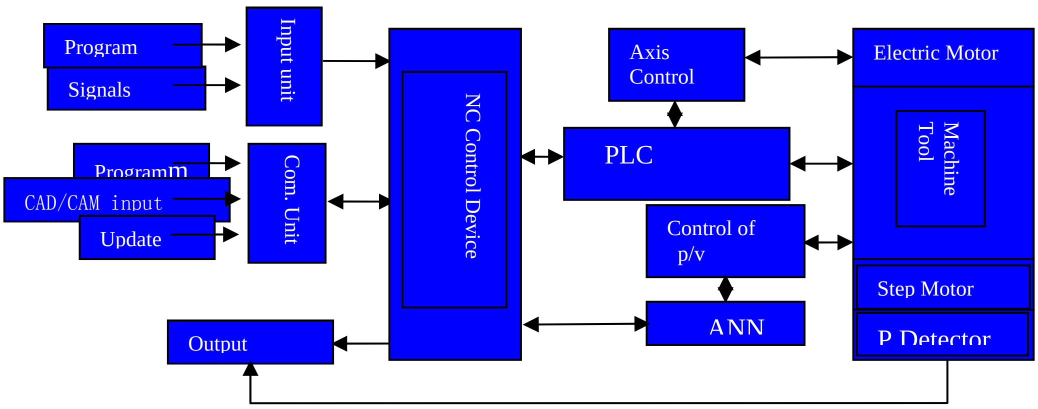

Fig. 5 A control system of a NC machining system

**4. Realization of Memetic Computation Integrating and Coordinating Intelligence Algorithms**

An error compensation system of a NC machining system can be defined by $S=(U,A,V,f)$, where $U$ is a finite number object domain of a NC machining system, $A=C\bigcup D$ is a non-empty set of attribute; $C$ is a set of error variable attributes such as rolling error, runout error, pitch error of movement etc., and $D$ is a set of error compensation decision attributes on domain $U$. $V=\bigcup_{a\in A}(V_a)$ is the attribute value set; $f:U\times A\to V$ is a error compensation decision system function; for each object $x\in U$ and there is a attribute value $a(x)\in V_a$.

**Definition 1.** In $S=(U,A,V,f)$ error compensation system of a NC machining system, a lower approximation set based on rough set [13] is defined as

$$P_{-}(D)=\bigcup\left\{X_j\in U\,\middle|\,ind(C):X_j\subseteq Y\right\} \tag{2}$$

A positive region of an input vector with respect to output error compensation decision based on rough set is defined as

$$POS_C(D)=\bigcup P_{-}(D) \tag{3}$$

Where $U|C=(X_1,\cdots,X_n)$ denotes the equivalence classes of *U* based on error variable attributes *C*, and $U|D=(Y_1,\cdots,Y_m)$ denotes the equivalence classes of *U* based on error compensation decision attributes *D*.

It is shown that an equivalence class $X_j$ which is based on error variable attributes $C$ can be classified into an equivalence class $Y$ which is based on error compensation decision attributes $D$ in the lower approximation set.

**Definition 2.** In $S=(U,A,V,f)$ error compensation system of a NC machining system, the significance of error variables which denotes the performance of information dependence relationships between error variable attributes and error compensation decision attributes is defined as

$$k=\frac{card\,(POS_C(D))}{card\,(U)} \tag{4}$$

Where $card(U)=|U|$ is the cardinality of an object domain $U$. It is shown that if $k=1$, database acquired of a machine error compensation system is referred as a concert data. Otherwise, the system is an inconsistent data [14].

**Definition 3.** In $S=(U,A,V,f)$ error compensation system of a NC machining system, the performance of information consistency is defined as

$$Q_C=\frac{card\,(U|C)}{card\,(U)} \tag{5}$$

Where $card(U|C)$ denotes the cardinality of an equivalence class $U|C$ based on error variable attributes on an universe and $card(U)=|U|$ is the cardinality of an universe *U*. It is shown that if $Q_C=1$, a machine error compensation system is referred as consistence system. Otherwise, the system is of inconsistent system. If $Q_{C-r}=1$, denotes an error variable $r\in C$ can be omissible in set C, then error variable attribute set and decision attribute set is still consistent with the equivalence relation in a machine error compensation system [14].

We may use the performance of information consistency of a machine error compensation system to discuss reduction of a knowledge representation of an error compensation control system. A simplification set contained the collection of relations which is not omitted is referred as $red(P)$. An intersection set of all simplification set in a machine error compensation system is referred as a core of error variable attributes [14] defined as

$$core(P) = \cap\ red(P) \tag{6}$$

Basic procedure of realization of optimization of error measurement points of a NC machining system based on rough sets is as following steps:

Input: $C$ and $D$ sets of error variable attributes and error compensation decision attributes of a NC machining system respectively.

Output: A set of core of error variable attributes in a machine error compensation system.

Step 1: Normalize and discrete of attribute values of $C$ and $D$ sets of error variable attributes and error compensation decision attributes of a NC machining system.

Step 2: Calculate the equivalence classes $U|C$ of U based on error variable attributes C, and the equivalence classes $U|D$ of U based on error compensation decision attributes D, and a positive region $POS_C(D)$ of an input vector with respect to decision output.

Step 3: Calculate the significance of error variables $k$ which denotes the performance of information dependence relationships between error variable attributes and error compensation decision attributes. If $k = 1$, it is shown that data of measurement points of error compensation control system is a concert data.

Step 4: If $k = 1$, the redundant error variables $r$, $r \in C$ is removed based on $Q_{C-r} = 1$, and find a core of error variable attributes in a machine error compensation system based on $core(P) = \cap\ red(P)$, so that reduce a knowledge representation and the input dimension of an error compensation control system.

It is shown that we may use the performance of information consistency of a machine error compensation system to discuss a realization of optimization of error measurement points of error compensation on a NC machining system based on rough sets at first, then use principal component analysis to select $r(r < n)$ principal components of error variable attributes so that transforms some relevance variables as a few of non-relevance variables to reduce the data space dimensions of training and a testing set for an error compensation control system.

Since error compensation on a machine tool is a non-linear dynamic process, this requires a dynamic feedback neural network on real-time implementation. Based on above error analysis on a NC machining tool, error compensation on a machine tool can be realized on 6 objects in 3D space as following: A line positioning error of movement in X axis, Y axis and Z axis direction is $\delta_x(x)$, $\delta_y(y)$ and $\delta_z(z)$ respectively. A vertical error of between X axis and Y axis, between X axis and Z axis, between Y axis and Z axis is respectively $\varepsilon_x(y)$, $\varepsilon_z(x)$, $\varepsilon_y(z)$

In a new dynamic feedback neural control network, the input of the net is consisted of three parts: Dimensional errors caused by geometric errors, kinematic errors, force deformation error, thermal deformation error, and the other errors, system implementation errors from a NC machine tool real-time implementation system input deviation and net feedback errors dynamically feedbacked from a delay unit. The input of delay unit comes from the output of error compensation in previously sampling period, thus allowing network input data is always maintain a high degree of accuracy. The output of BP network is data of 6 objects in 3D space of error compensation on machine tools. A neuron used as a neural computation unit is of a nonlinear characteristics such as

$$f(n) = -\frac{1}{2} + \frac{1}{1 + e^{-n}} \tag{7}$$

Training of a dynamic feedback neural network needs converge fast and get a global optimum. Taking advantage of ant colony algorithm on training of a dynamic feedback neural network does the global search so that network can converge to get a global optimum.

**5. An Experimental Simulation of Thermal Error Compensation for a NC Machine Tool**

A large portion of the dimensional errors of machined parts is formed by positioning errors in the axes of motion on a machine tool. Moreover, these positioning errors caused by temperature variables in procedure are about 50%~80%. A thermal error is determined by the composition of its different components on the structure and size, different heat capacity, thermal conductivity, thermal expansion, and heat environmental sources etc., coupled with nonlinear boundary conditions and thermal deformation temperature field variation of delay. Therefore, the feasibility of the proposed approach of error compensation for a NC machining system is validated by some of illustrations thermal error compensation of a NC machine tool here.

The measurement of thermal error compensation of a NC machine tool is got on the HMC800A type three-axis vertical machining center made in China. 572 group data is used as a sample data of error compensation of a NC machine tool. A temperature curve of measuring points of HMC800A type three-axis vertical machining center is shown as Figure 6.

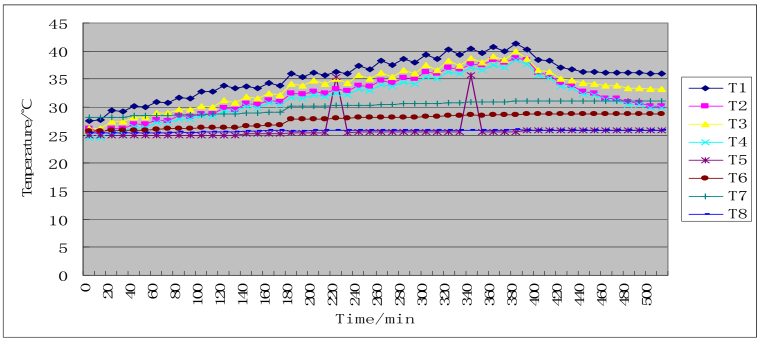


Figure 6. A Temperature Curve of Measuring Points

The temperature of different locations of machine tool part is used as a conditional attribute C, C = {T1, T2, T3, T4 and T5, T6, T7,T8},Where T1 denotes temperature of left seat of machine tool , T2 denotes temperature of left seat of machine tool bearing, T3 denotes temperature of right seat of machine tool , T4 denotes temperature of right seat of machine tool bearing, T5 denotes temperature of machine tool working table, T6 denotes temperature of left light scalar, T7 denotes temperature of right light scalar, T8 denotes ambient temperature.

The positioning error displacement is used as a result attributes D, D = {Y0, Y1, Y2, Y3, Y4, Y5.Y6, Y7, Y8, Y9, Y10}

Optimization of temperature measurement points of thermal error compensation of HMC800A type three-axis vertical machining center is based on rough set theory method. Data compression and feature extraction is based on principal component analysis. A core of error variable attributes in thermal error compensation of HMC800A type three-axis vertical machining center is got as following

$$core_D(C) = \{T1, T4, T5, T7,\}$$

A three layer dynamic feedback neural network is used for thermal error compensation on machine tool HMC800A. {T1, T4 ,T5, T6, T7 } is used for input of the net. The input of BP network comes also from system implementation errors and net feedback errors. The output of BP network is data of 6 objects in 3D space of error compensation on machine tools.

Global search on neural network parameters is completed by way of ant colony algorithm at first, then do local learning of neural network parameters by using BP adaptive algorithm. 572 group error data is used as a training sample. A Error curve of convergence of network optimization training is shown as Figure 7.

It is shown that a general BP net does not completely convergence after 3000 steps training by an ordinary BP algorithm [13,15], especially it will go to a local minimum when mean square error value reach at 0.1 in 3000 steps. Optimization training on a BP network based on ant colony algorithm does the global search so that network can converge to get a global optimum when mean square error value reach at 0.01 in 1000 steps.

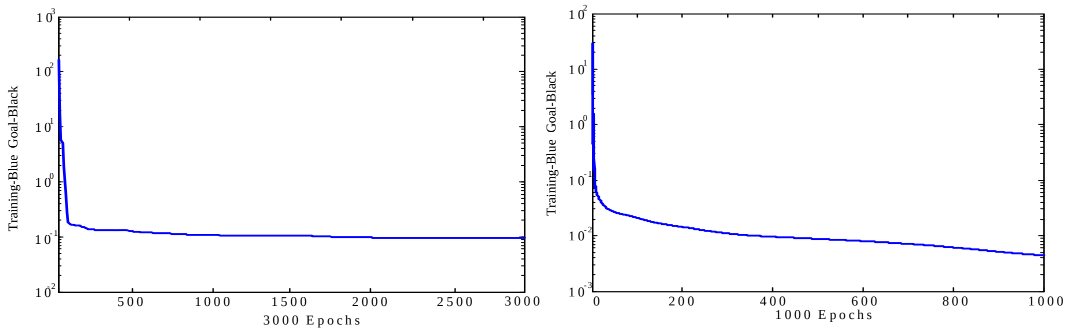


Figure 7. An Error Curve Of Convergence Of Network Optimization Training

The results of thermal error compensation on machine tool HMC800A based on comprehensive intelligence computation is shown in Figure 8.

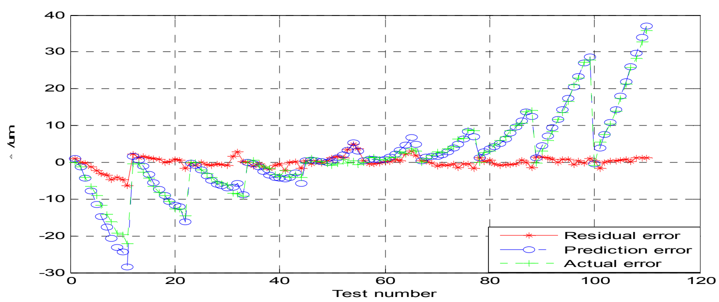


Figure 8. The Results Of Thermal Error Compensation On Machine Tool HMC800A

It is shown that for 110 temperature measurement points of thermal error sampled from 572 group error data to be compensated, residual error value of 57 measurement points exceeds the 6 $\mu m$ after thermal error compensation. Over 90% of the data displacement of positioning error compensated is consistent with the requirements of error compensation on a machine tool.

## 6. Conclusion

This paper presents a new approach of comprehensive error compensation for a NC machining system in a modern high-precision industrial machining procedure. An error compensation control system of a NC machining system is established based on a dynamic feedback neural network embedded in a NC machine tool. The main focus is on the development of Memetic computation integrating and coordinating Rough set algorithm to get an optimization of error measurement points of a NC machining system. Data compression and feature extraction based on PCA reduces the input dimension of a dynamic feedback neural network and reduce training time of the network. Global search on training of a dynamic feedback neural network is realized on taking advantage of ant colony algorithm. Thermal error compensation capabilities were tested by using industry standard equipment and procedures. It is shown that this approach can significantly improve compensation precision and real-time performance of error compensation on a NC machining system.

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