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Accuracy enhancement of five-axis CNC machines through real-time error compensation

W.T. Lei [a,*], Y.Y. Hsu [b]

[a] *Department of Power Mechanical Engineering, National Tsing Hua University, Hsinchu, Taiwan, ROC*
[b] *Department of Mechanical Engineering, Chung Hua University, Hsinchu, Taiwan, ROC*

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Abstract

Although error modeling and compensation have given significant results for three-axis CNC machine tools, a few barriers have prevented this promising technique from being applied in five-axis CNC machine tools. One crucial barrier is the difficulty of measuring or identifying link errors in the rotary block of five-axis CNC machine tools. The error model is thus not fully known. To overcome this, the 3D probe-ball and spherical test method are successfully developed to measure and estimate these unknown link errors. Based on the identified error model, real-time error compensation methods for the five-axis CNC machine tool are investigated. The proposed model-based error compensation method is simple enough to implement in real time. Problems associated with the error compensation in singular position of the five-axis machine tool are also discussed. Experimental results show that the overall position accuracy of the five-axis CNC machine tool can be improved dramatically.

Keywords: Accuracy enhancement; Five-axis machine tool; Probe-ball; Error compensation

1. Introduction

In the past decades, much research has focused on the machine tool accuracy of three-axis CNC machine tools in the presence of geometric and thermally induced errors [1–4]. Based on the established error model, a compensation method can be developed to improve the accuracy of the target machine tool [5,6]. The error compensation in the three-axis machine tool delivers very good results if the machine's operating condition is well-defined and repeatable. In contrast, previous studies on the five-axis CNC machine tool are mainly based on theory and simulation [7,8]. Due to the lack of a proper measurement device, some dominant errors in the error model of the five-axis CNC machine tool are not measurable. In [9], a neural network model was used for the error compensation, thus bypassing the problem. Since the error model describes the effects of individual error sources on the overall position errors exactly, it is obvious that error model-based compensation will deliver the most effective results. This research effort focuses on the identification of unknown components in the error model.

The components appearing in the error model of the five-axis CNC machine tool can be classified into two categories: motional errors and link errors. Motional errors are those associated with the inaccurate motion of the servo-driven linear or rotary axis. All motional errors of the servo-driven linear axis can be measured efficiently with modern laser interferometers [10]. In contrast, the motional errors of the rotary axis are only partly measurable, with an electronic level or multi-face mirror. Link errors are those due to the erroneous mounting of structural components such as column, spindle, and rotary block. Measurable link errors include the three squareness errors between the three linear axes. Link errors in the rotary block are normally not measurable, due to lack of accessibility.

To enhance the accuracy of five-axis CNC machine tools, model-based real-time error compensation has many advantages. For one, nearly all identified errors

* Corresponding author. Tel.: +886-3-574-2321; fax: +886-3-572-2840.
E-mail address: wtlei@pme.nthu.edu.tw (W.T. Lei).

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can be fully compensated. For another, high-level path definitions in the NC program, such as the spline, can be processed by the CNC's interpolator directly and avoid the typical problem of discontinuous feedrate during five-axis machining. In a previous study [11], a new measurement device with corresponding methods was presented to test the overall position errors of the five-axis CNC machine tool. Also, an estimation method was developed to identify the unknown link errors in the error model [12]. This study goes further and investigates model-based real-time error compensation.

2. Basic concept

In the information flow of five-axis machining, forward and backward kinematic transformations are performed at different levels. Usually, both transformations are based on an ideal kinematic chain, whereby geometric errors of the real machine are not considered. Since most five-axis CNC controllers only accept NC data defined in machine coordinates, backward transformation is performed in the post-processor of the CAD/CAM system. The tool path defined in the cutter location data (CLDATA) file is transformed from workpiece coordinates into machine coordinates to adapt to the input format of the target CNC controller.

In this paper, transformation based on the ideal kinematic model is named nominal transformation. The nominal backward transformation $F_{b,n}$ computes the axis position vector $\mathbf{u}$ in machine coordinates from given tool pose vector $\mathbf{v}$ in workpiece coordinates:

$$\mathbf{u} = F_{b,n}(\mathbf{v}) \tag{1}$$

The tool pose vector $\mathbf{v}$ is defined in workpiece coordinates and includes the tool tip position $\mathbf{P} = [x_w \;\; y_w \;\; z_w]$ and the tool orientation $\mathbf{Q} = [i_w \;\; j_w \;\; k_w]$. $\mathbf{Q}$ is a unit directional vector.

The nominal forward transformation $F_{f,n}$ computes tool pose vector $\mathbf{v}$ in workpiece coordinates from given axis position vector $\mathbf{u}$ in machine coordinates:

$$\mathbf{v} = F_{f,n}(\mathbf{u}) \tag{2}$$

Note that the solution for the forward transformation is unique. For each given axis position vector $\mathbf{u}$, there is one, and only one, corresponding tool pose vector $\mathbf{v}$. In contrast, the solution for the backward transformation is not unique. If the five-axis machine is not in singular position, there are in general two solutions for the backward transformation. It is necessary to select a suitable one according to predefined criteria, for example minimal driving energy or distance. If the five-axis machine is in the singular position, the position of one rotary axis is not solvable. In the case of the $X'Y'ZA'C'$ type five-axis milling machine, the machine is in singular position when the rotary C-axis is in the vertical direction. In this case, the k-component of the orientation vector $\mathbf{Q}$ is equal to one and the other components are zero. The rotation of the C-axis does not change the tool orientation in workpiece coordinates.

In driving the real five-axis machine with the axis position vector $\mathbf{u}_s$, the actual tool pose vector $\mathbf{v}_a$ deviates from the setting tool pose vector $\mathbf{v}_s$:

$$\mathbf{v}_a = F_e(\mathbf{u}_s,\mathbf{e}) \tag{3}$$

where F_e represents the error model of the real five-axis machine and $\mathbf{e}$ the set of geometric errors.

The task of model-based error compensation is to find a necessary correction vector d$\mathbf{u}$ for each axis position vector $\mathbf{u}_s$ such that despite the existing geometric errors, the tool takes the desired pose:

$$\mathbf{v}_s = F_e(\mathbf{u}_s + \mathrm{d}\mathbf{u},\mathbf{e}) \tag{4}$$

The necessary condition for finding the correction vector d$\mathbf{u}$ is that all errors in the error model must be known. There are different ways to find the vector d$\mathbf{u}$. Since the error model is highly nonlinear, iterations are normally necessary to get a solution with acceptable tolerance. For real-time error compensation, the iterative approach is not preferred. Since the errors are small, the relationship between the differential change of tool pose in workpiece coordinates and the differential change in machine axis coordinates can be assumed to be linear. This linear relationship in matrix form is known as the Jacobian matrix [13]. Because the solution for the forward transformation is always unique, it is better to use it to compute the Jacobian matrix:

$$\mathbf{J} = \frac{\partial F_{f,n}(\mathbf{u})}{\partial \mathbf{u}} \tag{5}$$

The computation of correction vector d$\mathbf{u}$ is then very simple by using the inverse Jacobian matrix:

$$\mathrm{d}\mathbf{u} = \mathbf{J}^{-1}\mathrm{d}\mathbf{v} \tag{6}$$

where $\mathbf{J}^{-1}$ is the inverse Jacobian matrix.

3. Error modeling and identification

Fig. 1 shows the target five-axis milling machine. The machine can be modeled as an open kinematic chain with several links connected in series by prismatic and rotational joints. At one end of the kinematic chain is the tool locked with the main spindle. The spindle block is fixed on the Z-slide. The Z-slide moves vertically along the column with a prismatic joint. The column on the other hand is bolted onto the machine bed. The other end of the kinematic chain begins with the workpiece, which is fixed onto the base surface of the C-turntable. The C-turntable is integrated with the A-tilting head, which on the other hand is mounted on the X-table. The

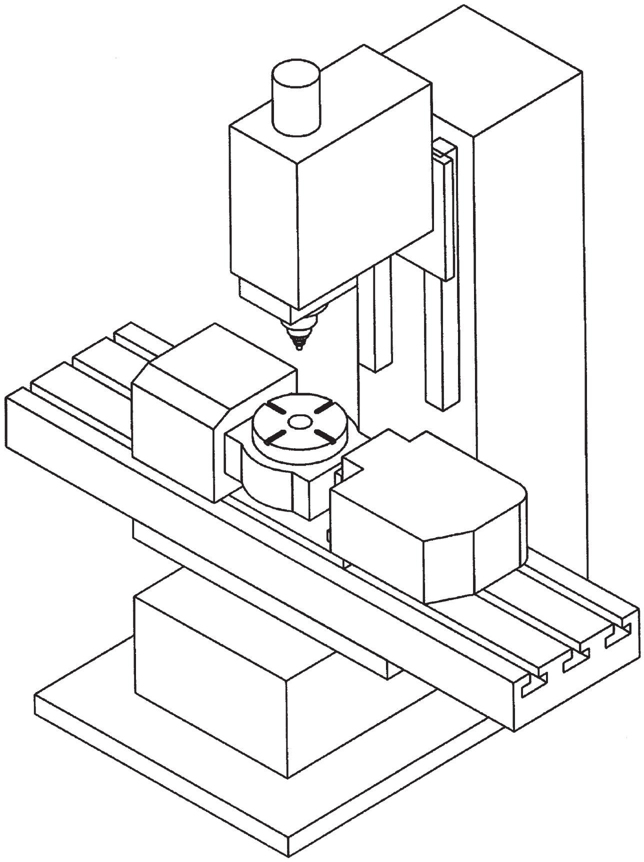

Fig. 1. Five-axis milling machine of the type $X'Y'ZA'C'$.

C- and A-axis together contribute to the tilt motion of the workpiece. The X-table moves horizontally on the Y-table with a prismatic joint. The Y-table moves on the machine bed with a prismatic joint too.

Fig. 2 illustrates the coordinate frames with constant offset parameters Z_0, Z_1, Z_2 and Z_3 between coordinate systems. The parameter L_t is tool length. After defining the homogenous transformation matrix (HTM) [14] for each kinematic component, the spatial relationship between the workpiece coordinate frame and the tool coordinate frame can then be expressed as

$$ {}^{w}T_t = {}^{w}T_b\ {}^{b}T_c{}^{c}T_a\ {}^{a}T_x\ {}^{x}T_y\ {}^{y}T_z\ {}^{z}T_s\ {}^{s}T_h\ {}^{h}T_t \tag{7} $$

where the index t represents the coordinate frame of the tool, h the tool holder, s the spindle, x, y, z the three linear axes, a and c the two rotary axes, b the base surface of the turntable and w the workpiece. Note that link errors in the rotary block ${}^{b}T_c$, ${}^{c}T_a$ and ${}^{a}T_x$ are dominant, unknown and need to be estimated.

The positioning with axis position vector $\mathbf{u}$ gives tool pose $\mathbf{v}$. The tool tip's position $\mathbf{P} = [x_w \;\; y_w \;\; z_w]$ is obtained as follows:

$$ [\mathbf{P} \;\; 1]^{\mathrm{T}} = {}^{w}T_{t,i}[0 \;\; 0 \;\; 0 \;\; 1]^{\mathrm{T}} \tag{8} $$

where ${}^{w}T_{t,i}$ describes the ideal relationship between the workpiece coordinate frame and the tool coordinate frame and can be obtained by setting all errors to zero. The vector $[0 \;\; 0 \;\; 0 \;\; 1]$ represents the origin point of the tool coordinate frame. Note that the workpiece coordinate frame is fixed on the turntable and rotates with the rotary axes C and A. Therefore, the tool orientation vector, represented by unit directional vector $\mathbf{Q} = [i_w \;\; j_w \;\; k_w]$, is determined only by the two rotary axes and can be obtained by transforming the unit vector $[0 \;\; 0 \;\; 1]$ in the tool coordinate frame into the workpiece coordinate frame:

$$ [\mathbf{Q} \;\; 0]^{\mathrm{T}} = {}^{w}T_{t,i}[0 \;\; 0 \;\; 0 \;\; 1]^{\mathrm{T}} \tag{9} $$

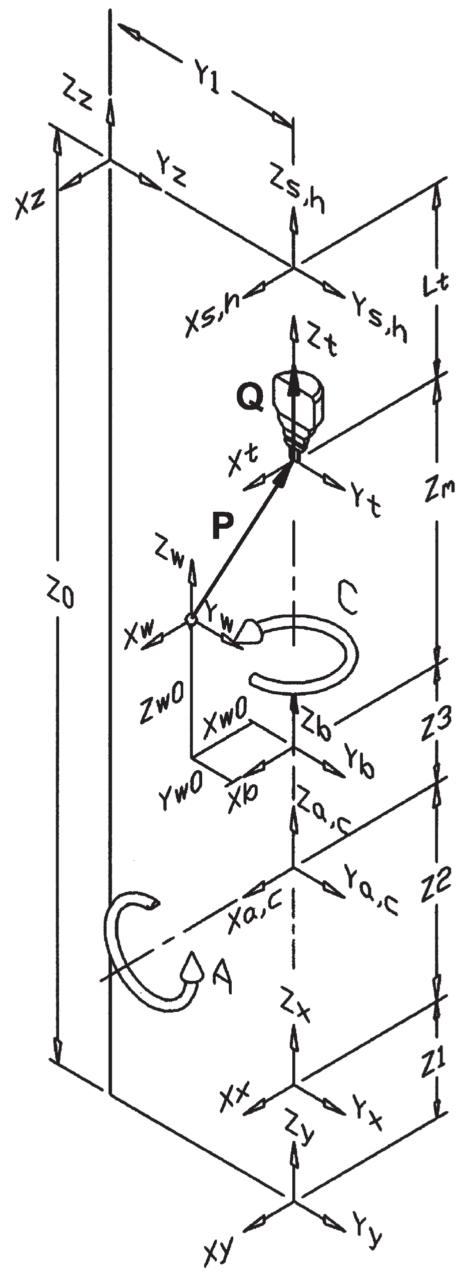

Fig. 2. The coordinate frames of the five-axis milling machine.

The nominal forward transformation of the target five-axis milling machine can be derived easily by using the matrix ${}^{w}T_{t,i}$ and can be explicitly expressed as follows:

$$x_w = z_m\sin(\theta_c)\sin(\theta_a) - y_m\sin(\theta_c)\cos(\theta_a) - x_m\cos(\theta_c) - X_{w0} \tag{10}$$

$$y_w = z_m\cos(\theta_c)\sin(\theta_a) - y_m\cos(\theta_c)\cos(\theta_a) + x_m\sin(\theta_c) - Y_{w0} \tag{11}$$

$$z_w = z_m\cos(\theta_a) + y_m\sin(\theta_a) - Z_3 - Z_{w0} \tag{12}$$

$$i_w = \sin(\theta_a)\sin(\theta_c) \tag{13}$$

$$j_w = \sin(\theta_a)\cos(\theta_c) \tag{14}$$

$$k_w = \cos(\theta_a) \tag{15}$$

where x_m, y_m, z_m, θ_a and θ_c are the setting position of the servo-controlled X-axis, Y-axis, Z-axis, A-axis and C-axis, respectively. The axis position vector is $\mathbf{u} = [x_m\ \ y_m\ \ z_m\ \ \theta_a\ \ \theta_c]$. X_{w0}, Y_{w0} and Z_{w0} are offsets between the workpiece coordinate frame and the base surface coordinate frame.

Explicit expressions of the overall position errors can be obtained after carrying out matrix multiplications and simplifying the equations by neglecting the second- and higher-order terms. The tool pose error d$\mathbf{v}$ includes the tool tip's position error $\mathrm{d}\mathbf{P} = [\mathrm{d}x_w\ \ \mathrm{d}y_w\ \ \mathrm{d}z_w]$ and the orientation error $\mathrm{d}\mathbf{Q} = [\mathrm{d}i_w\ \ \mathrm{d}j_w\ \ \mathrm{d}k_w]$, both are defined in workpiece coordinates. The errors d$\mathbf{P}$ and d$\mathbf{Q}$ can be expressed as

$$[\mathrm{d}\mathbf{P}\ \ 1]^{\mathrm{T}} = {}^{w}T_{t,i}[0\ \ 0\ \ 0\ \ 1]^{\mathrm{T}} - {}^{w}T_{t}[0\ \ 0\ \ 0\ \ 1]^{\mathrm{T}} \tag{16}$$

$$[\mathrm{d}\mathbf{Q}\ \ 0]^{\mathrm{T}} = {}^{w}T_{t,i}[0\ \ 0\ \ 0\ \ 1]^{\mathrm{T}} - {}^{w}T_{t}[0\ \ 0\ \ 0\ \ 1]^{\mathrm{T}} \tag{17}$$

The error model represented by Eqs. (16) and (17) is different from that presented in [11]. Eq. (16) describes the overall position errors of the tool in the workpiece coordinate frame. In contrast, the error model in [11] describes the overall position errors measured by the probe sensors. Although these two models are different, most error components are the same.

In the past, the error model was used for simulation since major error components were not known. Today, the spherical test [11] with the 3D probe-ball provides a new approach. With the measured overall position errors, the unknown link errors can be identified by using the least square estimation (LSE) method.

4. Compensation algorithm

Note that the tool pose error vector d$\mathbf{v}$ is defined in workpiece coordinates and the correction vector d$\mathbf{u}$ is defined in machine coordinates. A critical step in model-based error compensation is to derive the correction vector d$\mathbf{u}$ from the error vector d$\mathbf{v}$. As mentioned above, the nominal forward transformation functions are used to compute the Jacobian matrix describing the linear relationship between differential changes in the workpiece coordinates and the machine coordinates. From Eqs. (10)–(15), this linear relationship can be explicitly expressed as

$$\mathrm{d}x_m = (-\mathrm{d}x_wC_cS_a + \mathrm{d}y_wS_cS_a + \mathrm{d}i_wC_cS_az_m - \mathrm{d}i_wC_cC_ay_m - \mathrm{d}j_wS_cS_az_m + \mathrm{d}j_wS_cC_ay_m)/S_a \tag{18}$$

$$\mathrm{d}y_m = (-\mathrm{d}x_wS_cC_a^2 - \mathrm{d}y_wC_cC_a^2 + \mathrm{d}z_wC_aS_a + \mathrm{d}i_wS_a^2S_cz_m + \mathrm{d}i_wC_cS_aC_a^2x_m - \mathrm{d}j_wS_cS_aC_a^2x_m + \mathrm{d}j_wC_cS_a^2z_m)/C_a \tag{19}$$

$$\mathrm{d}z_m = (\mathrm{d}x_wS_aS_cC_a + \mathrm{d}y_wC_cS_aC_a + \mathrm{d}z_wC_a^2 - di_wS_cy_m - \mathrm{d}i_wC_cC_ax_m + \mathrm{d}j_wS_cC_ax_m - \mathrm{d}j_wC_cy_m)/C_a \tag{20}$$

$$\mathrm{d}\theta_a = (\mathrm{d}i_wS_c + \mathrm{d}j_wC_c)/C_a \tag{21}$$

$$\mathrm{d}\theta_c = (\mathrm{d}i_wC_c - \mathrm{d}j_wS_c)/S_a \tag{22}$$

where C_c, C_a, S_c and S_a are the simplified operators of $\cos(\theta_c)$, $\cos(\theta_a)$, $\sin(\theta_c)$ and $\sin(\theta_a)$, respectively. In Eqs. (18)–(22), $\cos(\theta_a)$ and $\sin(\theta_a)$ appear in the denominator and may cause problems.

4.1. Case 1: $\theta_a = 0^{\mathrm{o}}$

In this case, the C-turntable is in the horizontal position. The tool orientation vector is [0 0 1] in the workpiece coordinates and the five-axis machine is in its singular position. The nominal backward transformation is not solvable because the C-axis may take any position value. A small orientation deviation out of the singular position may cause the C-axis to adapt abruptly. A similar effect exists for five-axis machine tools of other kinematic types. In path planning, the singular position must be avoided through tilt mounting of the workpiece. In practice, the singular problem may occur after 3D workpiece mounting correction. For the sake of safety, correction with the C-axis must be suppressed. Only the orientation deviation in the YZ-plane is compensated with the A-axis. The corrections are as follows:

$$\mathrm{d}x_m = -C_c\mathrm{d}x_w + S_c\mathrm{d}y_w - y_m\mathrm{d}j_w \tag{23}$$

$$\mathrm{d}y_m = -S_c\mathrm{d}x_w - C_c\mathrm{d}y_w + x_m\mathrm{d}j_w \tag{24}$$

$$\mathrm{d}z_m = \mathrm{d}z_w \tag{25}$$

$$\mathrm{d}\theta_a = \mathrm{d}i_w \tag{26}$$

4.2. Case 2: $\theta_a = 90^{\mathrm{o}}$

In this case, the base surface of the C-turntable is vertical and the component k_w is zero. The position of the C-axis determines the tool orientation in the XY-plane of the workpiece coordinate frame. The corrections are simplified as follows:

$$dx_m = -C_c dx_w + S_c dy_w + z_m dj_w \tag{27}$$

$$dy_m = dz_w \tag{28}$$

$$dz_m = S_c dx_w + C_c dy_w - x_m dj_w \tag{29}$$

$$d\theta_a = di_w \tag{30}$$

$$d\theta_c = dj_w \tag{31}$$

5. Experimental results

To test the effectiveness of the proposed compensation method, the compensation function is developed and integrated in the CNC controller of the target five-axis milling machine. The self-developed CNC controller is an industrial PC with Pentium III microprocessor running at 330 MHz. The interface between the controller and the AC drivers is a motion card, which has five 16-bit D/A converters for the output of velocity commands and five 24-bit counters for the encoder inputs. The motion control software has been developed in C/C++ language and runs under the real-time NT-RTX operating system. The sampling time for the position control is 2 ms.

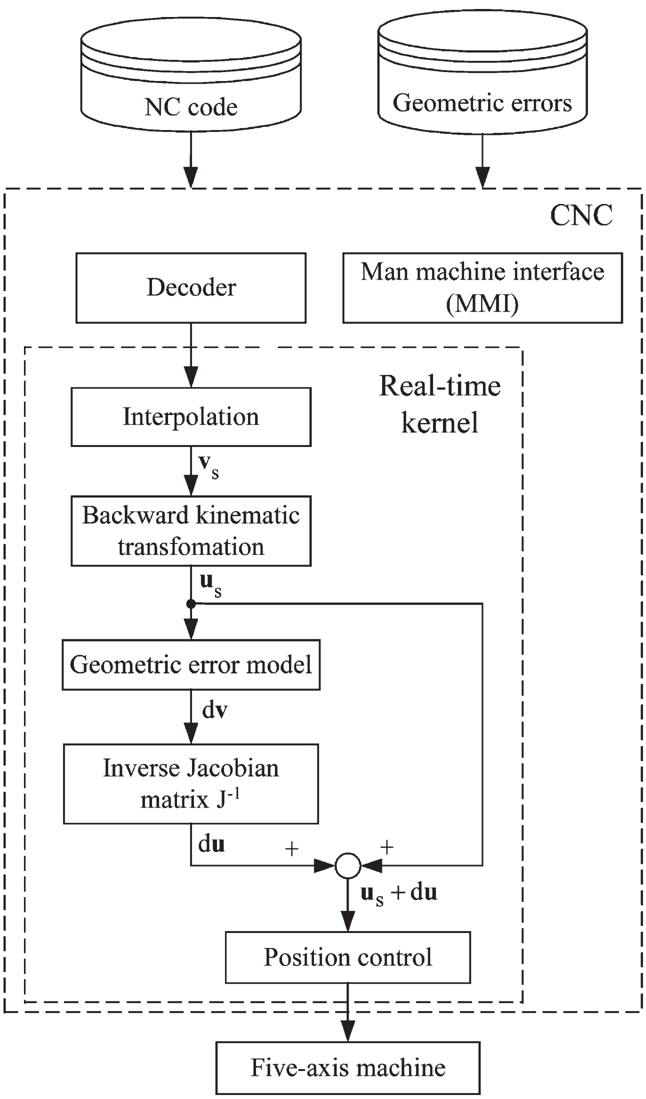

Fig. 3. The functional structure of real-time geometric error compensation.

The functional structure of the CNC software for the real-time error compensation is shown in Fig. 3. The real-time kernel program performs the path and orientation interpolation. The NC path input can be defined in either machine coordinates or workpiece coordinates. If interpolation is performed in the workpiece coordinates, backward transformation based on the ideal kinematic model follows to calculate the setting position in machine coordinates. The error compensation is activated in each real-time position control loop. The error model computes tool pose errors in workpiece coordinates for each setting axis position. From the tool pose errors, the correction vector in machine coordinates is then calculated.

The measurement of overall position error and the estimation of unknown link errors are already described in previous papers. Simulations show that errors in the rotary axes block are dominant, contributing up to 80% of the overall position errors. In contrast, the linear axes system contributes less than 20%.

Fig. 4 shows some test paths for the real-time error compensation. Fig. 5 shows the measured overall position errors before and after the real-time error compensation, whereby path F is used for both estimation and accuracy test. The accuracy enhancement is very impressive. The overall positioning accuracy can be improved by a factor of 7.8 in the *X* direction, 3.2 in the

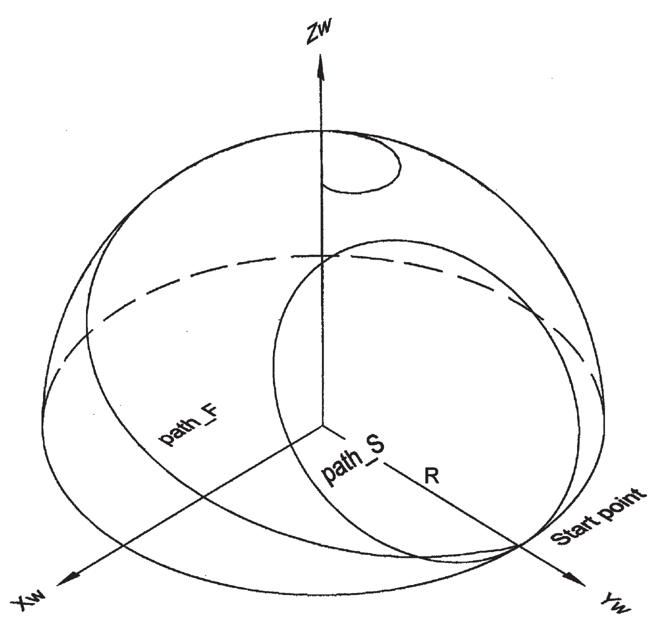

Fig. 4. The test path.

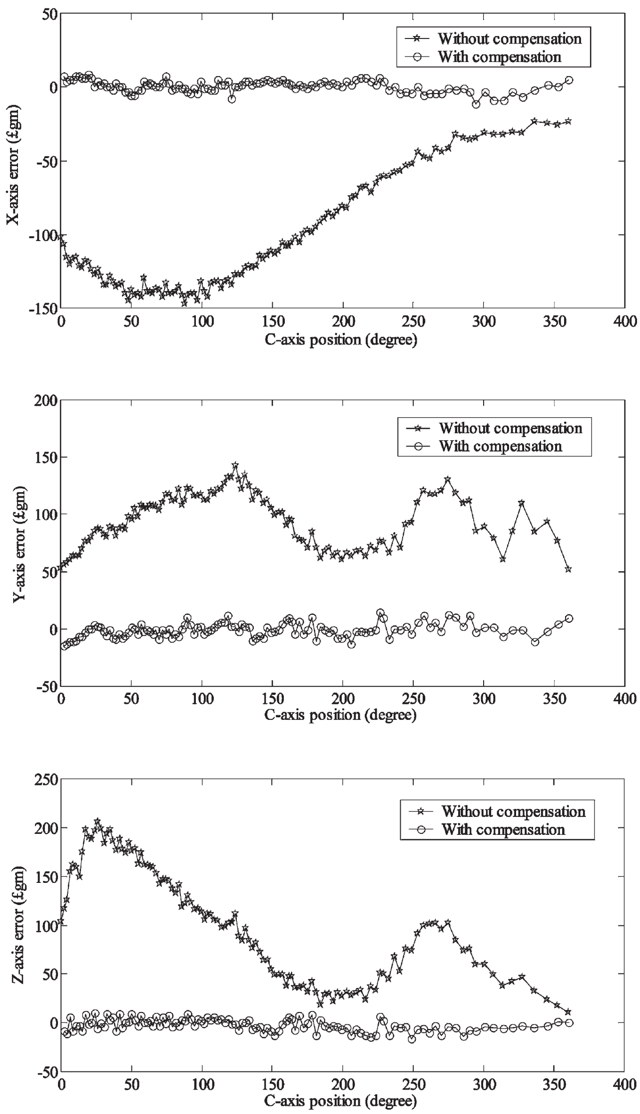

Fig. 5. Results of error compensation for path F.

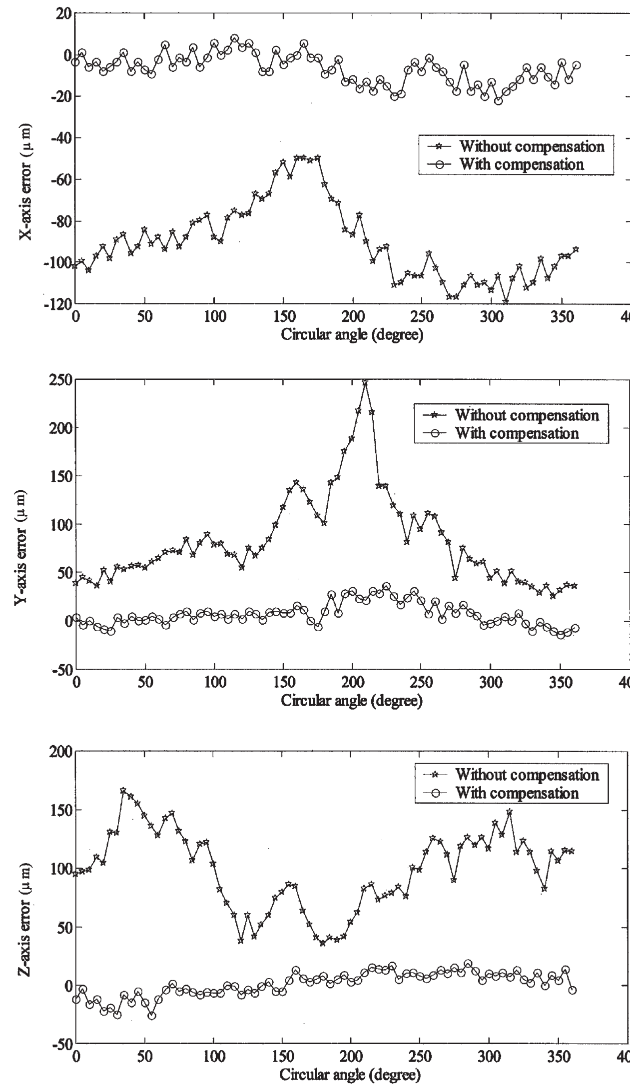

Fig. 6. Results of error compensation for path S.

Y direction and 8.2 in the *Z* direction. This high improvement rate is already predicted in simulation and justified now with real machine tests. These excellent results come from the fact that the non-measurable link errors in the rotary block are dominant, repeatable and can be identified accurately. The effectiveness of the real-time error compensation is proved further under the condition that different paths for identification and accuracy test are used. This time, path F is used for the estimation and path S is used for the evaluation. Fig. 6 shows the results. The accuracy enhancement is still impressive.

6. Conclusion

The ultimate goal of geometric error modeling is to compensate errors such that the accuracy of the CNC machine tool can be improved effectively. In previous studies, a new measurement device and methods were developed to identify unknown link errors in the error model. In this paper, the identified error model is used for real-time error compensation. Since all geometric errors are small, the relationship between differential changes in the machine coordinates and the workpiece coordinates can be regarded as linear. The proposed compensation method uses the linear relationship to calculate the correction vector in machine coordinates from the predicted tool pose error in workpiece coordinates. The algorithm is thus simple and suitable for real-time implementation. Practical tests show that the overall position errors can be reduced dramatically. With the error compensation function implemented in the CNC controller, the manufacturing cost and the assembling time of rotary block can be reduced while the accuracy of the five-axis machine tool is not sacrificed. Future work will focus on modeling the thermal effects on the error model so that the model-based error compensation can respond to different machine operating conditions.

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