行政院國家科學委員會專題研究計畫 成果報告

應用 R-test 量具進行五軸工具機幾何誤差量測鑑定與補償技術

研究成果報告(精簡版)

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中 華 民 國 100 年 12 月 09 日

中 文 摘 要 ： 本論文的的主要目的是應用 R-test 量具進行五軸工具機的轉動軸的位置幾何誤差項鑑定。CNC 數控工具機的誤差模型描述個別幾何誤差項與機器總成誤差間的關係，現今已可應用 R-test 量具直接量測到五軸工具機的總成誤差，若個別幾何誤差項為已知，則此時可應用幾何誤差模型預測幾何誤差藉此實現誤差補償。因此，本論文中依 ISO230 的幾何誤差定義，完整的建立五軸工具機 R-test 量具幾何誤差模型，並依此一模型,在只考量轉動軸的位置誤差(location error)前題下，簡化五軸幾何誤差模型。接著基於簡化模型及以 R-test 量具進行 K4 量測路徑的量測結果，可應用最小平方法精確估測旋轉軸的位置誤差項。最後並以路徑 K1 及路徑 K2 有效驗證誤差模型及鑑定方法的正確性，則此建立之誤差模型可應用於誤差補償以提升機器精度。

中文關鍵詞： 幾何誤差,五軸工具機,最小平方法, 位置誤差

英 文 摘 要 ： The main purpose of this study is to use an R-test measurement device to estimate the geometric location error of the axis of rotation of five-axis machine tools. The error model of CNC machine tool describes the relationship between the individual error source and its effects on the overall position errors. Now, the R-test measuring device can be used to measure the overall position errors of five-axis machine tools directly. To improve the accuracy of CNC machine tools, error sources and its effects on the overall position and orientation errors must be known.

This study thus based its definition on the geometric errors of ISO230 to construct a geometric error model used to measure errors in the five-axis machine tools for the R-test measurement device. This model was then used to reduce the five-axis geometric error model based solely on the location error of the axis of rotation. Moreover, based on the simplified model and the overall position errors measured by the R-test with path K4, the location errors of rotary axes and ball position errors can be estimated very accurately with the least square estimation method. Finally, paths K1 and K2 were used as為 testing paths. The results of the test showed that the model built in this study is accurate and is effective in

estimating errors.

英文關鍵詞： Geometric error； Least square estimation； Five-axis machine tools； R-test； Position errors.

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成果報告類型(依經費核定清單規定繳交)：■精簡報告　□完整報告

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中　華　民　國 100 年 9 月 10 日

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五軸工具機的精度提升一直是發展五軸工具機的關鍵技術之一,而如何藉由特定量具量測並鑑定誤差項,則是此一技術的研究重點. 本計畫的主要目的是應用 R-test 量具進行五軸工具機的轉動軸的位置幾何誤差項鑑定。此研究成果證實:應用建構的五軸工具機幾何誤差模型及 R-test 的量測結果,可有效鑑定出五軸工具機的轉動軸位置誤差項.最後,藉由建立之完整誤差模型可應用於誤差補償以提升五軸工具機的機器精度。

此研究的成果目前正與台灣發展五軸工具機的廠商協鴻公司,喬崴進公司及匠澤公司等進行相關應用技術的合作,即將鑑定出來的結果,應用 Heidenhain 控制器進行補償,可對提升國內五軸工具機廠商做出重大貢獻.

Modeling and identification for rotary geometric errors of five-axis machine tools with R-test measurement

Yung-Yuan Hsu

Abstract

The main purpose of this study is to use an R-test measurement device to estimate the geometric location error of the axis of rotation of five-axis machine tools. The error model of CNC machine tool describes the relationship between the individual error source and its effects on the overall position errors. Now, the R-test measuring device can be used to measure the overall position errors of five-axis machine tools directly. To improve the accuracy of CNC machine tools, error sources and its effects on the overall position and orientation errors must be known.

This study thus based its definition on the geometric errors of ISO230 to construct a geometric error model used to measure errors in the five-axis machine tools for the R-test measurement device. This model was then used to reduce the five-axis geometric error model based solely on the location error of the axis of rotation. Moreover, based on the simplified model and the overall position errors measured by the R-test with path K4, the location errors of rotary axes and ball position errors can be estimated very accurately with the least square estimation method. Finally, paths K1 and K2 were used as testing paths. The results of the test showed that the model built in this study is accurate and is effective in estimating errors.

Keywords: *Geometric error; Least square estimation; Five-axis machine tools; R-test; Position errors.*

1. Introduction

In addition to three servo-controlled linear axes, five-axis CNC machine tool has normally two extra servo-controlled rotary axes. These rotary axes can be used to adjust the cutting tool in an optimal orientation relative to the cutting surface of workpiece. The advantages of five-axis machining of sculptured surface include much higher metal removal rate, improved surface finish and significantly lower cutting time.

Enhancing the accuracy of CNC machine tools is vital task in the area of machine tools. According to relevant research reports, quasi-static errors account for 70% of volume errors in CNC machine tools. This kind of error includes both geometric and thermal errors.

This study researched geometric errors in quasi-static errors for five-axis machine tools. Regarding improvements in machine tool accuracy over the past decade, Slocum (1992) and Kiridena and Ferreira (1994) have explained that the geometric errors and thermal deformation in three-axis machine tools influenced accuracy [1, 2]. Using the error model establish by these authors, Ferreira and Liu (1986; 1993) have developed an error compensation technique to improve the accuracy of CNC machine tools [3,4]. In recent years, more research has been conducted involving five-axis machine tools. Srivastava et al. (1995) constructed a mathematical analysis model for geometric and thermal errors in five-axis machine tools using HTM and proposed an NC machine online compensation method [5]. The volume error for machine tool work space is the function of all error terms. To ensure the geometric accuracy of five-axis machine tools, machine assembly must go through a substantial, time-consuming calibration process.

Currently, certain types of measurement devices are able to measure geometric errors in machine tools; the most common and most efficient of which is the API 6D laser interferometer [6]. This measurement device can simultaneously measure six degrees of freedom on a linear motion axis. The DBB, another common measurement device, is used to examine dynamic errors in linear motion axes [7]. Lei et al. (2007) applied the DBB to test for errors in the rotary axis of five-axis machine tools [8]. Lei and Hsu (2002) developed a probe-ball measuring device that could directly measure the overall errors of a five-axis machine tool and, thus, evaluate its accuracy [9]. Weikert (2004) showed that the R-test, which can measure static and dynamic errors in five-axis simultaneous machines, still had limited applications in analyzing five-axis geometric and dynamic errors [10]. The LaserTRACER offers an efficient, high-precision measurement system for volumetric calibration, but this measurement system is very expensive [11].

Although the theoretical error model of five-axis machine tool is known, it is still impossible to improve the accuracy of five-axis machine tool with the error compensation technique based on it. The reason is there are some not directly measurable location and component errors in the error model, such as the inaccurate location and component errors of rotary axes block. These errors are exist as deviations between coordinate systems and are difficult to access after the mounting process. It is clear that the key step toward effective accuracy enhancement of five-axis machine tools is the identification of these unknown location and component errors of rotary axes.

The least square estimation (LSE) methods provide with mathematical procedures by which a linear model can achieve a best fit to experimental data in the sense of least-squared error. The methods are powerful and well-developed mathematical tools that have been proposed and used in a variety of areas for decades, including adaptive control, signal processing, and statistics[12]. In the field of errors estimation of five-axis machine tools, Lei and Hsu (2002) showed the probe-ball error model was constructed and based on the data accumulated by a probe-ball. For errors which the least square estimation method can be used to gain a precise estimate[13]. some other researches also used this method to estimate error components [14-16].

In this paper, the error model of the R-test measurement in five-axis machine tools be derived. the estimation of the unknown and not directly measurable location errors and ball position errors in the error model is addressed. Based on this relationship and the measured overall position errors with measuring path K4, the location errors of rotary axes and ball position errors can be estimated very accurately with the least square estimation methods.

2. Error model of R-test measurement

2.1 Geometric error definition of linear and rotary axes

Definitions in IS0230 related to error test standards for CNC machine tools include the definition of geometric errors and the testing method. A linear motion axis is defined as possessing six component errors (three translational and three rotational errors), and a location (perpendicularity) error exists between two linear motion axes. A rotary motion axis also possesses six component errors (three translational and three rotational errors), four location errors (two translational and two rotational errors). According to the above definitions, a five-axis machine tool with three linear and two rotary axes has a total of 41 geometric errors.

To describe three-axis machine tool geometric overall errors, establishing a geometric error model for the target machine is necessary. Assuming that the structure of the machine tool is a rigid body, a 4x4 HTM could be used to show the relationship between each kinematic and servo control axis, and the machine error model could undergo an individual kinematic and driver component HTM to obtain the order of products, depending on the machine kinematic chain [1].

Figure 1 displays a case study for the X-axis linear motion slide. The geometric error model for kinematic parameters, location errors, and component errors in the X-axis linear slide, showing the relationship of the x coordinate system with respect to the reference coordinate system ${}^{r}T_{x}$, is shown in the formula below.

$$
{}^{r}T_{x} = \begin{bmatrix} 1 & 0 & 0 & X_x \\ 0 & 1 & 0 & Y_x \\ 0 & 0 & 1 & Z_x \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & -COX & 0 & 0 \\ COX & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & -ECX & EBX & X_m + EXX \\ ECX & 1 & -EAX & EYX \\ -EBX & EAX & 1 & EZX \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}
$$

Where X_x, Y_x, Z_x are either the constant offset of the x home position with respect to the reference coordinate system in the x,y,z directions, respectively, or the kinematic parameter for the X-axis linear slide. *COX* is the location error between the linear X-axis and an ideal linear axis (in this example, the Y-axis of the reference coordinate system), which causes a small angular rotation between the two coordinate systems in the Z-axial direction. *EXX, EYX, EZX, EAX, EBX,* and *ECX* are the six component errors for the linear X axis, and X_m is the servo-controlled position of the X-axis slide.

The order of products for the kinematic parameter matrix, the location (perpendicularity) error matrix and the 6D component error matrix in the above formula depends on the pattern arrangement in the kinematic chain of the linear X-axis. First, regarding the 6D component error matrix of the X-axis linear slide, assuming that when the X-axis slide moves to the home position and the Z-axis of the x coordinate system is identical to the Z-axis of the reference coordinate system, the perpendicular error *COX* exists between the X-axis of the x coordinate system and the Y-axis of the reference coordinate system, as does the perpendicularity error matrix. When the X-axis slide moves to the X home position, the X-axis slide has the kinematic parameter matrix for the origin coordinate offsets.

The rotary axis geometric error model is described in Figure 2. Using the rotary motion of the C-axis as an example, the geometric error model (HTM) for the kinematic parameters, location errors, and component errors, the relationship of the c coordinate system with respect to the reference coordinate system, ${}^{r}T_{c}$, is shown in the formula below.

$$
{}^{r}T_c = \begin{bmatrix} 1 & 0 & 0 & X_c \\ 0 & 1 & 0 & Y_c \\ 0 & 0 & 1 & Z_c \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & BOC & XOC \\ 0 & 1 & -AOC & YOC \\ -BOC & AOC & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\begin{bmatrix} C_{ce} & -S_{ce} & EBC & EXC \\ S_{ce} & C_{ce} & -EAC & EYC \\ EAC*S_{ce}-EBC*C_{ce} & EAC*C_{ce}+EBC*S_{ce} & 1 & EZC \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)
$$

Where X_c, Y_c, Z_c are either the constant offset of the c home position with respect to the reference coordinate system in the x,y,z direction, respectively, or the kinematic parameter for the C-axis rotary turntable. *XOC* and *YOC* are the C-axis installation center and the ideal center, respectively, in the X, Y directional translational offset. *AOC* and *BOC* are, respectively, the location errors for the C-axis installation axis line and ideal coordinate system axis direction (in this example, the Y- and X-axis of the reference coordinate system), causing a small angular rotation in the directions of the X- and Y-axes between two coordinate systems. *EXC*, *EYC*, *EZC*, *EAC*, *EBC*, and *ECC* are six component errors for the C-axis. Finally, $S_{ce} = \sin(C_m + ECC)$, $C_{ce} = \cos(C_m + ECC)$, and C_m is the servo-controlled position of the C servo-axis.

In Equation (2), the first matrix is the kinematic parameter matrix for the offset in origin between two coordinate systems; the second matrix is the location error matrix for the C rotary-axis; and the third matrix is the component error matrix for the C rotary-axis. Thus, the C rotary-axis has ten geometric errors.

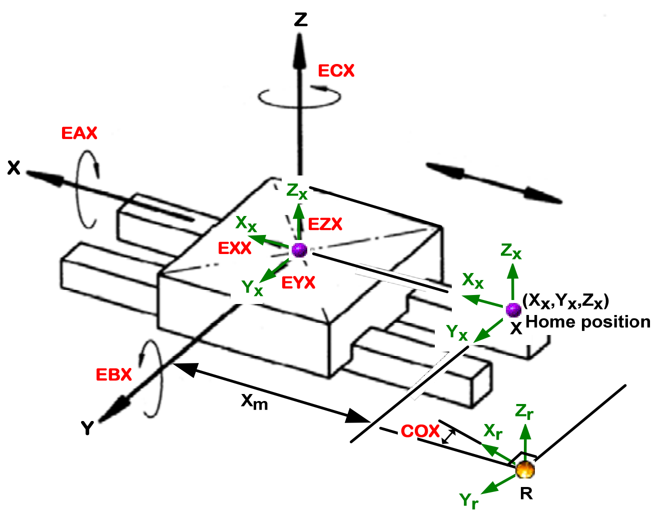


Figure 1. X-axis linear axis error definition

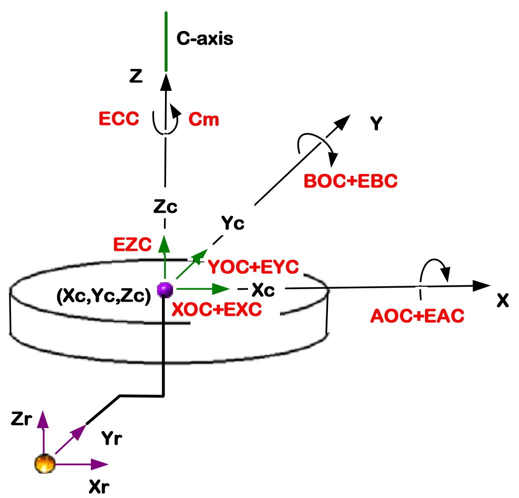


Figure 2. C-axis rotary axis error definition

2.2 Error model for R-test measuring in five-axis machine tools

Fig. 3 illustrates the investigated five-axis milling machine and its coordinate systems. The whole machine is modeled as a kinematic chain with several links connected in series by prismatic and rotational joints. At one end of the chain is the 3D measuring probe mounted on the spindle. The spindle block is mounted on the Z-slide. The Z-slide moves vertically on the Y-table with a prismatic joint. The Y-table moves on the machine column with a prismatic joint too.

At the other end, the kinematic chain begins with the master ball which is fixed on the C-turntable.

The C-turntable is integrated in the A-tilting head. The A-tilting head is mounted on the X-table. The X-table moves horizontally on the machine bed with a prismatic joint. Finally, based on the ISO230 definition and this machine's kinematic chain sequence, the location errors between three linear axes are *COX*, *BOZ*, and *AOZ*.

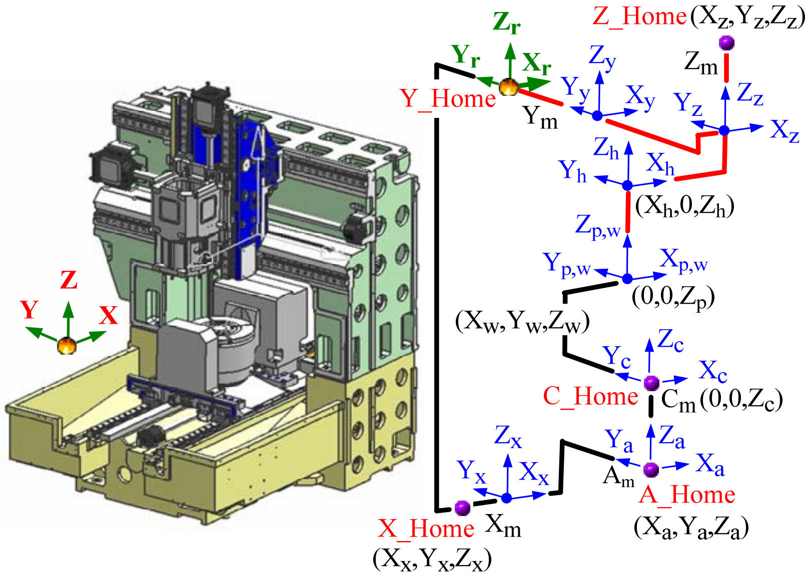


Figure 3. Coordinate systems with R-test

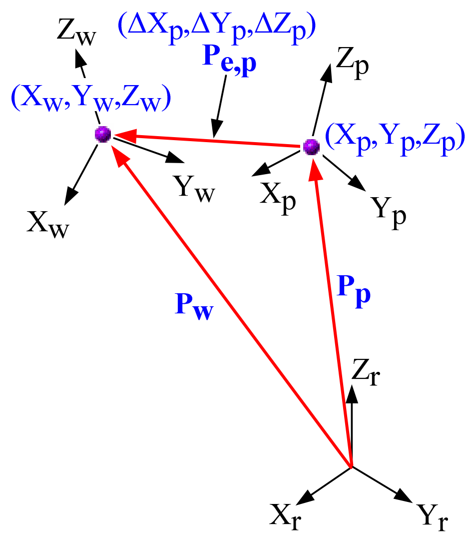


Figure 4. R-test measuring errors

As described above, there are total 44 errors in the error model. By using the HTMs described above, the spatial relationship between the workpiece coordinate system and the reference coordinate system can be expressed as

$$^{r}T_{w}={}^{r}T_{x}\ {}^{x}T_{a}\ {}^{a}T_{c}\ {}^{c}T_{w} \tag{3}$$

Similarly, the spatial relationship between the probe coordinate system and the reference coordinate system can be expressed as

$$^{r}T_{p}={}^{r}T_{y}\ {}^{y}T_{z}\ {}^{z}T_{h}\ {}^{h}T_{p} \tag{4}$$

As shown in Figure 4, the center of the master ball $\boldsymbol{P_w}=[X_w \quad Y_w \quad Z_w]$ deviates from the origin of the probe coordinate system $\boldsymbol{P_p}=[X_p \quad Y_p \quad Z_p]$ due to geometric errors. The $\boldsymbol{P_w}$ and $\boldsymbol{P_p}$ are computed from following equations:

$$[\boldsymbol{P_w} \quad 1]^T={}^{r}T_{w}\,[0 \quad 0 \quad 0 \quad 1]^T \tag{5}$$

$$[\boldsymbol{P_p} \quad 1]^T={}^{r}T_{p}\,[0 \quad 0 \quad 0 \quad 1]^T \tag{6}$$

The position error vector $\boldsymbol{P_{e,r}}$ in the reference coordinate system can be expressed as

$$\boldsymbol{P_{e,r}}=\boldsymbol{P_w}-\boldsymbol{P_p} \tag{7}$$

Since displacement sensors are designed in the 3D probe and measurements occur in the probe coordinate system, it is necessary to transform the position error vector $\boldsymbol{P_{e,r}}$ from the reference coordinate system into the probe coordinate system:

$$[\boldsymbol{P_{e,p}} \quad 0]^T = ({}^rT_p)^{-1}[\boldsymbol{P_{e,r}} \quad 0] = [\Delta X_p \quad \Delta X_p \quad \Delta X_p \quad 0]^T \tag{8}$$

where the ΔX_p, ΔY_p and ΔZ_p are the deviations in the probe coordinate system. Explicit expressions of the measured errors can be obtained after carrying out the matrix multiplications and neglecting the second and higher order errors as Table 1.

Table 1 show that the overall error in the direction of the X-axis, ΔX_p, is the product of each error multiplied by the error gain of each error. For example, the error contribution in the X-axis direction in *EBX* is $EBX*(+Z_a - C_a*Z_c - S_a*S_c*X_w - S_a*C_c*Y_w - C_a*Z_w)$. This table, which is considered a geometric error sensitivity analysis table, indicates that translational errors (such as *EXX*, *EYX*…) are machine kinematic parameter-independent, while rotational errors (such as *EAX*, *EBX*,…) are machine kinematic parameter-dependent.

Table 1 Error model and sensitivity analysis

		$\triangle X_p$	$\triangle Y_p$	$\triangle Z_p$	$\triangle I_p$	$\triangle J_p$	$\triangle K_p$
	Error	Error Gain	Error Gain	Error Gain	E. G.	E. G.	E. G.
X	*EXX*	-1	0	0	0	0	0
	EYX	0	-1	0	0	0	0
	EZX	0	0	-1	0	0	0
	EAX	0	$+Z_a+C_a*Z_c+S_a*S_c*X_w$ $+S_a*C_c*Y_w+C_a*Z_w$	$-Y_a+S_a*Z_w+S_a*Z_c$ $-C_a*C_c*Y_w-C_a*S_c*X_w$	0	C_a	S_a
	EBX	$-Z_a-C_a*Z_c-S_a*S_c*X_w$ $-S_a*C_c*Y_w-C_a*Z_w$	0	$X_a-S_c*Y_w+C_c*X_w$	$-C_a$	0	0
	ECX	$+Y_a-S_a*Z_c-C_a*S_c*X_w$ $-C_a*C_c*Y_w-S_a*Z_w$	$-X_a-C_c*X_w+S_c*Y_w$	0	$-S_a$	0	0
Y	*EXY*	1	0	0	0	0	0
	EYY	0	1	0	0	0	0
	EZY	0	0	1	0	0	0
	EAY	0	$-Z_h-Z_p-Z_m-Z_z$	$+Y_z$	0	-1	0
	EBY	$+Z_h+Z_p+Z_m+Z_z$	0	$-X_h-X_z$	1	0	0
	ECY	$-Y_z$	$+X_h+X_z$	0	0	0	0
Z	*EXZ*	1	0	0	0	0	0
	EYZ	0	1	0	0	0	0
	EZZ	0	0	1	0	0	0
	EAZ	0	$-Z_h-Z_p$	0	0	-1	0
	EBZ	$+Z_h+Z_p$	0	$-X_h$	1	0	0
	ECZ	0	$+X_h$	0	0	0	0
Per.	*COX*	$+Y_a-S_a*Z_c-C_a*S_c*X_w$ $-C_a*C_c*Y_w-S_a*Z_w$	$-X_m-X_a$ $-C_c*X_w+S_c*Y_w$	0	$-Sa$	0	0
	AOZ	0	$-Z_h-Z_p-Z_m$	0	0	-1	0
	BOZ	$+Z_h+Z_p+Z_m$	*0*	$-X_h$	1	0	0
Ball pos.	*XOW*	$-C_c$	$-C_a*S_c$	$-S_a*S_c$	0	0	0
	YOW	S_c	$-C_a*C_c$	$-S_a*C_c$	0	0	0
	ZOW	0	S_a	$-C_a$	0	0	0
A	*EXA*	-1	0	0	0	0	0
	EYA	0	-1	0	0	0	0
	EZA	0	0	-1	0	0	0
	EAA	0	$+S_a*S_c*X_w+S_a*C_c*Y_w$ $+C_a*(Z_w+Z_c)$	$-C_a*C_c*Y_w+S_a*(Z_w+Z_c)$ $-C_a*S_c*X_w$	0	C_a	S_a
	EBA	$-C_a*(Z_w+Z_c)-S_a*S_c*X_w$ $-S_a*C_c*Y_w$	0	$-S_c*Y_w+C_c*X_w$	$-C_a$	0	0
	ECA	$-S_a*(Z_w+Z_c)+C_a*S_c*X_w$ $+C_a*C_c*Y_w$	$-C_c*X_w+S_c*Y_w$	0	$-S_a$	0	0
	YOA	0	-1	0	0	0	0
	ZOA	0	0	-1	0	0	0
	BOA	$-C_a*(Z_w+Z_c)-S_a*S_c*X_w$ $-S_a*C_c*Y_w$	0	$-S_c*Y_w+C_c*X_w$	$-Ca$	0	0
	COA	$-S_a*(Z_w+Z_c)+C_a*S_c*X_w$ $+C_a*C_c*Y_w$	$-C_c*X_w+S_c*Y_w$	0	$-S_a$	0	0
	EXC	-1	0	0	0	0	0
	EYC	0	$-C_a$	$-S_a$	0	0	0

C	*EZC*	0	$+S_a$	$-C_a$	0	0	0
	EAC	0	$+S_c*S_a*X_w+C_c*S_a*Y_w+C_a*Z_w$	$-C_c*C_a*Y_w+S_a*Z_w-S_c*C_a*X_w$	0	C_a	S_a
	EBC	$-Z_w$	$-C_c*S_a*X_w+S_c*S_a*Y_w$	$-S_c*C_a*Y_w+C_c*C_a*X_w$	-1	0	0
	ECC	$+Sc*Xw+Cc*Yw$	$-C_a*C_c*X_w+C_a*S_c*Y_w$	$+S_a*S_c*Y_w-S_a*C_c*X_w$	0	0	0
	XOC	-1	0	0	0	0	0
	YOC	0	$-C_a$	$-S_a$	0	0	0
	AOC	0	$+S_c*S_a*X_w+C_c*S_a*Y_w+C_a*Z_w$	$-C_c*C_a*Y_w+S_a*Z_w-S_c*C_a*X_w$	0	C_a	S_a
	BOC	$-Z_w$	$-C_c*S_a*X_w+S_c*S_a*Y_w$	$-S_c*C_a*Y_w+C_c*C_a*X_w$	-1	0	0
Note: $C_a=\cos(A_m)$, $C_c=\cos(C_m)$, $S_a=\sin(A_m)$, $S_c=\sin(C_m)$.							

3.Error estimation

To reduce the scope of estimation, a reasonable approach is to set the errors to zero except location errors of rotary axes and ball position errors. The estimation focuses then only on the unknown, constant and not measurable location errors of rotary axes and ball position errors. The advantage of this approach is that the estimation can be done even if available measurement devices are limited, for example only linear or 6D laser interferometer is available. Obviously, the accuracy of estimation will be better if more powerful devices are used.

The least square estimation method can only estimate position-independent constant errors. When the contribution of the 21 geometric errors on the three machine tools and the 12 component errors on the 2 axes of rotation are smaller than the errors that need to be estimated, the 33 geometric errors mentioned previously would not cause a significant impact on the R-test measurement figures. The error models of the five-axis machine tool with R-test measurement device presented in Table 1 can thus be reduced, as can be seen in Table 2. The total number of geometric errors that need to be estimated is 11 (3 ball position errors and 8 location errors on the 2 axes of rotation). These error parameters form the parameter vector $\boldsymbol{a}$.

The reduced error model builds the mathematical base for the least square estimation and can be re-arranged into vector form to obtain the error gain functions $f_{i,x}(\boldsymbol{p}_j)$, $f_{i,y}(\boldsymbol{p}_j)$ and $f_{i,z}(\boldsymbol{p}_j)$ in the error gain matrix $\boldsymbol{H}$ for each setting position $\boldsymbol{p}_j$. For example, the location error *BOA* is defined as error parameter a_6. Its error gain function $f_{6,x}(\boldsymbol{p}_j)$ is $-C_a*(Z_w+Z_c)-S_a*S_c*X_w-S_a*C_c*Y_w$.

Table 2 Reduced error model

		$\triangle X_p$	$\triangle Y_p$	$\triangle Z_p$
	Error	Error Gain	Error Gain	Error Gain
Ball Pos.	$XOW(a_1)$	$-C_c$	$-C_a*S_c$	$-S_a*S_c$
	$YOW(a_2)$	$+S_c$	$-C_a*C_c$	$-S_a*C_c$
	$ZOW(a_3)$	0	$+S_a$	$-C_a$
A	$YOA(a_4)$	0	-1	0
	$ZOA(a_5)$	0	0	-1
	$BOA(a_6)$	$-C_a*(Z_w+Z_c)-S_a*S_c*X_w-S_a*C_c*Y_w$	0	$-S_c*Y_w+C_c*X_w$
	$COA(a_7)$	$-S_a*(Z_w+Z_c)+C_a*S_c*X_w+C_a*C_c*Y_w$	$-C_c*X_w+S_c*Y_w$	0
C	$XOC(a_8)$	-1	0	0
	$YOC(a_9)$	0	$-C_a$	$-S_a$
	$AOC(a_{10})$	0	$+S_c*S_a*X_w+C_c*S_a*Y_w+C_a*Z_w$	$-C_c*C_a*Y_w+S_a*Z_w-S_c*C_a*X_w$
	$BOC(a_{11})$	$-Z_w$	$-C_c*S_a*X_w+S_c*S_a*Y_w$	$-S_c*C_a*Y_w+C_c*C_a*X_w$

4. R-test measuring and estimation results

The block diagram of parameter estimation is shown in Figure 5. The parameters of the five-axis milling machine tool are calibrated and are shown in Table 3. The five-axis milling machine tool is tested with three different test paths: the K1, K2 and K4. As can be seen in Table 2, the K4 test path, which all five axes driven simultaneously, is ideal in estimating error measurement to effectively calculate all errors. Therefore, the K4 test path is used for estimation and the K1,K2 paths are used for justification. The overall position errors and the setting positions $\boldsymbol{p}_j$ of each error sampling are registered for the purpose of error estimation. The total number of samples for K4 is 241. K1 is 361, and K2 is 121.

Table 3. Parameters of the target five-axis machine

Parameter	Value (mm)	Parameter	Value (mm)
X_w	-217.504	Z_c	29.794
Y_w	-0.279	Z_p	184.670
Z_w	211.537		

After the measurements, the values of error gain functions $f_{i,x}(\boldsymbol{p}_j)$, $f_{i,y}(\boldsymbol{p}_j)$ and $f_{i,z}(\boldsymbol{p}_j)$ in the error gain matrix $\boldsymbol{H}$ are computed for each setting position $\boldsymbol{p}_j$. The elements of the measurement vector $\boldsymbol{q}$ are obtained through R-test measuring for each setting position $\boldsymbol{p}_j$. With the error gain matrix $\boldsymbol{H}$ and the measurement vector $\boldsymbol{q}$ known, the unknown error parameter vector $\tilde{\boldsymbol{a}}$ is obtained through solving Eq. (26) directly with the help of the mathematical tool software MATLAB. The solution of error parameter vector $\tilde{\boldsymbol{a}}$ involves great amount of computation with matrices and arrays. No iteration is necessary.

Figure 6 is shown the R-test measurement in the target five-axis machine tool with Heidenhain iTNC 530 controller, and the results of estimation based on the test K4 is shown in Table 4. For the sake of justification, the estimated location errors of rotary axes and ball position errors are set into the error model to compute the overall position errors along the K4 test path. The results are shown in Figure 7. The predicted and the really measured overall position errors are very close. The deviations in X-, Y- and Z-axis are in the range of ±12μm. To justify the effectiveness of the estimation further, the predicted and measured position errors along two different tests path K1 and K2 are also compared. The results are shown in Figure 8 and Figure 9. With these test paths, the global tendency matches also very good. The deviations are greater and rise to the range of ±15μm.

5. Conclusion

The error modeling technique is very useful in predicting the volumetric errors of CNC machine tools. Until now the implementation of this technique in five-axis machine tools faces great problems. Although the majority of component errors in the error model are measurable with modern measurement devices, there are still some component and location errors of the rotary axes that are not measurable.

In recent years, ISO/10791-6 has defined the error test methods for five-axis machine tools, and

R-test measurement devices are already in use as five-axis machine tools. In addition to measuring the accuracy of five-axis machine tools, the measurement device can also be used to analyze errors using the test results. In this study, a reduced error model is used for the least square estimation to increase the accuracy of estimation and to accelerate the estimation process. Tests with different paths prove that the proposed estimation method delivers very good results. The R-test device and the errors estimation method have great impact on the accuracy enhancement of five-axis machine tools. And the error model can be used for advanced purposes such as error compensation.

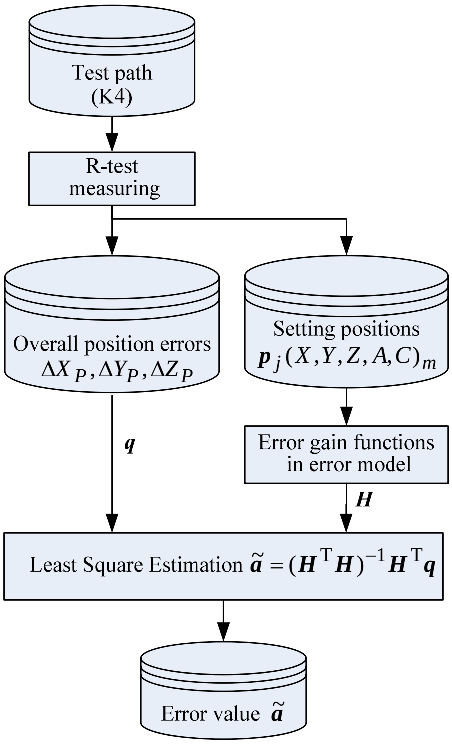
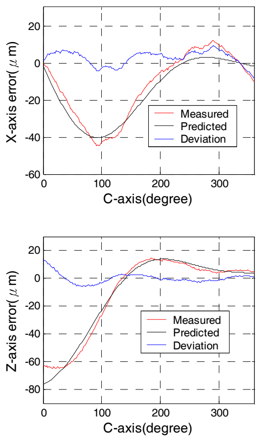


Figure 5. The block diagram of error estimation

Table 4. Results of the error estimation

Parameter	Value
$XOW(a_1)$	-3.2 (μm)
$YOW(a_2)$	-21.6 (μm)
$ZOW(a_3)$	-33.9 (μm)
$YOA(a_4)$	20.5 (μm)
$ZOA(a_5)$	32.5 (μm)
$BOA(a_6)$	12.3 (arcsec)
$COA(a_7)$	-7.2 (arcsec)
$XOC(a_8)$	1.4 (μm)
$YOC(a_9)$	-15.9 (μm)
$AOC(a_{10})$	-6.5 (arcsec)
$BOC(a_{11})$	-4.6 (arcsec)

Figure 6. R-test measuring in machine tools



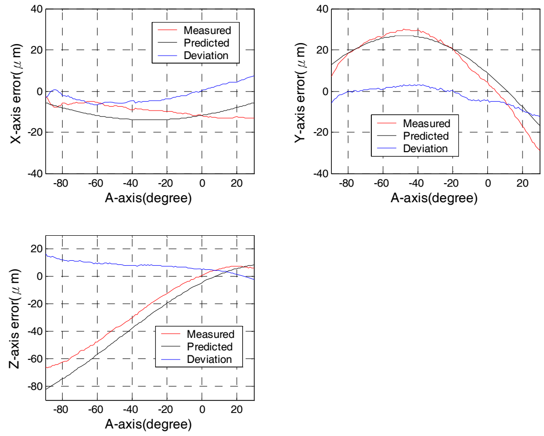


Figure 7. Comparison errors of K4 path   Figure 8. Comparison errors of K1 path

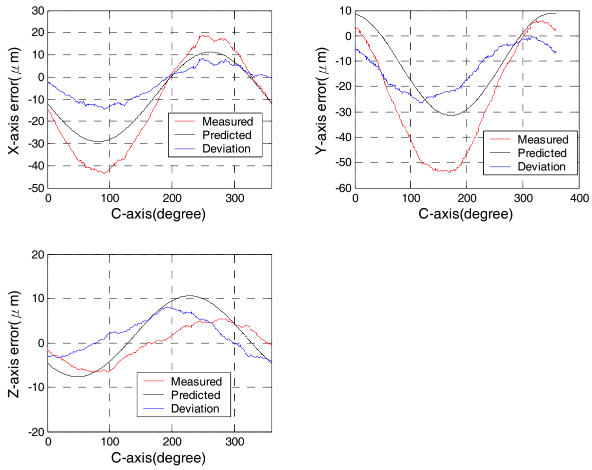


Figure 9. Comparison errors of K2

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附件四

國科會補助專題研究計畫項下出席國際學術會議心得報告

日期：100 年 9 月 20 日

計畫編號	NSC 99-2221-E-216-037		
計畫名稱	應用 R-test 量具進行五軸工具機幾何誤差量測鑑定與補償技術		
出國人員姓名	徐永源	服務機構及職稱	中華大學機械系 副教授
會議時間	100 年 7 月 27 日至 100 年 7 月 29 日	會議地點	法國巴黎
會議名稱	WASET 2011 INTERNATIONAL CONFERENCE PROGRAM		
發表論文題目	Kinematic parameter-independent modeling and measuring of three-axis machine tools		

一、參加會議經過

申請人於 7/26 晚上抵法國巴黎，並於 7/28 早上 11:20 進行為時 20 分鐘的論文報告,針對發表的論文與會者共計三人有提出問題，申請人皆充份回答,並獲致與會者的鼓掌贊同,申請者全程參與三天活動的專題演講及與申請人相近及有興趣領域的論文發表場次.

二、與會心得

申請人對於先進製造技術方面有更深的認知及明確知道現今技術的發展方向, 對申請人的未來研究有相當重要的啟發性。

三、考察參觀活動(無是項活動者略) ---無

四、建議

五、攜回資料名稱及內容

World Academy of Science, Engineering and Technology 79 2011

六、其他

Paper ID Code: FR79000 (Please accept our apologies for any inconveniences caused & double entries received)

Letter of Acceptance

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July 27-29, 2011

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Paris July 2011 WASET CONFERENCE PAPER Date : 2011-03-23 04:03:47 IP Adress :210.240.242.107	
Name Surname	Assoc. Prof. Dr. Yung-Yuan Hsu
Institution	Chung Hua University
Country	Taiwan
Alternative Email	Hyy.hsu@msa.hinet.net
Paper Title	Kinematic parameter-independent modeling of three-axis machine tools for geometric errors measurement and compensation
Abstract	he primary objective of this paper was to construct a “kinematic parameter-independent modeling of three-axis machine tools for geometric error measurement and compensation” technique. Improving the accuracy of the geometric error for three-axis machine tools is one of the machine tools’ core techniques. This paper first applied the traditional method of HTM to deduce the geometric error model for three-axis machine tools. This geometric error model was

	related to the three-axis kinematic parameters where the overall errors was relative to the machine reference coordinate system. Given that the measurement of the linear axis in this model should be on the ideal motion axis, there were practical difficulties. Through a measurement method consolidating translational errors and rotational errors in the geometric error model, we simplified the three-axis geometric error model to a kinematic parameter-independent model. Finally, based on the new measurement method and compensation corresponding to this error model, we established a truly practical and more accurate error compensation technique for three-axis machine tools.
Keywords	three-axis machine tool, geometric error, HTM, error compensation

Kinematic Parameter-Independent Modeling and Measuring of Three-Axis Machine Tools

Yung-Yuan Hsu

Abstract**—**The primary objective of this paper was to construct a "kinematic parameter-independent modeling of three-axis machine tools for geometric error measurement" technique. Improving the accuracy of the geometric error for three-axis machine tools is one of the machine tools' core techniques. This paper first applied the traditional method of HTM to deduce the geometric error model for three-axis machine tools. This geometric error model was related to the three-axis kinematic parameters where the overall errors was relative to the machine reference coordinate system. Given that the measurement of the linear axis in this model should be on the ideal motion axis, there were practical difficulties. Through a measurement method consolidating translational errors and rotational errors in the geometric error model, we simplified the three-axis geometric error model to a kinematic parameter-independent model. Finally, based on the new measurement method corresponding to this error model, we established a truly practical and more accurate error measuring technique for three-axis machine tools.

Keywords**—**Three-axis machine tool, Geometric error, HTM, Error measuring

I. Introduction

ENHANCING the accuracy of CNC machine tools is an important task in the area of machine tools. Errors which influence a machine tool's accuracy primarily originate from three categories: structurally-induced errors, driver-induced errors, and quasi-static errors. According to relevant research reports, quasi-static errors account for 70% of volume errors in CNC machine tools. This kind of error includes both geometric and thermal errors.

This paper researched geometric errors in quasi-static errors. The technique of building machine tool's geometric error model is well developed in the past few years [1]–[5]. The error model describes the position and orientation errors of tool relative to workpiece at specific machine position, whereby inaccurate influential factors come from kinematic link parameters and individual error sources. It is well known that the inaccurate motion of a linearly driven axis is associated with six motional errors, including one linear error, two straightness errors, and three rotational errors. With modern measurement devices such as the 6D laser interferometer [6], all six motional errors of the linearly driven axis can be measured rapidly. Based on the error model, the accuracy of three-axis machine tools can be dramatically improved through the error compensation [7]-[8].

Since 2008 a total volumetric compensation by Siemens for the controller 840 D and Heidenhain iTNC 530 in 2009. These functions allow for increasing the accuracy of machining centers if the volumetric errors were initially determined using suitable measuring technology. With the LaserTRACER [9] offers an efficient and high-precision measurement system for volumetric calibration.

Currently, geometric error modeling depends on the three-axis machine kinematic chain to create a geometric error model of three-axis machine tools, and the home position for which each motion axis is regarded as the motion axis's reference coordinate system. For this reason kinematic parameters between the coordinate systems for the linear axes and the rotary axes are needed to effective describe their relationship of motion. However, the ideal motion axis line and the center of revolution of the linear motion slide is difficult to define precisely, and therefore the kinematic parameter value cannot be defined. Furthermore, the fact that geometric errors defined on the ideal axis line of the linear motion slide must be measured by placing the measurement device on this axis line to avoid Abbe's error creates practical measuring difficulties when the linear motion slide is at a high position or when there is interference. The overall errors on the tool end in the geometric error model with kinematic parameters constructed based on the machine reference coordinate system. In actual machining, however, a certain point on the workpiece will be set as the origin of the workpiece coordinate system, which will be the error-free position. The errors will then correspond to this point rather than corresponding to the machine reference coordinate system.

For this reason, current errors modeling methods face the following three practical issues:

(1) The kinematic parameters in the model are unable to be accurately obtained.
(2) Avoiding causing the Abbe error during geometric error measurement creates practical operational difficulties with the applied measuring device.
(3) The largest problem with using traditional modeling and measurement methods is that the error model includes kinematic parameters which have a bearing on the contribution of rotational errors to overall errors: rotational errors measuring inaccuracy will magnify uncertainty of machine tools accuracy with overall errors, thus increasing the uncertainty in the error model.

Therefore it is necessary to establish a new modeling, measurement method for geometric errors of three-axis machine tools, which is more practical, convenient and accurate.

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II. Defining Geometric Errors for Linear Axes

Definitions in ISO230 related to error inspection standards for CNC machine tools include the definition for geometric errors and the method for test. A single linear motion axis is defined to possess six component errors(three translational errors and three rotational errors), and a location (perpendicularity) error exists between two linear motion axes. According to the above definitions, a three-axis machine tool with three linear axes would have a total of 21 geometric errors.

To describe three-axis machine tool geometric overall errors, it is necessary to establish a geometric error model for the target machine. Assuming the structure of the machine tool is a rigid body, then a 4x4 HTM could be used to show the relationship between each kinematic and servo control axis, and the machine error model could go through an individual kinematic and driver components HTM to obtain the order of products, depending on the machine kinematic chain [1].

Fig. 1 displays a case study for the X-axis linear motion slide. The geometric error model for kinematic parameters, location errors, and component errors in X-axis linear slide, showing the relationship of the x coordinate system with respect to the reference coordinate system ${}^{r}T_{x}$, is shown in the formula below.

$$ {}^{r}T_{x} = \begin{bmatrix} 1 & 0 & 0 & X_x \\ 0 & 1 & 0 & Y_x \\ 0 & 0 & 1 & Z_x \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & -COX & 0 & 0 \\ COX & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & -ECX & EBX & X_m + EXX \\ ECX & 1 & -EAX & EYX \\ -EBX & EAX & 1 & EZX \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

where X_x, Y_x, Z_x are the constant offset which the x home position with respect to the reference coordinate system in the x,y,z direction respectively, or the kinematic parameter for X-axes linear slide. *COX* is the location error between linear X axis and an ideal linear axis (in this example, Y-axis of the reference coordinate system) which will cause a small angular rotation at between two coordinate systems at the Z axial direction. *EXX, EYX, EZX, EAX, EBX* and *ECX* are the six component errors for linear X axis, and X_m is the servo-controlled position of the X-axis slide.

The order of products for the kinematic parameter matrix, the location (perpendicularity) error matrix, and the 6D component error matrix in the above formula is dependent upon the pattern arrangement in linear X axis's kinematic chain. First the 6D component errors matrix for the X axis linear slide. And assuming that when the X-axis slide goes home position the Z-axis of the X coordinate system is identical with the Z-axis of the reference coordinate system, then perpendicular error *COX* exists between the ideal motion axis (the X-axis of the X coordinate system) and the Y-axis of the reference coordinate system, and so does the perpendicularity error matrix. When X axis slide moves to the X home position, the X axis slide having the kinematic parameter matrix for the origin coordinate offsets.

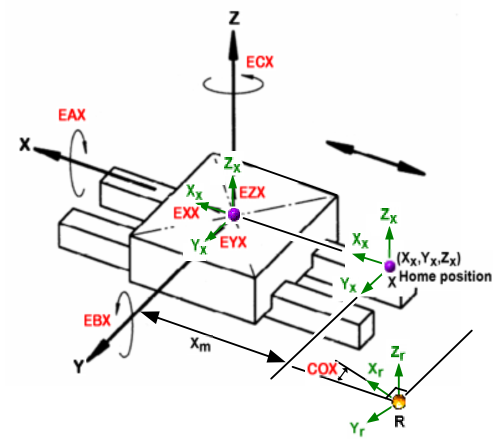

Fig. 1 X linear axis geometric error definition

III. Modeling and Measurement with Kinematic Parameter-Independence

A. Geometric Error Modeling

For an ideal three-axis machine tool, each tool position (X_w, Y_w, Z_w) and orientation (I_w, J_w, K_w) on the workpiece coordinate system for the three machine motion axes has a corresponding drive position to cut the needed work pieces and the tool orientation can only be defined on the (0,0,1) direction. Fig. 2 is the three-axis machine tool (Coordinate Measuring Machine, CMM) and its coordinating system definition. The machine's kinematic chain is linked by several link components and three linear motion axes. One end of the chain is a tool holder and the holder should hold the tool. The spindle block is mounted on the Z-slide. The Z-slide moves vertically with a prismatic joint. The Z-slide is bolted on the X-slide and the X-slide is then stacked on the Y-slide, making the three linear axes (x,y,z) perpendicular to each other. Y-slide is then moves on the beds with a prismatic joint. Finally, based on the ISO230 definition and this machine's kinematic chain sequence, the location errors are *COX*, *BOZ*, and *AOZ*.

Based on Fig. 3, the relationship of the tool (T) coordinate system with respect to the holder (H) coordinate system, ${}^{h}T_{t}$, is shown in the below.

$$ {}^{h}T_{t} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & Z_t \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2) $$

where Z_t is the length of the tool (probe).

The holder coordinate system with respect to the Z coordinate system, ${}^{z}T_{h}$, is expressed in the formula below.

$$ {}^{z}T_{h} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & Z_h \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3) $$

where Z_h is the Z directional offset of the holder origin in relation to the origin of the Z axis coordinate system.

The Z axis coordinate system with respect to X axis coordinate system, ${}^{x}T_{z}$, is express in the formula below.

$$ {}^{x}T_{z}=\begin{bmatrix}1&0&0&X_z\\0&1&0&Y_z\\0&0&1&Z_z\\0&0&0&1\end{bmatrix}\begin{bmatrix}1&0&BOZ&0\\0&1&-AOZ&0\\-BOZ&AOZ&1&0\\0&0&0&1\end{bmatrix} \begin{bmatrix}1&-ECZ&EBZ&EXZ\\ECZ&1&-EAZ&EYZ\\-EBZ&EAZ&1&Z_m+EZZ\\0&0&0&1\end{bmatrix} \quad (4)$$

where X_z, Y_z, Z_z are the offsets for Z home position in relation to X home position. *AOZ* and *BOZ* are location (perpendicular) errors for Z linear motion axis in relation to Y and X axis, respectively. *EXZ, EYZ, EZZ, EAZ, EBZ* and *ECZ* are the six component errors for Z linear axis, and Z_m is the servo-controlled position of the Z servo-axis.

The X axis coordinate system with respect to the Y coordinate system, ${}^{y}T_{x}$, is expressed in the formula below.

$$ {}^{y}T_{x}=\begin{bmatrix}1&0&0&X_x\\0&1&0&Y_x\\0&0&1&Z_x\\0&0&0&1\end{bmatrix}\begin{bmatrix}1&-COX&0&0\\COX&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix} \begin{bmatrix}1&-ECX&EBX&X_m+EXX\\ECX&1&-EAX&EYX\\-EBX&EAX&1&EZX\\0&0&0&1\end{bmatrix} \quad (5)$$

where X_x, Y_x, Z_x are offsets for X home position in relation to Y home position. *COX* is the location (perpendicular) error for X linear motion axis in relation to Y axis. *EXX, EYX, EZX, EAX, EBX* and *ECX* are the six component errors for X linear axis, and X_m is the servo-controlled position of the X servo-axis.

The Y axis coordinate system with respect to the reference coordinate system, ${}^{r}T_{y}$, is expressed in the formula below.

$$ {}^{r}T_{y}=\begin{bmatrix}1&-ECY&EBY&EXY\\ECY&1&-EAY&Y_m+EYY\\-EBY&EAY&1&EZY\\0&0&0&1\end{bmatrix} \quad (6)$$

where *EXY, EYY, EZY, EAY, EBY* and *ECY* are the six component errors for Y linear axis, and Y_m is the servo-controlled position of the Y servo-axis. In the above equation, the Y linear motion axis 6D error matrix follows the errors created by the ideal axis movement. In the process of deducing the entire error model, assuming that when Y motion axis goes to the Y home position the Y coordinate system is identical to the reference coordinate system, then the ideal axis line should also be identical to the Y-axis in the reference coordinate system and no perpendicular error exists between the Y coordinate system and the reference coordinate system.

Deducing another kinematic chain, Fig. 3 indicates that the end of the three-axis machine tool aligns with the end of the workpiece. For this reason, the workpiece coordinate system is defined on the end of the machine tool and the workpiece coordinate system (w) with respect to the workpiece origin coordinate system, ${}^{wo}T_{w}$ is expressed in the formula below.

$$ {}^{wo}T_{w}=\begin{bmatrix}1&0&0&X_w\\0&1&0&Y_w\\0&0&1&Z_w\\0&0&0&1\end{bmatrix} \quad (7)$$

where X_w, Y_w, Z_w is the translational offset for the workpiece coordinate system (w) in respect to the workpiece origin coordinate system (wo), which can be accurately defined through measurement tools.

The workpiece origin coordinate system (wo) with respect to the reference coordinate system (r), ${}^{r}T_{wo}$, without geometric errors is expressed in the formula below.

$$ {}^{r}T_{wo}=\begin{bmatrix}1&0&0&X_{wo}\\0&1&0&Y_{wo}\\0&0&1&Z_{wo}\\0&0&0&1\end{bmatrix} \quad (8)$$

where X_{wo}, Y_{wo} and Z_{wo} are the translational offset for the workpiece origin coordinate system (w) in respect to reference coordinate system (r).

For this reason, the spatial relationship between the tool coordinate system and the reference coordinate system can be obtained through the formula below.

$$ {}^{r}T_{t}={}^{r}T_{y}\ {}^{y}T_{x}\ {}^{x}T_{z}\ {}^{z}T_{h}\ {}^{h}T_{t} \quad (9)$$

The spatial relationship between the workpiece coordinate system and the reference coordinate system can be obtained through the formula below.

$$ {}^{r}T_{w}={}^{r}T_{wo}\ {}^{wo}T_{w} \quad (10)$$

Fig. 3 illustrates that, when it is an ideal machine, the tool coordinate system should be an identical point with the workpiece coordinate system. However, actual machines have geometric errors, so the position of the origin of the tool coordinate system with respect to the reference coordinate system $\boldsymbol{P_t}=[X_t \ \ Y_t \ \ Z_t]$, can be obtained through the formula below.

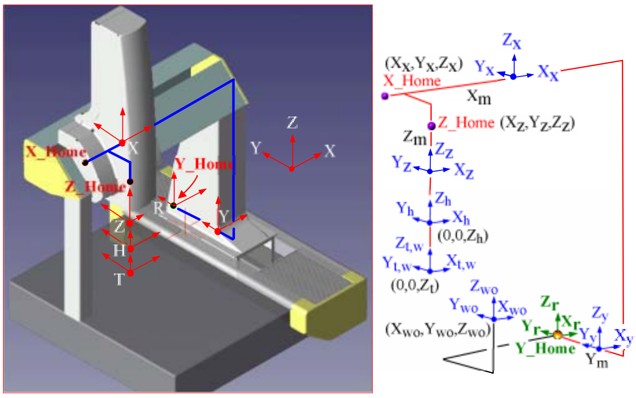

Fig. 2 Three-axis machine tools

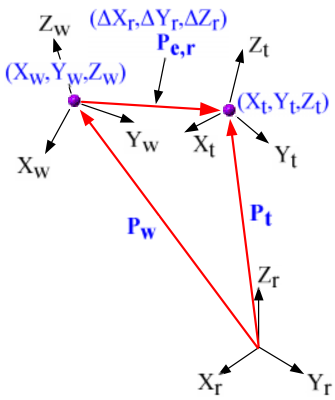

Fig. 3 Overall errors of the tool end

$$[\boldsymbol{P_t} \quad 1]^T = {}^rT_t [0 \quad 0 \quad 0 \quad 1]^T \tag{11}$$

The position of the origin of the workpiece coordinate system with respect to the reference coordinate system $\boldsymbol{P_w} = [X_w \quad Y_w \quad Z_w]$, can be obtained through the formula below.

$$[\boldsymbol{P_w} \quad 1]^T = {}^rT_w [0 \quad 0 \quad 0 \quad 1]^T \tag{12}$$

Now, the position error for the tool coordinate system with respect to the workpiece coordinate system in the reference coordinate system $\boldsymbol{P_{e,r}}(\Delta X_r, \Delta Y_r, \Delta Z_r)$ can be obtained through the formula below.

$$\boldsymbol{P_{e,r}} = \boldsymbol{P_t} - \boldsymbol{P_w} \tag{13}$$

The orientation error in the reference coordinate system $\boldsymbol{O_{e,r}}(\Delta I_r, \Delta J_r, \Delta K_r)$ can be obtained through the three formulas listed below.

$$[\boldsymbol{O_w} \quad 0]^T = ({}^rT_w - {}^rT_{w,ideal}) \; [0 \quad 0 \quad 1 \quad 0]^T \tag{14}$$

$$[\boldsymbol{O_t} \quad 0]^T = ({}^rT_t - {}^rT_{t,ideal}) \; [0 \quad 0 \quad 1 \quad 0]^T \tag{15}$$

$$\boldsymbol{O_{e,r}} = \boldsymbol{O_t} - \boldsymbol{O_w} \tag{16}$$

where ${}^rT_{w,ideal}$ and ${}^rT_{t,ideal}$ are the HTM for the workpiece coordinate system and tool coordinate system with respect, individually, to the reference coordinate system for ${}^rT_w$ and ${}^rT_t$, respectively, when geometric errors are not considered (the ideal machine).

Using small-angle approximations assumption and the second-order errors are negligible, and consolidating the geometric errors, the geometric error model for this three-axis machine tool is displayed in Table I. The overall error for the direction of X, ΔX_r, is the product of each error multiplied by each error's error gain. For example, the error contribution for the direction of X in *ECX* is $-ECX*Y_z$. This table, which is considered a geometric error sensitivity analysis table, indicates that linear errors (*EXX, EYX, EZX, EXY, EYY, EZY, EXZ, EYZ,* and *EZZ*) are machine kinematic parameter-independent, while rotary errors (*EAX, EBX, ECX, EAY, EBY, ECY, EAZ, EBZ, ECZ, COX, AOZ,* and *BOZ*) are machine kinematic parameter-dependent.

TABLE I
ERROR MODEL AND SENSITIVITY AND ANALYSIS

Error	ΔX_r	ΔY_r	ΔZ_r	ΔI_r	ΔJ_r	ΔK_r
EXX	1	0	0	0	0	0
EYX	0	1	0	0	0	0
EZX	0	0	1	0	0	0
EAX	0	$-Z_h-Z_t-Z_m-Z_z$	$+Y_z$	0	-1	0
EBX	$+Z_h+Z_t+Z_m+Z_z$	0	$-X_z$	1	0	0
ECX	$-Y_z$	$+X_z$	0	0	0	0
EXY	1	0	0	0	0	0
EYY	0	1	0	0	0	0
EZY	0	0	1	0	0	0
EAY	0	$-Z_h-Z_t-Z_m-Z_z-Z_x$	$+Y_z+Y_x$	0	-1	0
EBY	$+Z_h+Z_t+Z_m+Z_z+Z_x$	0	$-X_z-X_m-X_x$	1	0	0
ECY	$-Y_z$	$+X_z+X_m+X_x$	0	0	0	0
EXZ	1	0	0	0	0	0
EYZ	0	1	0	0	0	0
EZZ	0	0	1	0	0	0
EAZ	0	$-Z_h-Z_t$	0	0	-1	0
EBZ	$+Z_h+Z_t$	0	0	1	0	0
ECZ	0	0	0	0	0	0
COX	$-Y_z$	$+X_z+X_m$	0	0	0	0
AOZ	0	$-Z_h-Z_t-Z_m$	0	0	-1	0
BOZ	$+Z_h+Z_t+Z_m$	0	0	1	0	0

B. Measurement for Kinematic Parameter-independent

In defining geometric errors and deducing formulas above, the three-axis machine tool linear axis was structured by kinematic stacking and each motion axis had a home position. For this reason, kinematic parameters were necessary between linear axis coordinate systems to effectively describe their movement relative to each other. However, in practice, the position of the ideal motion axis line for the linear motion slide was difficult to clearly define. Moreover, to avoid Abbe's error, the measurement device must be placed on this axis line when measuring. This requirement creates practical measurement difficulties if the linear motion slide is at a high position or there is interference. For this reason, it is necessary to establish a new measurement method for a geometric error model without kinematic parameter.

Ideally, the geometric error model coordinate system should be set up on the ideal motion axis line for the linear slide to effectively describe the spatial errors caused by Abbe's error. For example, measurement of the Y linear slide, displayed in Fig. 5, had three translational errors (*EXY, EYY* and *EZY*) and three rotational errors (*EAY, EBY* and *ECY*). If, when measuring geometric errors, directions x,y,z between measurement axis line (M) and ideal motion axis line (I) each have offset L_x, L_y, L_z, then the 6D component error model for the measurement construction method and the results of the measurement are:

$$EXY'=EXY+L_x*(1-\cos(EBY))+L_x*(1-\cos(ECY))+L_y*\sin(ECY) +L_z*\sin(EBY) \quad (17)$$

$$EYY'=EYY+L_x*\sin(ECY)+L_y*(1-\cos(EAY))+L_y*(1-\cos(ECY)) +L_z*\sin(EAY) \quad (18)$$

$$EZY'=EZY+L_x*\sin(EBY)+L_y*\sin(EAY)+L_z*(1-\cos(EAY)) +L_z*(1-\cos(EBY)) \quad (19)$$

$$EAY'=EAY \quad (20)$$
$$EBY'=EBY \quad (21)$$
$$ECY'=ECY \quad (22)$$

When the rotational error slightly angled, then $\cos(EAY) \fallingdotseq 1$, $\cos(EBY) \fallingdotseq 1$, $\cos(ECY) \fallingdotseq 1$, and $\sin(EAY) \fallingdotseq EAY$, $\sin(EBY) \fallingdotseq EBY$, $\sin(ECY) \fallingdotseq ECY$. These three formulas can be simplified to:

$$EXY' \fallingdotseq EXY+L_y*ECY+L_z*EBY \quad (23)$$

$$EYY' \fallingdotseq EYY+L_x*ECY+L_z*EAY \quad (24)$$

$$EZY' \fallingdotseq EZY+L_x*EBY+L_y*EAY \quad (25)$$

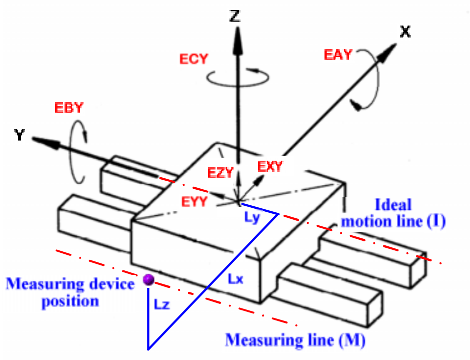

Fig. 4 Linear axis geometric error measuring method

As the above explanation indicates, when measuring rotational errors (*EAY, EBY* and *ECY*), the measuring line is independent of the position of the motion line so it is not necessary for the measuring device to be stacked on the ideal motion line (I). When measuring translational errors (*EXY, EYY* and *EZY*) however, the measurement position matters and therefore, the measurement device must be placed on the ideal motion line (I). If it is placed on line M from Fig. 5, then the spatial errors created by the rotational errors will be included with translational errors. Besides its own translational errors, the translational errors discovered by this method of measurement construction will also include errors which were created due to rotational errors. For this reason, the translational error measurement results obtained by this measurement method described above include the influence of rotational errors on the measurements. This result is explained in (23)-(25).

Additionally, when constructing this geometric error measuring, the kinematic parameter for L_x, L_y and L_z has a constant value. When the linear motion axis moves to a position, the spatial errors created by the rotational errors at that position (*EAY, EBY,* and *ECY*) will each be entered into the translational errors (*EXY, EYY,* and *EZY*) and the measuring line for this measurement device can be considered the ideal motion line for the linear motion axis, meaning rotational errors have no spatial errors for any position on this measuring line. Since the error gain of rotational errors is 0, the measuring position is the initial error position for rotational errors. Furthermore, in actual cutting and measuring, a certain position on the workpiece will be established as the origin of the workpiece coordinate system. Set up as an error-free position, all work position errors are no longer errors with respect to the geometric error model constructed by the machine ideal motion line but errors with respect to this point. For this reason, this measuring method has practical application value.

C. Error Model with Measurement Method

Using API 6D laser interferometer instrument as an example of applying the methods and principles of the measuring method described above to three-axis machine tools, we installed a reflect mirror to the tool holder on the spindle of the machine in Fig. 2 to individually measure the six component errors in a linear motion axis and the location (perpendicular) error for the three linear axes. When, for example, the 6D component errors were measured for Y linear motion axis, we first returned X, Y, and Z axes to their individual home positions, which were set as the zero error position, and then installed a reflect mirror to the tool holder on the machine's spindle to carry out measurements. At this point, because the measuring device's measurement position would react with Abbe's error, the Y axis 6D measurement results included all the errors created by the machine's kinematic parameter. Next, we measured the component and location (perpendicular) errors for the other two linear motion axes according to the principles described in the last section.

Applying the new measuring method to the three-axis CNC machine tool, we could simplify the original geometric error model containing kinematic parameters shown in Table I to the kinematic parameter-independent Table II. Considering, for instance, measuring the six component errors in X linear motion axis, there were three error contributions (*EZX, EAX* and *EBX*) to the tool end's overall errors, the contributing factors of which were 1, $Y_z, -X_z$. Under the premise that the machine possesses positioning repeatability, we can assume that when X axis slide is located at a specified position, the $Y_Z, -X_Z$ kinematic parameter will be a constant. Due to the fact that the reflection mirror was installed at the tool end of the spindle, the error contribution of $EAX*Y_Z$ and $EBX*(-X_Z)$ will be reflected in *EZX*. For this reason, these two kinematic parameters can be set to zero, and their other errors can be simplified in this way.

As Table II illustrates, all nine translational errors (*EXX, EYX, EZX, EXY, EYY, EZY, EXZ, EYZ* and *EZZ)* contribute to the tool end overall errors, but only five of the rotational errors (*EAX, EBX, EAY, EBY* and *ECY*) contribute while four (*ECX, EAZ, EBZ* and *ECZ*) do not. Therefore, only 17 (21-4) geometric errors need to be measured in this model. Also in Table II, considering the home positions for X, Y and Z motion axes in this model, the error gains for *EAY, EBY,* and *ECY* require revision to properly express the total physical significance of kinematic parameter. X_s, Y_s, and Z_s represent the stroke for X, Y, and Z linear motion axes, respectively.

TABLE II
ERROR MODEL WITH PARAMETRIC-INDEPENDENT

Error	$\triangle X_r$	$\triangle Y_r$	$\triangle Z_r$	$\triangle I_r$	$\triangle J_r$	$\triangle K_r$
EXX	1	0	0	0	0	0
EYX	0	1	0	0	0	0
EZX	0	0	1	0	0	0
EAX	0	$-Z_m$	0	0	-1	0
EBX	Z_m	0	0	1	0	0
ECX	0	0	0	0	0	0
EXY	1	0	0	0	0	0
EYY	0	1	0	0	0	0
EZY	0	0	1	0	0	0
EAY	0	$-(Z_s+Z_m)$	0	0	-1	0
EBY	Z_s+Z_m	0	X_s-X_m	1	0	0
ECY	0	$-(X_s-X_m)$	0	0	0	0
EXZ	1	0	0	0	0	0
EYZ	0	1	0	0	0	0
EZZ	0	0	1	0	0	0
EAZ	0	0	0	0	-1	0
EBZ	0	0	0	1	0	0
ECZ	0	0	0	0	0	0
COX	0	X_m	0	0	0	0
AOZ	0	$-Z_m$	0	0	-1	0
BOZ	Z_m	0	0	1	0	0

Constructing a kinematic parameter-independent three-axis geometric error model and measurement method based on the above measuring method is both practical and accurate. Furthermore, compensating for persistent geometric errors can also be facilitated by using this geometric error model to establish a geometric error compensation model to effectively compensate for three-axis geometric errors. The three-axis machine tool geometric error compensation scheme is displayed in Fig. 5. First, a laser interferometer device based on the above measurement construction method was used to measure the 21 geometric errors in the three axes. The measurement data was used to carry out coordinate translational, aligning it with the error model coordinate system. The measurement results were then plugged into the three-axis kinematic parameter-independent error model. The results indicated that when the three-axis machine tool moved to **u**(x,y,z) and the tool end spatial errors are **du**, then the compensation applied by the kinematic parameter-independent error compensation model is –**du**. Finally, the x,y,z motion axis direction errors, compensated through a controller, were returned to their ideal position at $\boldsymbol{u_c}$.

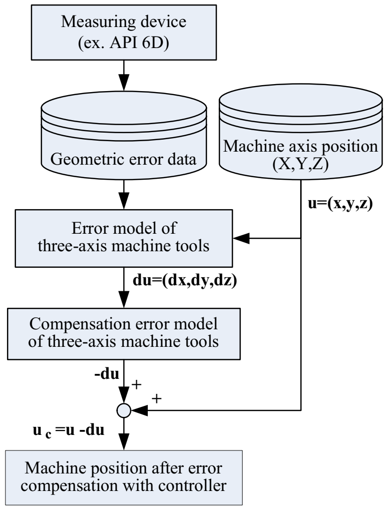

Fig. 5 Three-axis machine tools error compensation scheme

IV. CONCLUSION

The three-axis geometric error models derived by traditional methods all set the machine reference coordinate system at a fixed point on the machine's base and depend on the machine kinematic chain to derive a machine kinematic parameter-dependent model. For practical applications, this dependence makes kinematic parameters impossible to accurately obtain, measurement device operations inconvenient, and overall errors overvalued. For this reason, this paper created a measurement method-integrated "modeling for geometric error model of three-axis machine tools with kinematic parameter independent" technique. This technique, which integrated simple geometric error measuring methods, which constructed the corresponding three-axis geometric error model, and whose geometric error model is machine kinematic parameter-independent, is a practical, convenient, and accurate integrated three-axis geometric error modeling and measurement method.

ACKNOWLEDGE

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國科會補助計畫衍生研發成果推廣資料表

日期:2011/10/12

<table>
<tr><td rowspan="3">國科會補助計畫</td><td colspan="3">計畫名稱: 應用R-test量具進行五軸工具機幾何誤差量測鑑定與補償技術</td></tr>
<tr><td colspan="3">計畫主持人: 徐永源</td></tr>
<tr><td colspan="3">計畫編號: 99-2221-E-216-037- 學門領域: 自動化機械技術</td></tr>
<tr><td rowspan="2">研發成果名稱</td><td colspan="3">(中文) 應用R-test量具進行五軸工具機幾何誤差量測鑑定技術</td></tr>
<tr><td colspan="3">(英文) Modeling and identification for rotary geometric errors of five-axis machine tools with R-test measurement</td></tr>
<tr><td>成果歸屬機構</td><td>中華大學</td><td>發明人
(創作人)</td><td>徐永源</td></tr>
<tr><td rowspan="2">技術說明</td><td colspan="3">(中文) 本技術是應用 R-test量具進行五軸工具機的轉動軸的位置幾何誤差項鑑定。CNC數控工具機的誤差模型描述個別幾何誤差項與機器總成誤差間的關係，現今已可應用R-test量具直接量測到五軸工具機的總成誤差，若個別幾何誤差項為已知，則此時可應用幾何誤差模型預測幾何誤差藉此實現誤差補償。因此，本論文中依ISO230的幾何誤差定義，完整的建立五軸工具機R-test量具幾何誤差模型，並依此一模型,在只考量轉動軸的位置誤差(location error)前題下，簡化五軸幾何誤差模型。接著基於簡化模型及以R-test量具進行K4量測路徑的量測結果，可應用最小平方法精確估測旋轉軸的位置誤差項。最後並以路徑K1及路徑K2有效驗證誤差模型及鑑定方法的正確性，則此建立之誤差模型可應用於誤差補償以提升機器精度。</td></tr>
<tr><td colspan="3">(英文) The technique is to use an R-test measurement device to estimate the geometric location error of the axis of rotation of five-axis machine tools. Now, the R-test measuring device can be used to measure the overall position errors of five-axis machine tools directly. To improve the accuracy of CNC machine tools, error sources and its effects on the overall position and orientation errors must be known.
This study thus based its definition on the geometric errors of ISO230 to construct a geometric error model used to measure errors in the five-axis machine tools for the R-test measurement device. Based on the simplified model and the overall position errors measured by the R-test with path K4, the location errors of rotary axes and ball position errors can be estimated very accurately with the least square estimation method. Finally, the results of the test showed that the model built in this study is accurate and is effective in estimating errors.</td></tr>
<tr><td>產業別</td><td colspan="3">機械製造業</td></tr>
<tr><td>技術/產品應用範圍</td><td colspan="3">工具機業</td></tr>
<tr><td>技術移轉可行性及
預期效益</td><td colspan="3">完整的技術可移轉至國內各大工具機廠商,
此技術成果,可應用Heidenhain控制器進行幾何誤差補償,可提升國內五軸工具機廠商的機器精度.</td></tr>
</table>

註：本項研發成果若尚未申請專利，請勿揭露可申請專利之主要內容。

99 年度專題研究計畫研究成果彙整表

計畫主持人：徐永源	計畫編號：99-2221-E-216-037-
計畫名稱：應用 R-test 量具進行五軸工具機幾何誤差量測鑑定與補償技術	

成果項目			量化：實際已達成數（被接受或已發表）	量化：預期總達成數(含實際已達成數)	量化：本計畫實際貢獻百分比	單位	備註（質化說明：如數個計畫共同成果、成果列為該期刊之封面故事...等）
國內	論文著作	期刊論文	0	0	100%	篇	
		研究報告/技術報告	0	1	10%		PMC 機械零組件通報 雜誌
		研討會論文	0	0	100%		
		專書	0	0	100%		
	專利	申請中件數	0	1	10%	件	R-test 誤差鑑定方法
		已獲得件數	0	0	100%		
	技術移轉	件數	0	0	100%	件	
		權利金	0	0	100%	千元	
	參與計畫人力（本國籍）	碩士生	0	1	10%	人次	章弘育
		博士生	0	0	100%		
		博士後研究員	0	0	100%		
		專任助理	0	0	100%		
國外	論文著作	期刊論文	0	1	60%	篇	投稿於--INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING
		研究報告/技術報告	0	0	100%		
		研討會論文	0	1	10%		WASET 2011 INTERNATIONAL CONFERENCE PROGRAM
		專書	0	0	100%	章/本	
	專利	申請中件數	0	0	100%	件	
		已獲得件數	0	0	100%		
	技術移轉	件數	0	0	100%	件	
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		博士生	0	0	100%		
		博士後研究員	0	0	100%		
		專任助理	0	0	100%		

其他成果 (無法以量化表達之成果如辦理學術活動、獲得獎項、重要國際合作、研究成果國際影響力及其他協助產業技術發展之具體效益事項等，請以文字敘述填列。)	目前此一研究成果與國內工具機廠商 (1)協鴻公司 (2)喬崴進公司 (3)匠澤公司 進行產學技術合作,提升工具機廠商五軸工具機精度,並對其工程師進行相關的技術授課及輔導.

	成果項目	量化	名稱或內容性質簡述
科教處計畫加填項目	測驗工具(含質性與量性)	0	
	課程/模組	0	
	電腦及網路系統或工具	0	
	教材	0	
	舉辦之活動/競賽	0	
	研討會/工作坊	0	
	電子報、網站	0	
	計畫成果推廣之參與（閱聽）人數	0	

國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估 ■達成目標 □未達成目標（請說明，以 100 字為限） □實驗失敗 □因故實驗中斷 □其他原因 說明：
2. 研究成果在學術期刊發表或申請專利等情形： 論文：□已發表 ■未發表之文稿 □撰寫中 □無 專利：□已獲得 ■申請中 □無 技轉：□已技轉 □洽談中 ■無 其他：（以 100 字為限）
3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）（以 500 字為限） 本研究主要目的是應用 R-test 量具進行五軸工具機的轉動軸的位置幾何誤差項鑑定。依 ISO230 的幾何誤差定義,建立 R-test 量具於五軸工具機進行誤差量測的幾何誤差模型,並依此一模型,在只考量轉動軸的位置誤差前題下,簡化五軸幾何誤差模型,接著基於簡化模型應用 R-test 量測數據及最小平方法鑑定轉動軸的位置誤差項。最後以 path K1 及 path K2 為測試路徑進行驗證, 結果顯示,本研究所建構模型正確且誤差鑑定方法非常有效.