Calculation and Compensation Method for Fixture Errors in Five-Axis CNC Machine Tools

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Abstract. In recent years, five-axis machine tools have become key equipment in the manufacturing industry; however, the accuracy with which the mechanical parts are manufactured is sometimes limited by fixture errors, which are induced by fixture manufacture and installation processes. Therefore, reducing the effect of fixture errors to enhance the geometric dimension accuracy of manufactured mechanical parts has become a focus for high-precision mechanical part manufacturing. In this study, we design a fixture error compensation method referring to the tilted work plane (TWP) command of computer numerical control (CNC) five-axis machine tools. Our method renders it unnecessary to consider the workpiece profile and fixture locator arrangement, adjust the fixture locator or modify the tool path, and make a very-high-precision fixture. The fixture error resulting from fixture manufacture and installation can be effectively compensated for with our method. A machine tool probing system measures the position and orientation of the fixture locator, and the cosine theorem and a homogeneous transformation matrix are used to calculate the fixture error according to the measurement result. Finally, the calculated value to compensate for errors is set in the TWP command of the five-axis CNC machine tool controller, and the controller automatically rotates and offsets the fixture to compensate for the error. To validate the feasibility of our error compensation method, we use a workpiece with step and hole features. Our results show that the geometric dimension accuracy of the workpiece is significantly improved, with an 85% average improvement rate for the hole-machined workpiece and a 56% average improvement rate for the step-machined workpiece. Therefore, the fixture error compensation method designed in this study can effectively reduce the effect of fixture errors on the geometric dimension accuracy of workpieces.

Keywords: fixture errors, five-axis, CNC machine tools, compensation, touch probe.
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1 INTRODUCTION

In traditional machining, if the machined workpiece exceeds the tolerance, the fixture error must be addressed by repairing or adjusting the fixture and locator. Repairs and adjustments sometimes stop the workflow. In recent years, prompted by the trend toward automated production, the five-axis machine tool has become a critical piece of equipment within the manufacturing industry. In this study, the five-axis machine tool is used as the mechanical part machine tool, and the complicated operations of fixture repair and adjustment are improved. Errors introduced during the mechanical part machining of the five-axis machine tool can be directly corrected by calculating and analyzing the fixture error and compensating for it.

The error relationships between the workpiece and fixture include: (1) error of the contact surface and contact direction of the workpiece and locator, (2) geometric error of the locator, and (3) error of the workpiece deformation resulting from fixture clamping. Salisbury and Peters [13] indicated that the contact surface error of a locator and workpiece was a factor leading to the deviation of the workpiece in the fixture. They used the Newton–Raphson method for approximating a computing equation in real numbers and complex domains to develop a mathematical model that evaluates the effect of contact surface errors on the position and orientation of a cylindrically shaped workpiece. Rong et al. [12] developed a locating error analysis method based on geometric dimensioning and tolerancing (GD/T) for setup planning and fixture design. With this method, the fixturing coordination system was defined by synchronizing locating elements with locating features, the actual locating situation was simulated, and a locating error evaluation algorithm was developed through sensitivity analysis. This method has been used in computer-aided design (CAD) business software. Wan et al. [18] used differential motion theory to build models for three factors—machine tool, fixture, and datum—that may influence the final machining result of the workpiece. These models evaluate position and orientation errors in the machine tool, fixture, and datum on the workpiece, and adjust the length of the locators to reduce the errors of tool motion with respect to the workpiece. Tang et al. [16] converted the locators of fixtures into six locating points and derived a linearized model from the first-order Taylor expansion to convey the relationship between the locating point errors and locating errors. The homogeneous transformation matrices were used to calculate the tolerance parameterization of the plane, cylindrical, and free-form surface features of the workpiece. The result was very close to the result generated by the 3DCS commercial tolerance-analysis software. When the fixture clamps the workpiece and if the clamping force is large, the workpiece undergoes elastic deformation; thus, when the machining process is completed and the fixture is released, the workpiece reverts to an initial state, and errors are introduced. Li and Melkote [8] used the discrete elastic contact model to represent each fixture-workpiece contact. They calculated the deformation of the workpiece during clamping to improve the overall workpiece deflection and reaction force characteristics. Sánchez et al. [14] studied workpiece and locator contact deformation and the deformation error of the overall workpiece during fixture clamping and machining, importing the error information into a CAD/CAM database to provide a new error compensation method. Qin et al. [9] analyzed workpiece position errors, workpiece elastic deformations, and inconsistent datum errors to evaluate the increased workpiece position errors in the workpiece locating and clamping processes. Raghu and Melkote [11] analyzed workpiece elastic deformation of a workpiece and considered locator elastic deformation. The deformations at the contact points were obtained by solving a constrained optimization model, and the part response points were used to check the effect of geometric errors and compliance on the workpiece location error. Zuo et al. [21] used the Jacobian–Torsor theory to build a model for error propagation. According to this theory, the workpiece, fixtures, and machine tool are regarded as an assembly; thus, the errors can be grouped in a sequential manner and described by the parameters of the small displacement torsor. Qin et al. [10] proposed a general approach, in which the effect of the locator on the workpiece can be characterized according to the position and orientation of the workpiece. From this methodology, the fixture model was formulated. The overall errors of a system consisting of the workpiece and the fixture in the design of the fixture locating scheme were considered, and the locating principles and criteria of this robust optimal design were proposed using the model to upgrade the localization quality of the fixture. Khodaygan [5,6] successively proposed two methods for estimating the locating error of a workpiece. In order to eliminate the locating error, a mathematical model was built to represent the relationship between the workpiece and the error source; then, the length of the locators was adjusted to compensate for the displacement and rotation errors of the located workpiece. A mathematical model for the contact surface of the workpiece and locators was built to analyze the overall deviation and rotation of the workpiece. Yang et al. [20] used a stream of variation (SoV) model for fixture analysis based on differential motion vectors, equivalent fixture errors, and kinematic analysis. The SoV can analyze the complex interactions of multistage machining processes, and the differential motion vectors can use the fixture-, datum- and machining-induced variations in the multistage variation propagation for the 3-2-1 fixturing layout. The kinematic analysis method can solve general fixture problems (i.e., the method is not confined to the 3-2-1 fixturing layout). The variation propagation model, which uses the concept of the equivalent fixture error, can simulate fixture, datum, and machine tool errors. He et al. [4] proposed the locator-induced fixing errors of a fixture and analyzed the effect of the fixing errors on the machining accuracy considering the 3-2-1 positioning fixture. Abedini et al. [1] used a genetic algorithm to calculate the positional tolerance of the holes of a workpiece to identify the optimal locating layout and minimum machining error of the locators of the fixture under the 3-2-1 locating approach. Fallah and Arezoo [3] proposed a mathematical model for calculating actual and theoretical coordinate systems; a homogeneous transformation matrix (HTM) was generated, and the machining codes and tool paths of the computer numerical control (CNC) were directly modified by using this HTM in order to eliminate the effect of fixture locators' height error on the workpiece machined surfaces. Kunz et al. [7] analyzed excessive tool load resulting from fixture errors in micromilling that would influence the machining accuracy of the curved surface feature in four-axis machining; then, they proposed the conductive touch-off method to improve the machining depth and surface accuracy. Duret et al. [2] analyzed several possible fixture errors including the geometric parameters of the fixture, the clamping force in different fixture types, and the influence of friction on the contacts of the workpiece-fixture. Wan et al. [17] solved the nonlinear programming problem of minimizing the total complementary energy of the frictional workpiece-fixture subsystem in the machining system to determine the local contact deformations of the workpiece-fixture system. Wang and Huang [19] observed the possible datum surface imperfections, fixture locator errors, and machine tool errors in the machining process by using the concept of equivalent fixture error. They also developed a compensation simulation methodology according to the causes and order of errors.

Researchers have identified different possible fixture errors in different ways. Though the fixture errors can be determined, an effective and efficient processing method to reduce fixture errors does not exist. While Wan et al. [18] and Khodaygan [5,6] adjusted the locators to reduce errors, each adjustment may require recalculation making the process complicated. Rong et al. [12], Sánchez et al. [14], and Fallah and Arezoo [3] proposed modifying the tool path to reduce errors; however, when numerous tool paths have to be modified, many application problems occur. Furthermore, many previous studies have analyzed and compensated for the fixtures of two-axis turning machines or three-axis milling machines, but not five-axis machine tools. This study combines a machine tool probing system with the cosine theorem and HTM operations to measure and calculate the errors resulting from the fixture locators. The five-axis machine tool controller is set by the calculated values for error compensation, and the tilted work plane (TWP) command of the five-axis CNC machine tool enables the workpiece to automatically implement rotate and offset operations according to the preset value for fixture error compensation. With this approach, the fixture error is compensated for, and this compensation increases the geometric dimension accuracy of a workpiece manufactured by a five-axis CNC machine tool. The method designed in this study can effectively compensate for the fixture error of fixture manufacture and installation, without the need to adjust the fixture, modify the tool path, or make very-high-precision fixtures.

Compared to existing fixture error compensation methods, which focus on workpieces with specific shapes and regularly arranged fixture locators, the method designed in this study is applicable to the machining processes of workpieces with complex shapes.

The structure of this paper is as follows. Section 2 introduces the experimental equipment and system used in this study, including the five-axis CNC machine tool and TWP command. Section 3 describes the fixture with the 3-2-1 layout design, and the effect of fixture errors on the geometric dimension accuracy of the workpiece. Section 4 describes the calculation and compensation methodology and process of fixture errors for the 3-2-1 layout. Section 5 describes the machining results and includes a discussion about the fixture error compensation method designed in this study to validate its feasibility. Section 6 summarizes this paper.

2 EXPERIMENTAL EQUIPMENT AND SYSTEM

The five-axis CNC machining center used in this study is shown in Figure 1. This machining center is combined with a FANUC Series 31i-MODEL B5 controller to implement the fixture error compensation by the TWP command. The TWP command is the advanced design of the G68 coordinate rotation command, which is often used in the five-axis machine tool to implement fixed-angle machining. The TWP command can simultaneously implement offset and rotation operations. This study uses the Roll-Pitch-Yaw setting to complete fixture error compensation. The algorithm designed in this study implements derivation according to the Roll-Pitch-Yaw setting [15] so that the result can be directly imported into the Roll-Pitch-Yaw setting field of the TWP command, as shown in Figure 2. The {X,Y,Z} coordinate system is the original coordinate system. The {I,J,K} represents the rotation angle of each axis. The {X',Y',Z'} coordinate system is the coordinate system after the offset and rotation operations of the {X,Y,Z} coordinate system. The point P is the reference position point of the {X',Y',Z'} coordinate system. In Figure 2, (a) indicates the offset settings and rotation settings of the {X',Y',Z'} coordinate system including the absolute representation and relative representation; (b) indicates the rotation sequence of the {X',Y',Z'} coordinate system; (c) indicates the reference position offset of the {X',Y',Z'} coordinate system; (d) indicates the rotation angle of each axis of the {X',Y',Z'} coordinate system.

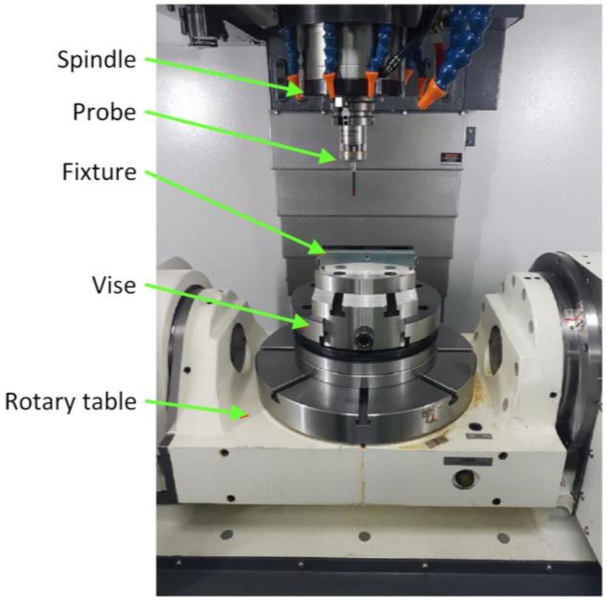

Figure 1: Five-axis CNC machining center.

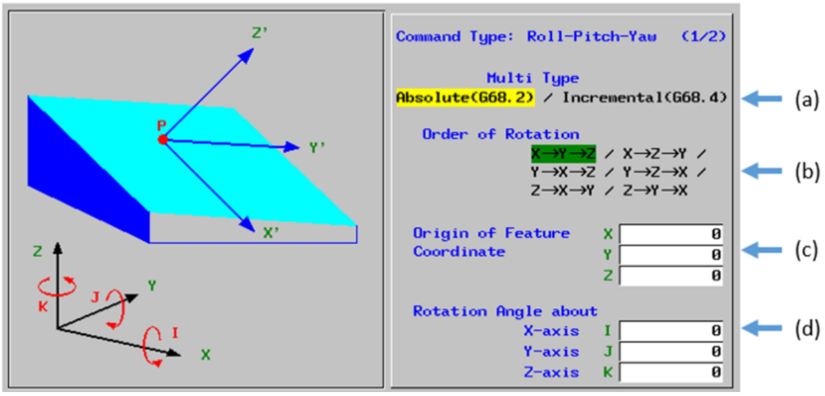

Figure 2: Controller TWP command with Roll-Pitch-Yaw setting.

3 FIXTURE DESIGN AND ERROR SOURCE ANALYSIS

The purpose of the fixture is to accurately clamp and locate the workpiece, thus restricting or controlling the six degrees of freedom of the workpiece in the space. As shown in Figure 3, the fixture design with the 3-2-1 layout means the three faces of a workpiece are mutually perpendicular, and the first plane XY is confined by three locators; thus, the three degrees of freedom—α, β and Z—are constrained. Another plane, XZ, is confined by two locators, thus constraining two degrees of freedom, Y and γ. The third plane, YZ, is confined by one locator and therefore constrains the last degree of freedom, X. Therefore, the "3-2-1" of a fixture design with a 3-2-1 layout refers to the number of locators on each positioning plane. The supporting direction of each locator has a relative relationship to the positioning plane. The supporting direction of the locator on positioning plane XY is the Z-direction. The supporting direction of the locator on positioning plane XZ is the Y-direction. The positioning direction of the locator on positioning plane YZ is the X-direction. In addition, the larger the spacing between the locators on the same positioning plane, the better the positioning effect (i.e., the locators are decentralized as much as possible without influencing the machining).

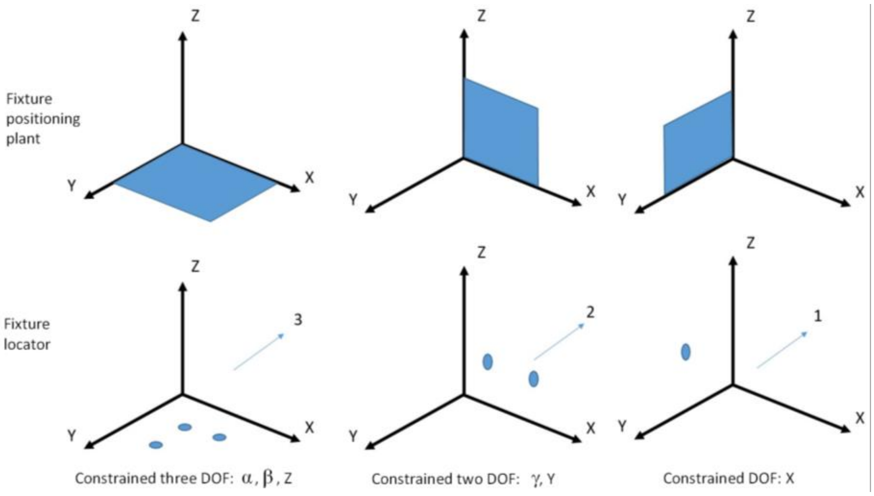

Figure 3: "3-2-1" fixture-design principle.

The fixture can be manufactured by machine tools. Although the fixed locator is generated by machining, it lacks the freedom to adjust the locator. The adjustment-type fixture can prolong the service life of a fixture; even if the locator has wear-related loss in the workpiece machining process, the usability of the fixture can be maintained by changing or adjusting the locator. The lock-type fixture, e.g., clamping cap, is used to fix large workpieces, avoiding the excessive cutting force that could lead to workpiece deformation or movement during the machining process. Fixtures other than the adjustment-type fixture and lock-type fixtures are almost always manufactured by the machining of a machine tool. If the machining process results in errors in the position and direction of the locator of the fixture, as shown in Figure 4, then the actual position and orientation of the workpiece in the fixture will be influenced in a way that is different from the ideal position and orientation of workpiece. Therefore, the workpiece machining result will have a large dimensional error. Figure 5 shows that the workpiece has a stepping surface, and when the length of locator $\{a_1, a_2\}$ has an error $\{b_1, b_2\}$, the workpiece in the fixture will tilt.

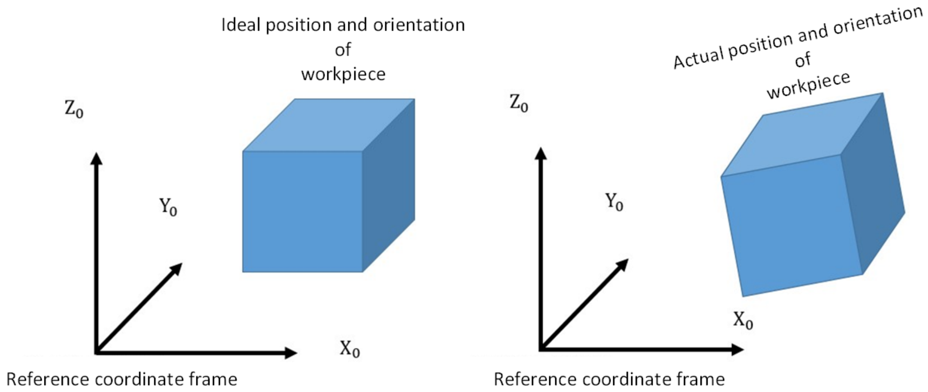

Figure 4: Effect of fixture error on workpiece position and orientation.

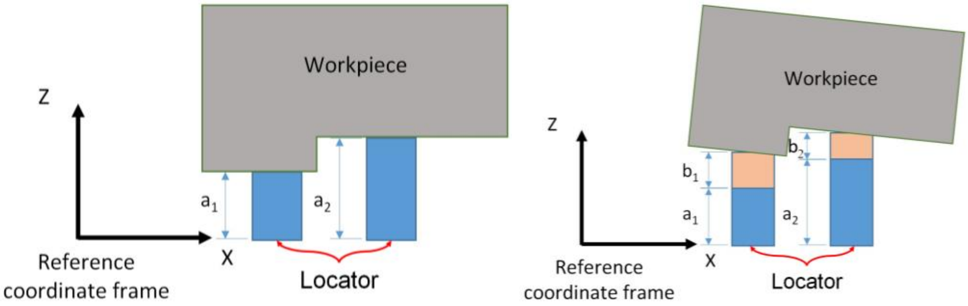

Figure 5: Error in length of locator results in workpiece tilt.

4 FIXTURE ERROR CALCULATION AND COMPENSATION

To prevent fixture errors from influencing the machining results, we designed a fixture error calculation and compensation method. This method can be used for refined calculation of the relative relationship between the fixture reference coordinate frame and the part program coordinate frame of the workpiece, as shown in Figure 6. The reference position offset of the TWP command setting and the rotation angle of each axis are obtained, and the workpiece dimensional error resulting from the fixture errors can be compensated. This study combines HTM with the cosine theorem to calculate the reference position offset between the fixture reference coordinate frame and part program coordinate frame, and the rotation angle of each axis. Following this calculation, the TWP command of the five-axis machine tool controller is used for fixture error compensation.

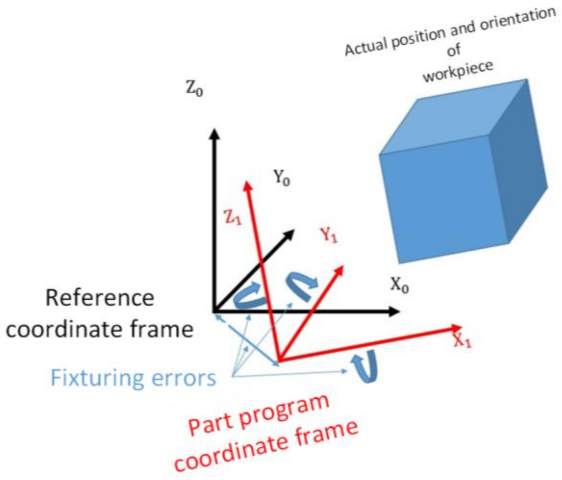

Figure 6: Relationship between fixture reference coordinate frame and part program coordinate frame.

This study uses the position information of six locators on a fixture with a 3-2-1 layout to calculate the reference position offset and rotation angle of each axis for the TWP command. The calculation procedure is described in ten steps:

Step 1: Define the part program coordinate frame as the coordinate frame numbered "0." The position information of locators in the coordinate frame numbered "0" is obtained by the machine tool probing system.

Step 2: In terms of a fixture with the 3-2-1 layout, vectors $\overrightarrow{AB}$ and $\overrightarrow{AC}$ can be obtained from the coordinates A(A_x^0, A_y^0, A_z^0), B(B_x^0, B_y^0, B_z^0), and C(C_x^0, C_y^0, C_z^0) of three locators on the first plane in the coordinate frame numbered "0," as expressed by Equations (4.1) and (4.2). Considering the length error, Equations (4.1) and (4.2) shall be modified to Equations (4.3) and (4.4), where A_z, B_z, and C_z are the ideal locator lengths. The normal vector $\vec{n}$ of this plane will be orthogonal to $\overrightarrow{AB}$ and $\overrightarrow{AC}$, as expressed in Equation (4.5).

$$\overrightarrow{AB} = (A_x^0 - B_x^0, A_y^0 - B_y^0, A_z^0 - B_z^0) \tag{4.1}$$

$$\overrightarrow{AC} = (A_x^0 - C_x^0, A_y^0 - C_y^0, A_z^0 - C_z^0) \tag{4.2}$$

$$\overrightarrow{AB} = (A_x^0 - B_x^0, A_y^0 - B_y^0, A_z^0 - B_z^0 - (A_z - B_z)) \tag{4.3}$$

$$\overrightarrow{AC} = (A_x^0 - C_x^0, A_y^0 - C_y^0, A_z^0 - C_z^0 - (A_z - C_z)) \tag{4.4}$$

$$\vec{n} = \overrightarrow{AB} \times \overrightarrow{AC} = (n_x^0, n_y^0, n_z^0) \tag{4.5}$$

Step 3: The angle between normal vector $\vec{n}$ and Z_0 can be obtained by the cosine theorem, and the component angles α and β of the angle in X_0 and Y_0 axial directions are calculated, expressed as Equations (4.6) and (4.7), respectively. The coordinate frame numbered "1" is established by normal vector $\vec{n}$, and a relationship between the coordinate frame numbered "0" and the coordinate frame numbered "1" is established, as shown in Figure 7.

$$\alpha = -\tan^{-1}(\frac{n_y^0}{n_z^0}) \tag{4.6}$$

$$\beta = n_x^0 \cdot \left|\frac{1}{n_x^0}\right| \cos^{-1}(\frac{\sqrt{(n_y^0)^2 + (n_z^0)^2}}{\sqrt{(n_x^0)^2 + (n_y^0)^2 + (n_z^0)^2}}) \tag{4.7}$$

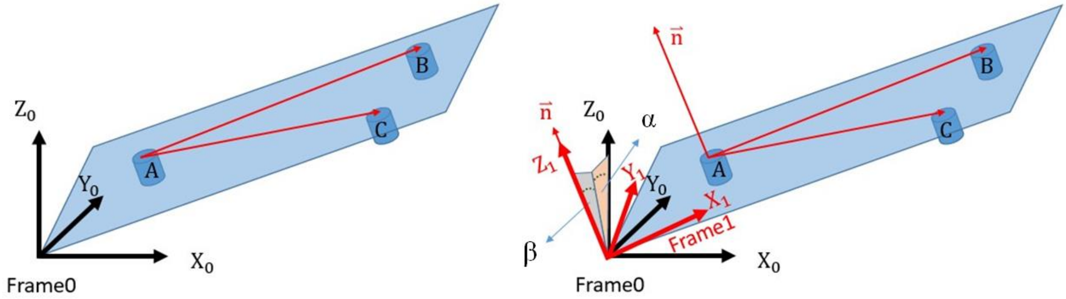

Figure 7: Relationship between coordinate frame numbered "0" and coordinate frame numbered "1".

Step 4: The Z_1 axial direction of coordinate frame numbered "1" is parallel to normal vector $\vec{n}$. The HTM H_1^0 is established by rotation angles α and β as the rotation relationship between the coordinate frame numbered "0" and the coordinate frame numbered "1," as expressed in Equation (4.8).

$$H_1^0 = \begin{bmatrix} \cos\beta & 0 & \sin\beta & 0 \\ \sin\alpha\sin\beta & \cos\alpha & -\cos\beta\sin\alpha & 0 \\ -\cos\alpha\sin\beta & \sin\alpha & \cos\alpha\cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.8}$$

Step 5: The coordinates of two locators on the second plane in the coordinate frame numbered "1" are D(D_x^1, D_y^1, D_z^1) and E(E_x^1, E_y^1, E_z^1). Another rotation angle γ can be calculated by the cosine theorem, and the coordinate frame numbered "2" is established on the coordinate frame numbered "1." However, the locator length is different from the length in the former calculation of two angles. As shown in Figure 8, the distance between locators D and E in the Y-direction of coordinate frame numbered "2" is $\overline{DS}$, $\overline{RE}$ is the distance between locators D and E in the X-direction of coordinate frame numbered "1," and $\overline{DR}$ is the distance between locators D and E in the Y-direction of coordinate frame numbered "1." The rotation angle γ is the difference between ∠RDE and ∠SDE, expressed as Equations (4.9), (4.10), and (4.11), and modified to Equation (4.12).

$$\angle RDE = \tan^{-1}(\frac{\overline{RE}}{\overline{DR}}) \tag{4.9}$$

$$\angle SDE = \cos^{-1}(\frac{\overline{DS}}{\sqrt{(\overline{DR})^2 + (\overline{RE})^2}}) \tag{4.10}$$

$$\gamma = -\tan^{-1}(\frac{\overline{RE}}{\overline{DR}}) + \cos^{-1}(\frac{\overline{DS}}{\sqrt{(\overline{DR})^2 + (\overline{RE})^2}}) \tag{4.11}$$

$$\gamma = -\tan^{-1}(\frac{D_x^1 - E_x^1}{D_y^1 - E_y^1}) + \cos^{-1}(\frac{|D_z - E_z|}{\sqrt{(D_x^1 - E_x^1)^2 + (D_y^1 - E_y^1)^2}}) \quad (4.12)$$

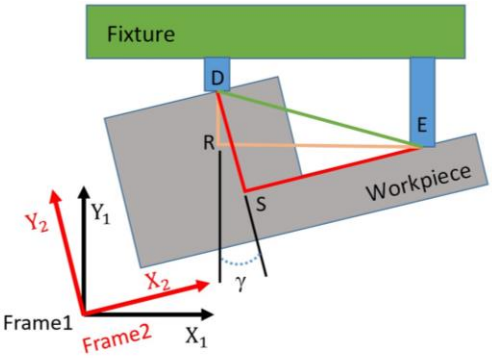

Figure 8: Plain view of relationship between coordinate frame numbered "1" and coordinate frame numbered "2".

Step 6: The HTM H_2^1 of coordinate frame numbered "2" and coordinate frame numbered "1" is established by rotation angle γ, as expressed by Equation (4.13).

$$H_2^1 = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 & 0 \\ \sin\gamma & \cos\gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.13)$$

Step 7: H_1^0 is multiplied by H_2^1 to obtain the HTM H_2^0 of coordinate frame numbered "2" and coordinate frame numbered "0," as expressed by Equation (4.14), where α, β, and γ are the angular deviations.

$$H_2^0 = \begin{bmatrix} \cos\beta\cos\gamma & -\cos\beta\sin\gamma & \sin\beta & 0 \\ \cos\gamma\sin\alpha\sin\beta + \cos\alpha\sin\gamma & \cos\alpha\cos\gamma - \sin\alpha\sin\beta\sin\gamma & -\cos\beta\sin\alpha & 0 \\ -\cos\alpha\cos\gamma\sin\beta + \sin\alpha\sin\gamma & \cos\gamma\sin\alpha + \cos\alpha\sin\beta\sin\gamma & \cos\alpha\cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.14)$$

Step 8: The position of each locator in the coordinate frame numbered "0" is calculated by H_2^0, as expressed by Equation (4.15), to obtain the locator position in the coordinate frame numbered "2."

$$\begin{bmatrix} A_x^2 & B_x^2 & C_x^2 & D_x^2 & E_x^2 & F_x^2 \\ A_y^2 & B_y^2 & C_y^2 & D_y^2 & E_y^2 & F_y^2 \\ A_z^2 & B_z^2 & C_z^2 & D_z^2 & E_z^2 & F_z^2 \\ 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} = (H_2^0)^{-1} \cdot \begin{bmatrix} A_x^0 & B_x^0 & C_x^0 & D_x^0 & E_x^0 & F_x^0 \\ A_y^0 & B_y^0 & C_y^0 & D_y^0 & E_y^0 & F_y^0 \\ A_z^0 & B_z^0 & C_z^0 & D_z^0 & E_z^0 & F_z^0 \\ 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \quad (4.15)$$

Step 9: The locator position in the coordinate frame numbered "2" is compared with the ideal locator position in a fixture with the 3-2-1 layout to obtain the position deviation vector d, as expressed in Equation (4.16) to Equation (4.19). The HTM H_3^0 of the coordinate frame numbered "3" and coordinate frame numbered "0" is established, as expressed in Equation (4.20).

$$d_x = F_x^2 - F_x \quad (4.16)$$

$$d_y = D_y^2 - D_y = E_y^2 - E_y \quad (4.17)$$

$$d_z = A_z^2 - A_z = B_z^2 - B_z = C_z^2 - C_z \quad (4.18)$$

$$d = [d_x \quad d_y \quad d_z \quad 1]^T \tag{4.19}$$

$$H_3^0 = \begin{bmatrix} \cos\beta\cos\gamma & -\cos\beta\sin\gamma & \sin\beta & d_x \\ \cos\gamma\sin\alpha\sin\beta + \cos\alpha\sin\gamma & \cos\alpha\cos\gamma - \sin\alpha\sin\beta\sin\gamma & -\cos\beta\sin\alpha & d_y \\ -\cos\alpha\cos\gamma\sin\beta + \sin\alpha\sin\gamma & \cos\gamma\sin\alpha + \cos\alpha\sin\beta\sin\gamma & \cos\alpha\cos\beta & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.20}$$

Step 10: The HTM H_3^0 is the result of the fixture error analysis. The fixture error compensation imports the analysis result (angular deviations α, β, and γ, and offsets d_x, d_y, and d_z) into the reference position offset of the TWP command and the rotation angle of each axis. Thus, the effect of fixture error on the geometric dimension accuracy of the workpiece can be reduced.

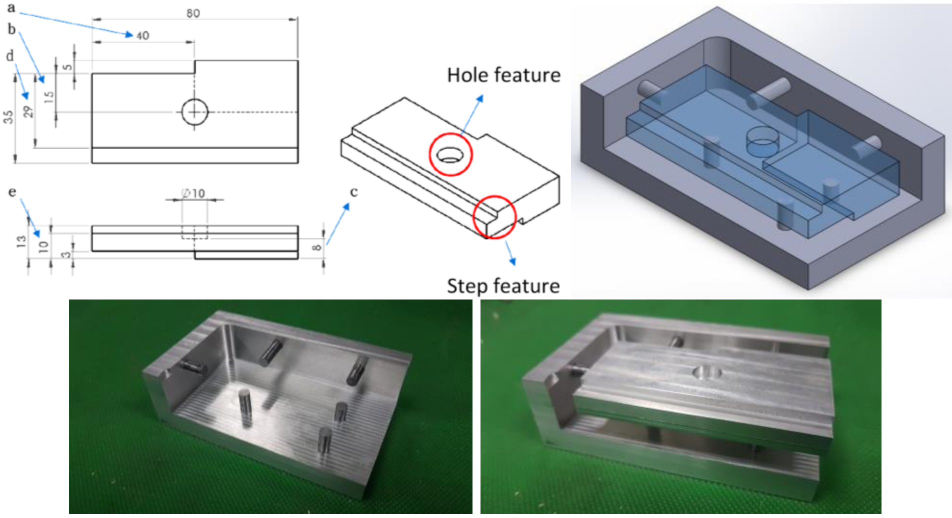

Figure 9: Workpiece and fixture design for machining experiments.

5 EXPERIMENTAL RESULTS AND DISCUSSION

The experimental process of the fixture error compensation is to locate and fix the fixture; use the Renishaw OMP400 machine tool probing system to measure the relative positions of the fixture locators and fixture reference point; substitute the position information of each locator in the fixture error computing process; calculate the fixture error; and import the result into the TWP command. This study designs a workpiece with step and hole features, as shown in Figure 9. The dimension of the two features is measured. There is a significant difference in accuracy after compensation, and the rate of improvement is compared. The center position, height, and roundness of the hole on the XY plane are measured to confirm whether the tilted machining plane leads to an elliptic hole. A possible cause for the machining plane tilt is the error of XY angles α and β. In addition to the step height, the Y-direction parallelism is measured to determine the error of the Z-axis angle γ. The error calculation result is shown in Table 1, and the feature dimension measurement results before and after compensation are shown in Table 2. In this study, the ZEISS CONTURA G2 coordinate measuring machine is used to measure the workpieces before and after compensation. As shown in Table 2, the hole machining result shows that the position and dimension are markedly improved—the Z-axis rate of improvement is 91.53%, the minimum rate of improvement is 80.47%, and the average rate of improvement is 85%. However, it is difficult to see the improvement in roundness accuracy, as the ellipticity of the hole is low before compensation; thus, the rate of improvement is only 39.68%. In terms of the step machining result, the average rate of improvement is 56%. Therefore, the fixture error can be effectively compensated by our compensation method.

Result of rotation angle of each axis [degree]		Result of reference position offset [mm]	
α	0.1066	d_x	−0.1819
β	−0.0217	d_y	0.1141
γ	−0.0065	d_z	−0.0663

Table 1: Results of reference position offset and rotation angle of each axis.

Feature	Test item	Before compensation [mm]	Error [mm]	After compensation [mm]	Error [mm]	Rate of improvement
Hole	X-coordinate position (a)	40.1505	0.1505	39.9706	−0.0294	80.47%
	Y-coordinate position (b)	15.0802	0.0802	14.9860	−0.0140	82.54%
	Depth (c)	8.1170	0.1170	7.9901	−0.0099	91.53%
	Roundness	0.0126		0.0076		39.68%
Step	Y-coordinate position (d)	29.0888	0.0888	28.9638	−0.0362	59.23%
	Step height (e)	10.2052	0.2052	10.0977	0.0977	52.38%
	Parallelism	0.0775		0.0323		58.32%

Table 2: Machined workpiece inspection result.

6 CONCLUSION

In the machining of mechanical parts, the fixture positioning method and locator accuracy can significantly influence the accuracy of machining results. The minor errors of the locator are magnified to influence the workpiece, leading to more obvious geometric dimension errors. The five-axis CNC machine tool has recently become key equipment in the manufacturing industry, and this study uses the TWP command of the five-axis CNC machine tool for fixture error calculation and compensation design. The method described in this paper prevents the need for the complicated operations of fixture repair or adjustment and reduces the geometric dimension error of machined mechanical parts.

In this study, a machine tool probing system is used to measure the position and orientation of fixture locators. Then the errors resulting from the fixture locators are calculated with the cosine theorem and HTM according to the measurement results. Finally, the TWP command Roll-Pitch-Yaw setting of the five-axis machine tool controller is set by using the calculated values for error compensation. In this setup, the fixture rotate and offset operations are automatically implemented by the TWP command of the five-axis machine tool controller, and the workpiece can compensate for the fixture error to increase the geometric dimension accuracy of the workpiece. Finally, the fixture error compensation is tested, the workpiece is designed with step and hole features, and the results before and after fixture error compensation are compared to confirm the feasibility of the methodology. The experimental results show that the geometric dimension accuracy of a workpiece is markedly improved after fixture error compensation, with the hole machining result showing an average improvement rate of 85% and the step machining result showing a 56% average improvement rate. Therefore, the fixture error compensation method designed in this study can effectively reduce the effect of fixture errors on the geometric dimension accuracy of the workpiece. In addition, compared to other fixture error compensation methods, the one designed in this study can effectively compensate for the fixture error resulting from the fixture manufacture and installation processes without considering the profile of the workpiece or the arrangement of the fixture locators, adjusting the fixture locators, modifying the tool path, and making very-high-precision fixtures.

At present, the proposed calculation and compensation method was implemented offline and is not suitable for applications in fully-automated manufacturing processes. Therefore, in future works, this study will develop an online calculation and compensation system based on the proposed calculation and compensation method, which integrates a touch-trigger probe and can automatically compute and update the TWP command in a five-axis CNC controller to complete a fully automatic high-accuracy manufacturing system.

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