

Reduction of a RRTTT machine tool geometric model by combinatorial analysis to improve volumetric accuracy

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Abstract

To significantly improve manufacturing processes, the intrinsic geometric deviations of machine tool must be optimized. Despite the international standard ISO 230-1, many geometric errors model are developed in the literature. In this paper, the modeling of a RRTTT five-axis machine tool including geometric error related to the international standard is carried out. The reduction and determination of model parameters is based on a combinatorial analysis coupled with rank analysis. The goal is to find all groups of position and orientation axes errors to model the volumetric accuracy actually measured. This task is performed by probing a datum sphere with a touch probe integrated in the machine tool. Finally, a combination of optimal parameters is determined in order to better map volumetric accuracy.

Keywords: Machine tool calibration; volumetric accuracy; geometric errors model; combinatorial analysis; indirect measurement.

1 Introduction

5-axis machine tools are multi-axis structural loops with a large number of types of structures [1, 2], currently considered as common manufacturing system. In this paper, structural loops with three linear axes and two rotary axes are considered.

The main function of this loop is to maintain the relative position and orientation between the tool and the workpiece. Between both, a relative deviation, namely volumetric accuracy (V_{XYZ}) in ISO 230-1 [3], is principally generated by geometric errors [4]. To significantly improve the manufacturing

process, it is necessary to minimize V_{XYZ} . This goal may be achieved through identification and compensation of geometric errors.

Assuming infinite rigid bodies hypothesis, each axis of the structural loop is composed of two solids constituting a link with one degree of freedom biased by geometric errors, called motion errors. According to ISO 230-1 [3], the six motion errors of linear axis are: one linear positioning motion error along the direction of motion, two straightness motion errors in two orthogonal directions of motion, and three angular motion errors (i.e. roll, pitch and yaw in the case of horizontal axis). According to ISO 230-7 [5], the six motion errors of rotary axis are: one angular positioning motion error around the direction of motion, two tilt motion errors in two orthogonal directions of motion, one axial error motion along the direction of rotary axis and two radial motion errors in orthogonal directions.

Structural loop is made up of axes which are composed of solids. Due to manufacturing and assembly errors, geometric deviation appears between nominal and real motion direction of the structure. ISO 230 defines the sufficient position and orientation errors of straight line and average line respectively in the case of linear and rotary axis. There are two orientation errors for one straight line (e.g. E_{A0Z} et E_{B0Z} in Figure 1) and four position and orientation errors of average line (e.g. E_{X0C} , E_{Y0C} et E_{A0C} , E_{B0C} in Figure 1). Moreover, one zero position error is defined for each axis (i.e. E_{Z0Z} and E_{C0C} in Figure 1).

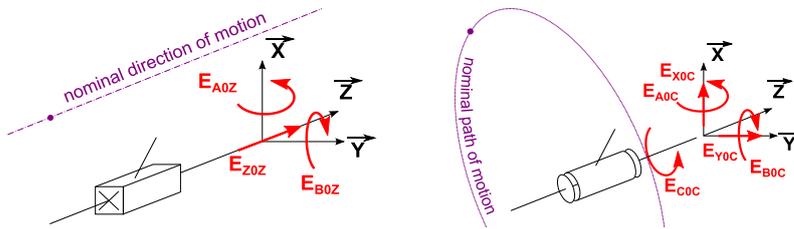


Figure 1: Position and orientation errors of linear Z-axis and rotary C-axis.

Table 1. Sufficient geometric errors on five-axis machine tool ([3], [5])

| Type of axis | Motion errors per axis | Zero position error per axis | Position and orientation errors per axis | Number of axes | Total of errors |
|--------------|------------------------|------------------------------|--|----------------|-----------------|
| Linear | 6 | 1 | 2 | 3 | 27 |
| Rotary | 6 | 1 | 4 | 2 | 22 |
| | | | | | 49 |

Hence, for a RRTTT structural loop, without considering errors of the tool spindle, the total number of sufficient geometric errors is equal to forty-nine (Table 1). These errors are not all required to characterize the volumetric accuracy. Indeed, due to the selection of reference position and orientation of machine coordinate system, and the possibility to set to zero the zero positions,

the international standard ISO230-1 [3] gives the minimum of eight position and orientation error parameters, in addition to the thirty motion errors, to fully characterize a five-axis machine tool. The reduction of model to drop the position and orientation errors from nineteen to eight is not clearly justified. Reduction may be difficult to understand, and very difficult to be applied to any architecture of machine tool. Therefore, there is a requirement to analyze the reduction methods of geometric error models.

Abbaszadeh-Mir et al. [6], develop a geometric model with position and orientation axes errors. Six parameters are defined between each axis, and six parameters describe tool deviations as well as six for the workpiece deviations (mounting errors). Reduction is done thanks to the rank study of the jacobian matrix given by the inverse geometric model. A method based on the mathematical analysis of singularities of linear systems is used to assist in selecting a minimal set of twenty parameters for the calibration of a five axis machine tool. Identification is performed by telescoping magnetic ball-bar measurement.

Yu et al. [7], define a high efficiency computable model with clear physical meanings. The model is reduced and a combination of twenty groups of parameters including motion errors as well as position and orientation errors is proposed.

Bohez et al. [8] adopt a model with nine position and orientation errors, found by minimum number of rigid bars to form a single rigid body. A reduction is performed by a linear dependencies study. Identification of parameters is done by measurement of a machined test part on Coordinate Measuring Machine (CMM).

Lei and Hsu. [9, 10] build a model with sixty-one geometric parameters including thirty motion errors, thirteen position and orientation errors, eighteen mounting errors associated respectively with the spindle block and the Z-slide, with the spindle-tool interface, and with turntable and workpiece. An identification of fifty-nine parameters is done with probe-ball measurement and 5D laser interferometer.

Tsutsumi and Saito [11] assess an identification of eight rotary axis parameters of thirteen position and orientation errors of axes in the 5-axis machine tool. Identification is carried out by using telescoping magnetic ball-bar.

Lin and Shen [12] propose a geometric model based on motion errors and seven squareness parameters. A matrix summation approach is performed to simplify the homogenous matrix transform approach and provides a clearer physical interpretation.

Table 2. Papers comparison of geometric errors modelisation and identification on 5-axis machine tool

| References | Motion errors | Position and orientation errors | Mounting errors | Independent errors |
|---------------------------|---------------|---------------------------------|-----------------|--------------------|
| ISO230 [3, 5] | 30 | 19 | 0 | 38 |
| Abbaszadeh-Mir et al. [6] | 0 | 30 | 12 | 20 |

| | | | | |
|-------------------------|----|----|----|----|
| Yu et al. [7] | 30 | 30 | 0 | 20 |
| Bohez et al. [8] | 30 | 9 | 0 | 32 |
| Lei and Hsu. [9, 10] | 30 | 19 | 12 | 59 |
| Tsutsumi and Saito [11] | 0 | 30 | 0 | 13 |
| Lin and Shen [12] | 30 | 7 | 0 | - |

From this literature review (Table 2), when motion errors are taken into account, the number of geometric parameters is the same (i.e. thirty geometric parameters). Indeed, motion errors depend on the axis position and cannot be reduced. It is not the case for the position and orientation errors. The reduction of these errors is often made without clear justification. Thus the number of independent errors which have a different effect on volumetric accuracy needs to be clarified.

This paper aims at building a geometric errors model consistent with ISO 230, in order to perform compensation on a RRTTT 5-axis machine tool. This model is made up of a sufficient number of geometric parameters which have independent effects on volumetric accuracy. The proposed approach consists in performing a model reduction. Thus, an analysis of functional combinations of parameters is carried out to minimize volumetric accuracy previously measured. Therefore, the paper is organized as follows: Section 2 presents the geometric model of a five-axis machine tool based on international standard; Section 3 deals with the volumetric accuracy simulation and physical procedure for parameters identification; Section 4 is dedicated to the reduction of this model by combinatorial analysis to find the best combinations of functional geometric parameters.

2 Geometric errors model

Geometric model is based on infinite rigid body assumption. Each degree of freedom between two successive bodies S_i and S_{i+1} , respectively attached with R_i and R_{i+1} frames, constitutes the $i+1$ axis.

Sufficient geometric parameters are introduced between two consecutive bodies. The non-ideal $i+1$ axis model are defined and calculated by homogenous transformation matrices without first order simplification. In other words, all rotation matrix are completely defined. The non-ideal $i+1$ axis model is depicted in Equation 1 and in Figure 2 with:

- T_N is the nominal geometry of S_i ;
- T_{POE} represents the position and orientation error between nominal axis and straight or average line : three or five parameters for linear or rotary axis respectively;
- T_M is the nominal motion joint;
- T_{ME} depicts the six motion errors of axis: linear positioning motion errors, straightness errors, roll, pitch and yaw in the case of linear axis.

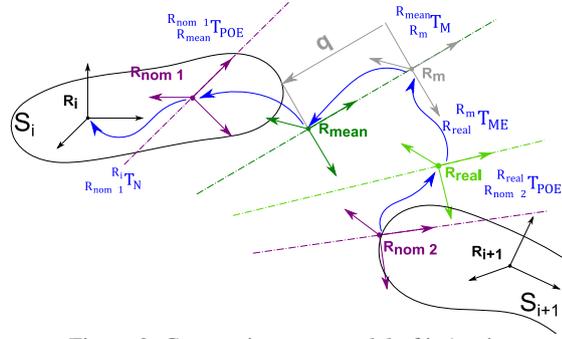


Figure 2: Geometric errors model of i+1 axis.

Equation 1: Geometric errors model of i+1 axis.

$${}_{R_{nom 2}}^{R_i} T_{axis\ i+1} = {}_{R_{nom 1}}^{R_i} T_N \cdot {}_{R_{mean}}^{R_{nom 1}} T_{POE} \cdot {}_{R_m}^{R_{mean}} T_M \cdot {}_{R_{real}}^{R_m} T_{ME} \cdot {}_{R_{nom 2}}^{R_{real}} T_{POE}$$

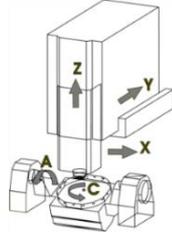


Figure 3: Mikron UCP710 5-axis machine tool structure.

This modelling is performed on each axis of the RRTTT Mikron UCP710 five-axis machine tool which is shown in Figure 3. Six parameters of tool mounting and six parameters of workpiece mounting are introduced. So, sixty-one geometric parameters are considered in the next step. These sixty-one errors are composed of thirty motion errors, nineteen position and orientation errors and twelve mounting errors.

3 Volumetric accuracy simulation and measurement

The main objective of this study is the certification of geometric errors effects (i.e. one error or a set of errors) on volumetric accuracy by virtual machine building. This development allows the quantitative evaluation of deviation between measurement and the simulation of error effects. This deviation can be calculated on both geometric errors and effects on volumetric accuracy.

a. Simulation

A simulation of volumetric accuracy V_{XYZ}^{vm} expressed everywhere in the workspace is performed by using a developed virtual machine (*vm*).

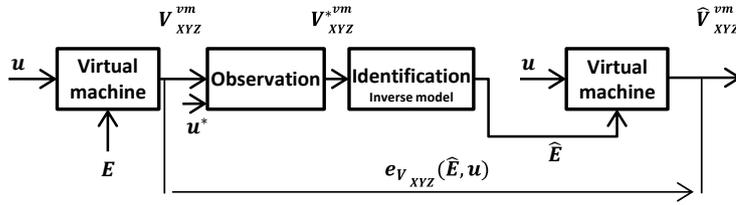


Figure 4: Procedure of volumetric accuracy modelling by virtual machine.

The inputs are one vector E of geometric parameters and a vector of excitement u (Figure 4). A restricted excitement vector u^* can be chosen. It corresponds with particular joint configurations of u . A mapping of the resulting observed volumetric accuracy V_{XYZ}^{*vm} for this restricted excitement vector u^* allows the identification of one vector of \hat{E} -parameters. Therefore these parameters are estimated. This vector is the combination of sufficient parameters to depict volumetric accuracy (V_{XYZ}^{*vm}). With the identified parameters, it is possible to map the identified volumetric accuracy \hat{V}_{XYZ}^{vm} everywhere in the workspace. The second model of virtual machine (Figure 4) is different from the first model. Indeed, the inputs are different. The first model uses imposed E -vector (i.e. imposed geometric parameters), whereas the second uses identified \hat{E} -vector.

Then, the goal is to assess the pertinence of this second model to a broader set of excitation vectors (covering most points of the workspace). The pertinence can be evaluated with an error. The error of calculation $e_{V_{xyz}}(\hat{E}, u)$ can be defined between these models (Equation 2). This error allows testing and verifying the robustness of the estimation procedure (i.e. the identification).

Equation 2: error of calculation.

$$e_{V_{xyz}}(\hat{E}, u) = \hat{V}_{XYZ}^{vm}(\hat{E}, u) - V_{XYZ}^{vm}(E, u)$$

b. Measurement of volumetric accuracy V_{XYZ}^{*mr}

Within an industrial context, it is important to implement a rapid procedure both on the setting and the measurement to minimize the downtime of the machine tool. It is also essential to perform a raw measurement of joint coordinates, thus avoiding to affect the measurements by the unwanted treatments and compensations of the industrial CNC.

This process requires the integration of a 3D touch probe, and the collection of raw data on linear and rotary encoders. Moreover, it is necessary to synchronize in real time the control of the machine tool and the external measurement. This process includes several tasks which are:

- Procedure to acquire the machine zero point by counting distance-coded reference marks;
- Absolute machine coordinate collection (X, Y, Z, A, C) in real time (f = 33kHz) and directly on Heidenhain encoders;

- Collection of trigger signal directly on Renishaw RMP600 touch probe ($U_{(k=2)} = 0,25\mu\text{m}$ with feedrate of 240mm/min);
- Synchronized recording of coordinates with trigger signal;
- Fetch stored data on dSpace hardware.

The components of position of volumetric accuracy V_{XYZ}^{*mr} are measured thanks to the probing of a datum sphere directly clamped on the rotary table. The volumetric accuracy is equal to the difference between actual position of the datum sphere and the ideal position. Fifty different joint configurations are used to maximize the motion along of the travel range axes, as depicted in Figure 5. They are uniformly distributed along the path of the A-axis and for nine turns of the C-axis. $V_{XYZ}^{*mr}(u^*)$ is shown in Figure 6. It is a vector with one hundred and fifty components (i.e. three components of position multiplied by fifty joint configurations).

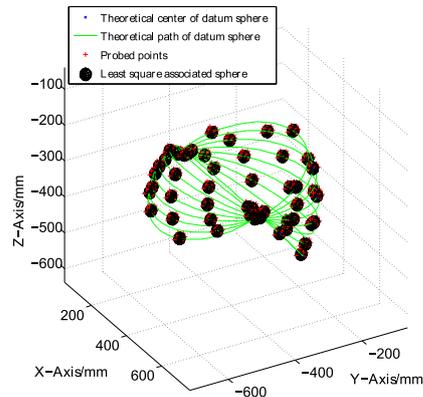


Figure 5: Location of datum sphere in machine workspace.

The measurement of the datum sphere in fifty joint configurations allows mapping the position components of the measured volumetric accuracy (Figure 6). The influence of position and orientation errors of axis is clearly observable in Figure 6. Indeed, the nine oscillations correspond to the nine turns of rotary table.

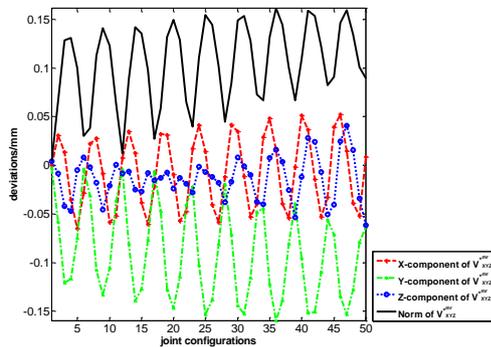


Figure 6: Norm and components of V_{XYZ}^{*mr} for each of the fifty configurations.

4 Model reduction and identification

In the next step a focus is made on geometric errors parameters without taking into account motion errors. Combinations of position and orientation errors of axis as well as mounting errors of tool and workpiece will be identified. However, the proposed measurement process with a datum sphere does not allow the identification of the orientation component of tool and workpiece mounting errors.

From the nominal links and joint parameters of the structural loop, the sensitivity Jacobian matrix J is obtained using the little displacement theory which is based on first order approximation [6]. It is built to propagate the effect of errors on the position of center location of tool (i.e. centre of tool frame) for the fifty joint configurations. These errors are the nineteen position and orientation errors of axis and the six mounting errors of tool and workpiece. So J is a 150×25 matrix (Equation 3).

Equation 3: Model for identification.

$$J_{[150 \times 25]} \times E_{[25 \times 1]} = V_{XYZ}^{*mr}$$

Combinatorial analysis of possible combinations of fourteen geometric errors is carried out. Then, J is reduced to effects of combinations (i.e. $J_{[150 \times 14]}$) and a rank analysis is performed. Thanks to these studies, it is possible to minimize E according to the Equation 4.

Equation 4: Minimization of E .

$$\hat{E} = \operatorname{argmin}_{\mathbb{R}^n} (\|J \times E - V_{XYZ}^{*mr}\|_2)$$

The E -vector is composed of fourteen components. It is the concatenation of eight errors among nineteen of structural loop and six position components of mounting error.

Among the $C_8^{19} = 78\,582$ possible combinations of geometric parameters, only twenty allow to resolve the Equation 4. The combinations which appear in ISO 230 and in [6], are included among the twenty combinations. It was proved that whatever the size of the vector V_{XYZ}^{*mr} the number and the composition of combinations are the same. In other words, if just the components of position or all components (i.e. position and orientation) of V_{XYZ}^{*mr} are used in Equation 4, combinations of eight geometric errors of the structural loop are the same. This result was demonstrated by using the previous virtual machine and the study of $e_{V_{xyz}}(\hat{E})$. Moreover, this study shows that combinations don't have the same performance on calculation error minimization and consequently on the compensation of simulated volumetric accuracy. An analysis of the error $e_{V_{xyz}}(\hat{E})$ for a E -vector of parameters and in the particular case of $u = u^*$ is highlighted in Figure 7.

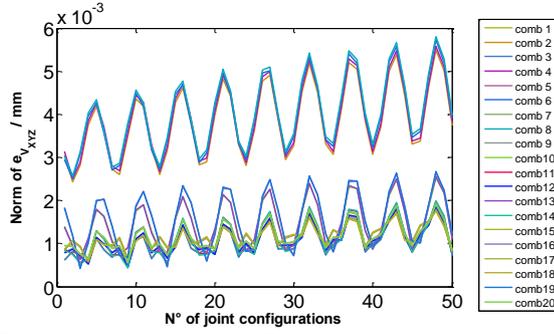


Figure 7: Residue of calculation for all combinations and for a chosen E -vector.

After identification of parameters (Figure 8), the residue of estimation can be calculated (Equation 5).

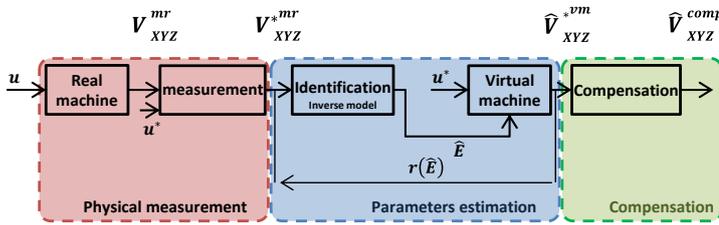


Figure 8: Identification procedure.

This residue is the difference between the measured volumetric accuracy for a chosen vector of excitement u^* (i.e. fifty joint configurations) and simulated volumetric accuracy $\hat{V}_{XYZ}^{*vm}(u^*)$ from virtual machine and estimated parameters.

Equation 5: Residue of estimation.

$$r(\hat{E}) = V_{XYZ}^{*mr}(u^*) - \hat{V}_{XYZ}^{*vm}(\hat{E}, u^*)$$

To improve manufacturing process, the focus is on volumetric accuracy $V_{XYZ}^{mr}(u)$ in the workspace. It is necessary to carry out correction of $V_{XYZ}^{mr}(u)$ by compensation of identified geometric errors \hat{E} . The Figure 9 depicts the residue $r(\hat{E})$ for the twenty combinations. All combinations characterise the volumetric accuracy in the same way because all twenty curves are superimposed. The residue may be explained by the presence of motion errors, thermal effects and terms of second order or higher order, and due to measurement.

This study demonstrates that there are twenty potential combinations of sufficient parameters. They produce the same residue of estimation but few of them exhibit a lower sensitivity to calculation approximations. A priori, few characterize better volumetric accuracy of the actual machine.

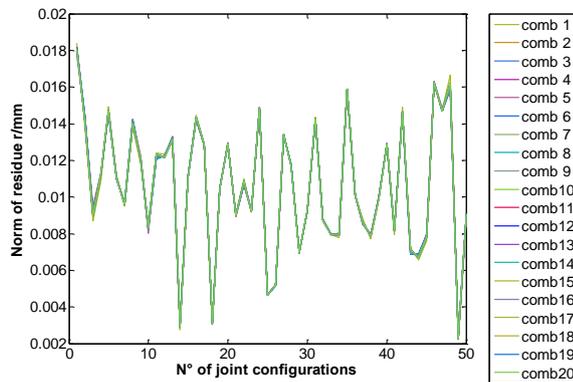


Figure 9: Residue of estimation $r(\hat{E})$ for twenty combinations

Conclusion

In this paper, a geometric errors modeling based on international standard of a 5-axis machine tool was developed. The generic property of this geometric modeling and the parameter identification can be applied on another type of structure (e.g. robot, CMM). The determination of the necessary and sufficient parameters to optimally map volumetric accuracy was carried out by combinatorial analysis. A measurement with touch probe and datum sphere is used to identify the parameters' values of a potential combination.

The use of such a model for compensation should decrease drastically the volumetric accuracy in the machine workspace. Further works will complete the identification of the motion errors and provide a criterion to define and choose the best compensation strategy.

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