A strategy for geometric error characterization in multi-axis machine tool by use of a laser tracker

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Keywords: Laser tracker, volumetric verification, geometrical errors, regression functions, kinematic model.

Abstract. This paper aims to present different methods of volumetric verification in long range machine toll with lineal and rotary axes using a commercial laser tracker as measurement system.

This method allows characterizing machine tool geometric errors depending on the kinematic of the machine and the work space available during the measurement time. The kinematic of the machine toll is affected by their geometric errors, which are different depending on the number and type of movement axes. The relationship between the various geometrical errors is different from relationship obtained in machine tool whit only lineal axes. Therefore, the identification strategy should be different. In the same way, the kinematic chain of the machine tool determines determines the position of the laser tracker and available space for data capture.

This paper presents the kinematic model of several machine tools with different kinematic chains use to improve the machine tool accuracy of each one by volumetric verification. Likewise, the paper thus presents a study of: the adequacy of different nonlinear optimization strategies depending on the type of axis and the usable space available.

1. Introduction

The incorporation of rotary axes in machines of three, five or more axis, multi axis machine, increases the flexibility of these ones in relation with machines with only linear axis. In the same way, multi-axis machines allow the machining of complex parts.

Machined part accuracy is essentially determined by machine tool performance from the point of view of compliance to tolerance, surface definition, etc. Accuracy is one of the most important performance measures, the ability to control errors to optimize performance while maintaining cost is crucial in the machine tool industry. Different techniques have been used in to improve the accuracy of a machine depending on the source of error to study.

Assessment of the sources of error affecting the accuracy of the machine tool (MT) can be divided into quasi-static errors and dynamic errors. Quasi-static errors are errors in the machine that occur relatively slowly. This category is formed by geometric and kinematic error, thermal errors, etc [1]. However, dynamic errors are caused by structural vibration, spindle error motion, controller errors, etc. Unlike the quasi-static errors, these errors are more dependent on the working conditions of the machine. Overall, quasi-static errors account for about 70 percent of the total errors of a machine [2].

Generally machine tool accuracy is obtained by reducing the influence of qausi-static errors, especially geometric error. Since these source of error is the main contributor to overall error of the machine tool. The different verification techniques used in order to improve the accuracy of the machine reducing the influence of geometric errors are divided into direct measurement techniques [3-4] and indirect measurement techniques of errors [5-8]. Verification by direct measurement of errors is based on the calculated independently to each one geometrical error of the machine tool using measurement system with known dimensions. Errors obtained in a position of the MT obtained with direct measurement method cannot be directly extrapolated to rest of work space. Currently, the manufacturing sector demand accuracy throughout all machine tool workspace. Limitation of direct measurement cause that indirect measurement prevails in this type of machines. Meanwhile, verification through indirect measurement of errors is based on a measurement of the overall effect of all of them in the machine tool work space, volumetric error (ve). The gradual incorporation of long range measurement systems in industry has provided that verification through interferometry by tracking as the verification technique most widely. Tracking interferometry has distinguished itself from other techniques, reducing the amount of time and operator training needed for verification. Mainly it provides a decrease in the time of preparation of data capture and subsequent treatment.

This paper presents a high precision volumetric model based on a laser tracker (LT) as measurement system, whereby error compensation is performed in a long range MT with two linear axes and a rotation axis. The paper thus presents a study of: the adequacy of different nonlinear optimization methods, the regression functions to be used depending on the type of axis and the usable space available.

2. Basic operating principle of volumetric verification

Volumetric verification consists of minimizing the difference between real points and theoretical points which are introduced for numerical control (NC) (Fig. 1). Theoretical points are introduced as trajectory, mesh or cloud of points depending on the possibilities and necessity of the technique employed. The determination of the technique depends on the sequence of movements and the errors that affect to the MT, structure and type of the machine.

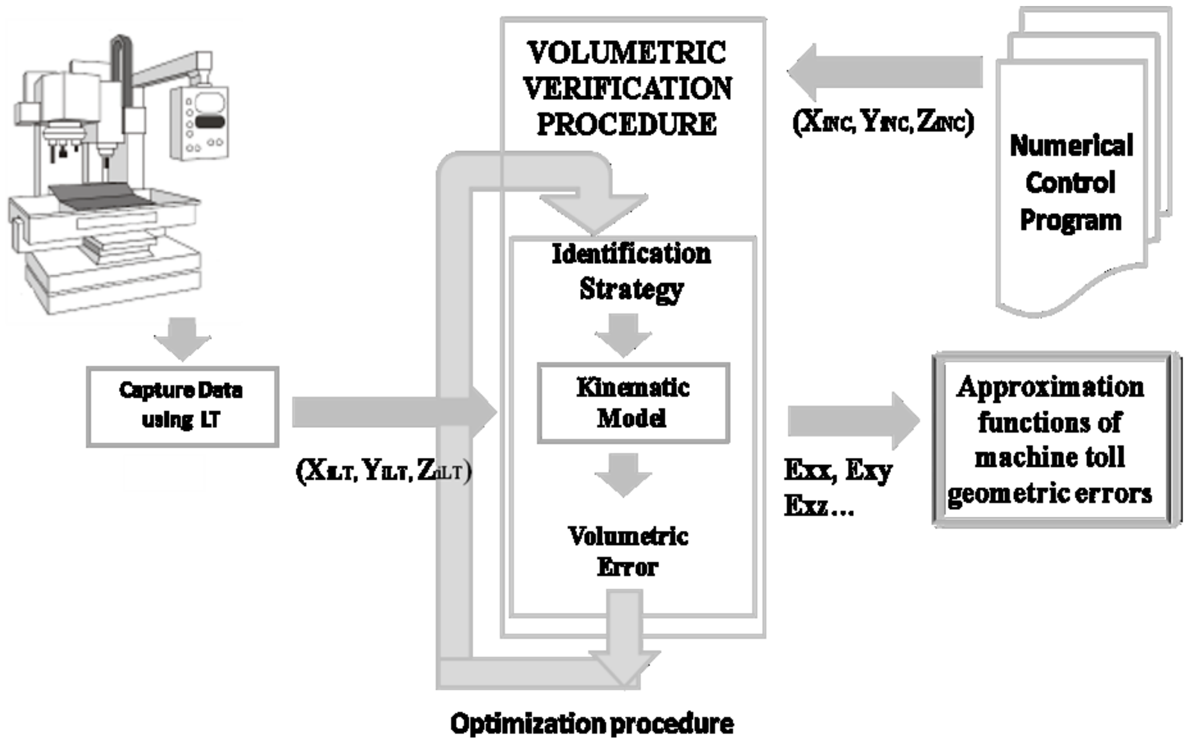

Fig. 1: Operation scheme of volumetric verification using laser tracker as measurement system

Machine tool geometric error identification strategy depends on the type and configuration of the machine as well as the purpose of verification [5, 6].The difference between theoretical and real point represents the influence combined of machine errors for each point, volumetric error (ve)

Eq.1. Minimizing the machine tool volumetric error using non-lineal optimization techniques, the approximation functions of each error can be obtained, if there are enough measured points.

$$Er_i(x,y,z) = \left| P_i(x,y,z) - f(x,y,z) \right| \tag{1}$$

$$ve = \frac{\sum_{i=}^{n} Er_i}{n} \tag{2}$$

Where Pi represents the measured point coordinates of the machine tool, measured using a laser tracker, and f(x, y, z) the machine tool point coordinates Pi obtained from the kinematic model of the machine (Fig 1).

2. Kinematic model of multi-axis machine tools

The development of kinematic models based on machine structure is one of the most important steps for an error compensation strategy. The MT kinematic model is used to understand and mathematically describe the motion of the machine [5,6,9]. The sequence of movements that describes the kinematic model is determined by the type of machine, the geometrical structure and the number of axes of the same. The position of a tool tip relative to a measurement system in cartesian coordinates (LT) is determined by the following: the programmed nominal position, the position of the tip of the tool with respect to the reference machine (offsets T) and the geometric errors of the axes.

The combination of the different axes of the machine tool depending on the number of axes and the type of movement each one provides different structural configurations and different kinematic models. These can be classified according to the movement of the workpiece and the tool as RFTT, TRFT, RRFTTT, TRRFTT etc. F determines the fixed part of the machine. Letters on the right of F represent the axes that move with the tool and letter on the left of F represent the axes that move with the piece [9].

The structural configuration RRFTTT covers 20% of global demand. Herein three lines provide the associated axis movement of the piece and two rotary axes are associated with head movement. Structural configuration TRRFTT covers 40% of global demand. Here linear axes along two rotary axes provide the movement associated with workpiece and two linear axes provide the movement associated with head (tool). TFTTRR and TTRRFT structure configuration covers 15% and 2.5% global demand respectively (Fig. 2).

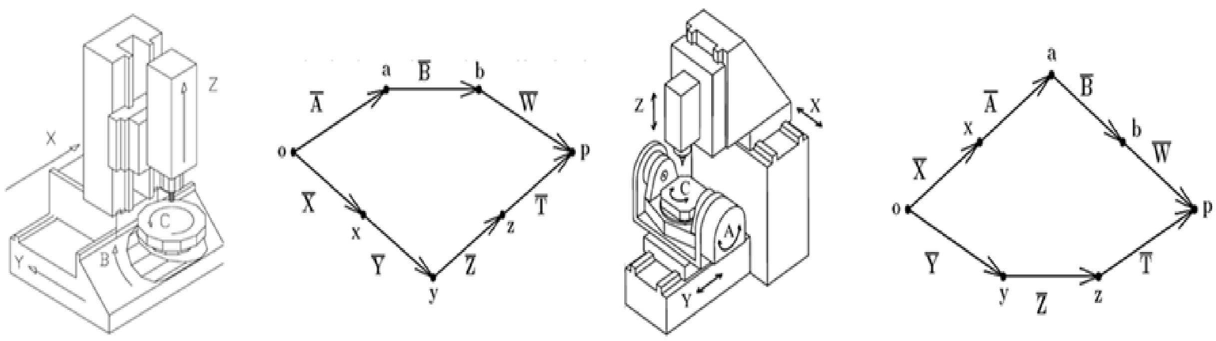

Fig. 2: Kinematic models with RRFTTT and TRRFTT structural configurations

To simplify the study of volumetric verification strategy in multi-axis machine tool, the geometric configuration of the machine from which this work has been realized, corresponds to a grinder XCFZ (Fig. 3).

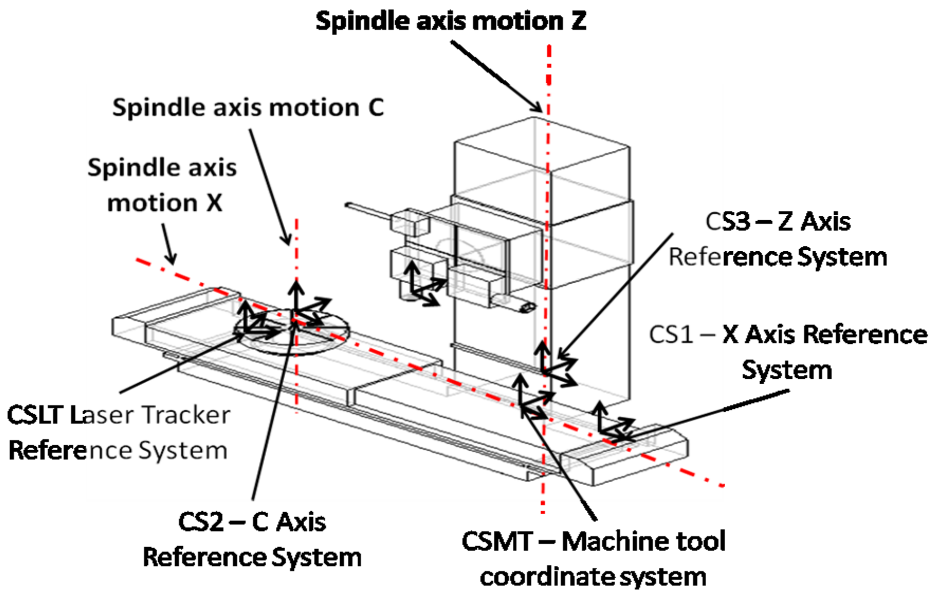

Fig. 3: Kinematic chain of a machine with XCFZ configuration

To obtain the modelling kinematic behaviour, it is necessary to use 6 auxiliary coordinate systems (Fig 3).

- 1 global coordinate system (CS) CS0.
- 3 coordinate systems CS1, CS2, CS3 associated with the axes of movement of the machine x, c, z respectively.
- 1 coordinate system associated with the tool CSR.
- 1 laser tracker coordinate system CSLT.

The machine configuration XCFZ determines the placement of the LT on the rotary table associated with the movement of rotation axis around the z-axis. Meanwhile the reflector will occupy the position reserved for the tool (Fig 4).

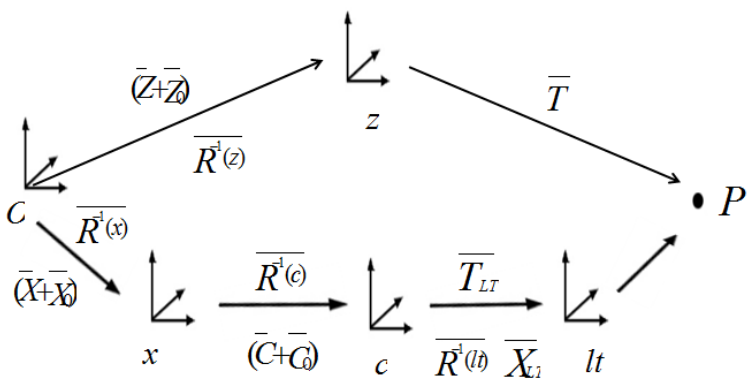

Fig. 4: Kinematic model of a machine with XCFZ configuration

$$\overline{X_{LT}} = \overline{\overline{R}}^{-1}(lt)\left(\overline{\overline{Rg}}(c)\overline{\overline{R}}(c)\overline{\overline{R}}(x)\left(\left(\overline{Z}_0 + \overline{Z}\right) + \overline{\overline{R}}^{-1}(z)\overline{T} - \overline{X} - \overline{\overline{R}}^{-1}(x)(\overline{C}_0 + \overline{C})\right) - \overline{T_{LT}}\right) \quad (3)$$

$\overline{T}$ represents the milling tool offset.

$$\overline{T} = \begin{pmatrix} x_T \\ y_T \\ z_T \end{pmatrix} \quad (4)$$

$\overline{\overline{R}}(k)$ represents the rotation error matrix on the k axis of the machine tool with: EAK roll error of axis *K,* EBK yaw error of axis K and ECK pitch error of axis *K* with $k = X, C, Z$

$$\overline{\overline{R}}(k) = \begin{pmatrix} 1 & ECk & -EBk \\ -ECk & 1 & EAk \\ EBk & -EAk & 1 \end{pmatrix} \tag{5}$$

$\overline{\overline{Rg}}(c)$ represents the rotational matrix around *z-axis.*

$$\overline{\overline{Rg}}(c) = \begin{pmatrix} Cos(c) & -Sin(c) & 0 \\ Sin(c) & Cos(c) & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{6}$$

$\overline{X}$ represents the linear error vector in the x-axis of the machine with: EXX, linear positioning errors for *X-axis*; ECX, straightness errors between C and X- axis; EZX, straightness errors between Z and X- axis.

$$\overline{X} = \begin{pmatrix} -X + EXX \\ ECX \\ EZX \end{pmatrix} \tag{7}$$

$\overline{C}$ represents the linear error vector in the c-axis of the machine with: EXC, straightness errors between *X* and *C- axis*; ECC: linear positioning errors for *C-axis;* EZC: straightness errors between *Z* and *C- axis*.

$$\overline{C} = \begin{pmatrix} EXC \\ ECC \\ EZC \end{pmatrix} \tag{8}$$

$\overline{Z}$ represents the linear error vector in the z-axis of the machine with: EXZ, straightness errors between *X* and *z- axis*; EYZ, straightness errors between *Y* and *Z- axis*; EZZ, linear positioning errors for *Z-axis* ; EBO, Squareness error *Y;* EAO, Squareness error *X*

$$\overline{Z} = \begin{pmatrix} EXZ - Z \cdot EBO \\ EYZ - Z \cdot EAO \\ Z + EZZ \end{pmatrix} \tag{9}$$

$\overline{X}_{LT}$ translation vector between LT coordinate system LT (CSLT) and MT coordinate system (CSMT)

$$\overline{X}_{LT} = \begin{pmatrix} x_{LT} \\ y_{LT} \\ z_{LT} \end{pmatrix} \tag{10}$$

$\overline{\overline{R}}(lt)$ rotation matrix between CSLT and CSMT.

$$\overline{\overline{R}}(lt)=\begin{pmatrix}1 & R_{LTz} & -R_{LTy}\\ -R_{LTz} & 1 & -R_{LTx}\\ R_{LTy} & -R_{LTx} & 1\end{pmatrix} \tag{11}$$

$\overline{W}$ represents the part coordinates.

In an ideal kinematic model, at P (0, 0, 0) all CSs are at the origin of the global system CS0.Therefore, all axes should be cut in space. This hypothesis is discarded due to the kinematic structure that describes the layout of the elements responsible for the movement. Therefore, it is necessary to introduce an offset between each axis $\overline{C_0 Z_0}$, which will be considered depending on the software for control of the MT.

$$\overline{C_0}=\begin{pmatrix}XOC\\ YOC\\ ZOC\end{pmatrix} \tag{12}$$

$$\overline{Z_0}=\begin{pmatrix}XOZ\\ YOZ\\ ZOZ\end{pmatrix} \tag{13}$$

3. Regression functions for multi-axis machines

Volumetric error reduction depends on polynomial regression functions used to characterize the geometric errors .To realise a proper volumetric verification of any machine tool with rotational axes, such as XCFZ, it is necessary to obtain the approximation functions of each of the errors of a rotational axis, as well as approximation functions of lineal ones.

The characterization of errors of a linear axis is done using simple, Legendre or Chebyshev polynomials as regression functions from which the error function is characterized [5,6]. The influence of polynomial regression functions in error reduction are widely study on other papers.

$$\tilde{f}(x)=a_0+a_2x+a_2x^2+...+a_nx^n \tag{14}$$

Equation 13 presents the approximation function of a geometric error in a lineal axes, where a_i represent the optimization parameters to identification. From which, the effect of the lineal axis geometrical errors on *ve* are minimized obtaining $\tilde{f}(x)$.

The physical behaviour of the geometric errors on rotary axis makes it impossible to characterize them by a simple polynomial of order three. This is due to the periodic behaviour of these geometric errors. To realize a better characterization of the errors, periodic functions must be used.

$$\tilde{f}(x)=\sum_{i=1}^{n} A_i\cdot sen\left(\frac{2\pi}{T}\cdot\theta_{i\,z}+\varphi_i\right) \tag{15}$$

Where A_i and B_i are the amplitude of the error, T period error, θ_z the rotated angle in each position and φ_i offset of the origin.

4. Measurement strategies to be used in relation with available space to measure

To tackle the volumetric verification of a machine with linear and rotational axis XCFZ, the method of optimization is extended in comparison with the methods for machines with three linear axe [5, 6].

In order to realise the characterization of all geometric errors of a machine regardless of the measurement strategy to used, it is necessary to place the LT on a profile attached to the turntable. Consequently, the LT is available to measure the range of axes x and z in different positions of c between 0º and 360º. This measurement method is limited; either by protective housings of the machine or by the structure of it, therefore the range of the axes to measure depends on the strategy selected (Fig. 5).

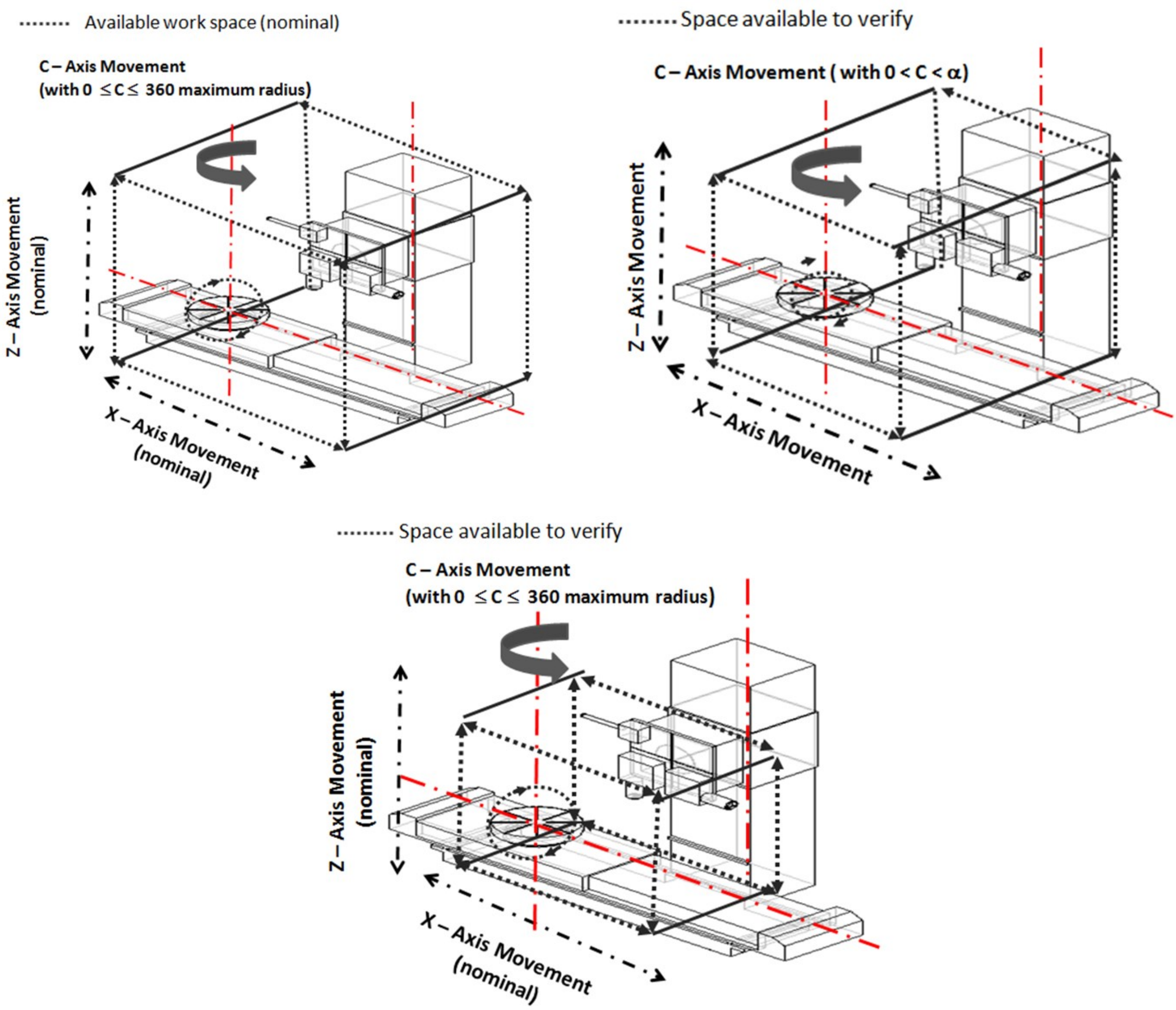

Fig. 5: Space available to verify in relation with machine tool protective housings and measurement strategy. A) Without restrictions. B) With restrictions in C axis. C) With restrictions in X-Z axes.

Depending on the available space to measure (Fig. 5), the optimization methods are divided in:

1. Joint optimization of the errors from linear and rotational axis. The use of joint optimization as a technique of volumetric verification requires that a plane of point XY could be measured in different positions of C axis (Fig.5 A). This plane is limited either by the housings for the protection of the machine or by the structure of the same, leaving limited the volume of the machine used in the verification (Fig. 5 C or F ig. 5 B).
2. Independent optimization of linear and rotational axes. This strategy requires two independent measurements. In the first one, a set of points forming a XZ plane is measured in a position of C (Fig.5 B). This measurement is used to characterize only error of the linear axes. The second measurement is formed by a point XZ which is measured in different positions of C. From which, the geometrical errors of the rotary axis are characterized (Fig. 5 C).

3. Combined optimization of linear and rotational axes. This method requires of two tests. In the first test, a plane of points in C=0 is measured. It is used to realise an independently geometrical error characterization of lineal axis (Fig.5 B). Once these errors are characterized, a new plane XZ which is capable of being measured at different position of C is measured, test 2. This test is influenced by rotational and lineal axes errors (Fig. 5 C).

5. Test and results

Using the parametric synthetic data generator [], an extensive study of the different verification methods of a machine tool with configuration XCFZ are realised.

Characterizing the error of the rotation axis, Table 1, performs the measurement of two points formed by the offset of the reflectors from 0 ° to 360 ° in 5 ° intervals. Similarly, the characterization of the linear axis error was made by measuring a grid of points in C XZ = 0 with 0 ≤ X ≤ ≤ Z 1400 0 ≤ 600, Table 2.

Table 1. Characterization of rotary axis

Average Initial Error (µm)	**194.91**
Maximum Initial error (µm)	**213.46**
Average Final Error (µm)	112.57
Maximum Final Error (µm)	186.06
Residual Error (%)	**57.75**

Table 2.Characterization of lineal axes

Average Initial Error (µm)	**598.48**
Maximum Initial error (µm)	**978.03**
Average Final Error (µm)	122.38
Maximum Final Error (µm)	347.72
Residual Error (%)	**21.01**

If instead of performing a separate characterization of the different axes of movement, it is performed a joint optimization with which a lower error reduction is obtained (Table 3). However, these results are extrapolated to all work space. It is due to points used in the characterization of the errors are affected by errors of lineal and rotary axis.

Table 3. Joint characterization

Average Initial Error (µm)	**555.84**
Maximum Initial Error (µm)	**987.67**
Average Final Error (µm)	114.11
Maximum Final Error (µm)	247.98
Residual Error (µm)	**20.53**

The behaviour of the machine and the value of the errors before and after compensation can be observed using coloured maps and histagrams.

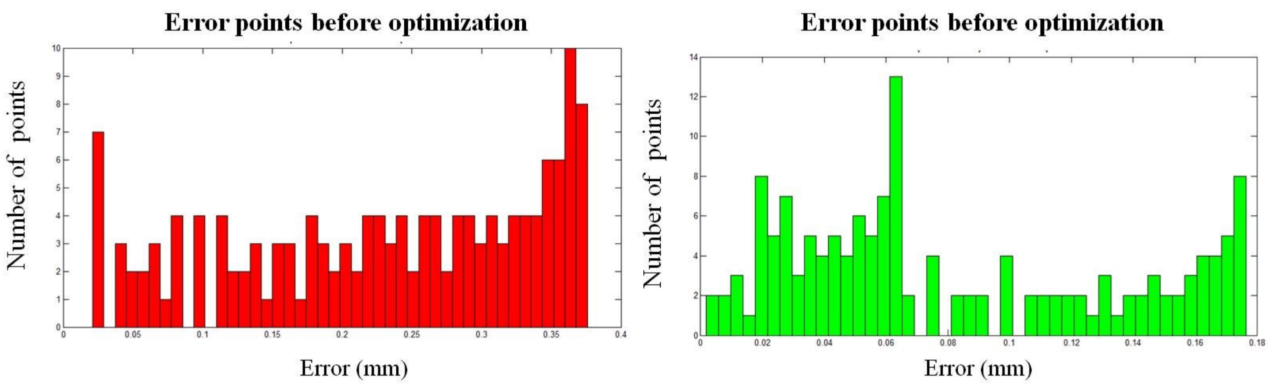

Fig. 6: Uncompensated errors (l.) – Compensated errors. (r.). Histogram

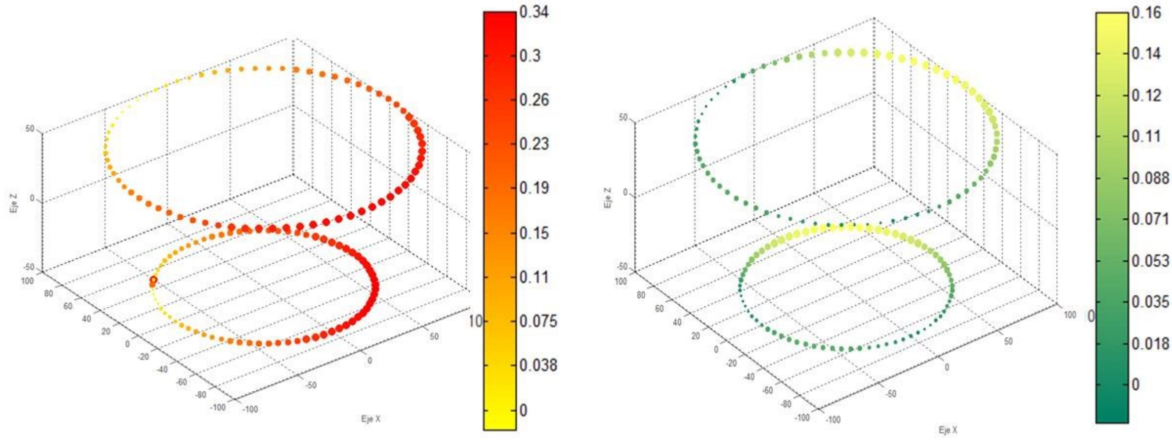

Fig. 7: Uncompensated errors (l.) – Compensated errors. (r.). Color maps

The color map of figure 7 provides information on the error reduction at each of the point of the workspace. Histogram of figure 6 provides information about volumetric error in all workspace regardless of working area.

Summary

The approximation functions obtained by intensive process of parameter identification provide a mathematical compensation of the combined effect of all geometrical errors.

The use of LT as measurement system, which works with an absolute coordinate system, requires the incorporation of this into the kinematic model of the machine tool. The LT will occupy the position of the part meanwhile the reflector will occupy the position reserved for the tool. Likewise, when you are working with machine with rotary axis is required the incorporation of rotation matrix of the rotary axes.

The availability of space in verification limits the work space to measure and the method of measurement to use. If there are spacial limitations, a combined optimization of the different types of axis is the best choice.

Acknowledgements

This work was supported by the DICON Innpacto Project (2011-2014). Development of new advanced dimensional control in manufacturing processes high-impact sectors.

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