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Analysis of the measurement capacity of a machine tool

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Abstract

Industrial sectors that demand manufacturing of high quality components within specified tolerances are looking for cost reductions without affecting the quality of the product. The verification of workpieces is normally carried out in post-process with coordinate measuring machines which increase the manufacturing cycle time. Machine tools can carry out contact measuring operations with a probe, and since there is a growing need to inspect the workpieces in process, using the machine tool itself for verification while the workpiece remains clamped to the machine can lead to an improvement in manufacturing times, reduction of costs and energy saving.

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Keywords: Machine Tool; Measurement; Uncertainty.

Nomenclature

MT	Machine Tool
CMM	Coordinate Measuring Machine
LT	Laser Tracker

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1. Introduction

Industrial sectors such as aeronautics, automotive, renewable energies, etc. demand the manufacturing of large-scale components with high precision. The transportation of these large-scale components to an environmentally controlled metrological laboratory is a difficult task which leads to increases in manufacturing times and increase in costs, and sometimes the workpieces are too large to fit in a Coordinate Measuring Machine (CMM). They have to be measured in process. To reach this goal, traceable dimensional metrology techniques must be incorporated in the Machine Tool (MT) in order for the resultant manufacturing program to produce the desired output within the specified tolerance [1]. The integration of the workpiece verification process into the MT can reduce the manufacturing time as there is no need of transportation of the workpiece to a measurement laboratory. While the workpiece remains clamped in the MT, the same coordinate system used during the manufacturing process can be used in measurements and in re-works, reducing manufacturing times, machining waste materials and therefore reducing costs without losing product quality.

MT errors are the difference between the actual tool path and the desired path. Errors can be classified in two categories namely quasi-static errors and dynamic errors. Quasi-static errors are those between the tool and the workpiece that are slowly varying with time and related to the structure of the machine tool itself. These sources include the geometric errors, kinematic errors, thermally induced errors, etc., on the other hand, dynamic errors are caused by sources such as spindle error motion, vibrations, controller errors, etc. [2]. For 3-axis MT, there are 21 components of geometric and kinematic errors: each axis has 6 errors of movement, 3 of rotation and 3 of translation over each axis, and between each pair of axis there is a squareness error. Geometrical errors can be measured individually with direct measurement techniques or all together with indirect measurements. UNE-ISO 230-1:2014 [3] is an international standard that specifies methods for testing the accuracy of machine tools with direct measurements, operating either under no-load or under quasi-static conditions. Indirect measurement produces a global correction of the MT workspace based on multi-axis movement and its kinematic model [4].

In previous work [4,5] measuring a mesh of points of the MT workspace allowed obtaining the approximation functions of each geometric error. A volumetric verification based on non-linear optimization was applied improving MT accuracy. With the approximation functions of the geometric errors obtained in [5] we have developed a program to simulate 1000 volumetric verifications with slight variations on the input parameters in order to estimate the MT uncertainty. We determinate an uncertainty area (U) for each point of the MT workspace, for the case of a three-dimensional measurement, the obtained shape is the ellipsoid with axes ux(P), uy(P), uz(P). The ellipsoid represents the volume in which it is more likely to find the true value of the measured point.

Once the uncertainty for each point of the workspace is determined, it is necessary to check that measurements carried out with the MT are within the uncertainties calculated to assure the traceability on measurements. With this purpose, an object must be measured with the MT and check if the measures are within the uncertainty area.

2. Experimental procedure

The methods and procedures are going to be applied over a 3-axis MT with a XYFZ configuration but can be extrapolated to other cases; in our particular case the MT it is an ANAYAK VH-1800 with computer numerical control (CNC) Fagor 8025. The MT has integrated in its software a matrix of error compensation that can compensate position errors and therefore improve the accuracy. However, during the test presented in this paper, the matrix of compensation is disabled in order to identify the MT geometrical errors.

The object that is going to be measured is a calibrated hole plate of outside dimensions 460 x 460 mm made from aluminum. The nominal distance between rings centers is 50 mm. It is important to know the coefficient of thermal expansion of the plate corpus ($\alpha_{plate}=24 \cdot 10^{-6}\ K^{-1}$) and monitor the plate temperature during the measurements in order to compensate for possible errors due to thermal expansion.

Twenty eight holes of the calibrated plate are measured. For each hole, four points are measured to determine the best fitted circle center. Each point is measured at the same time by the MT, using a probe, and with a Laser Tracker (LT), with the retro-reflector magnetically attached to the probe. When the probe makes contact with the hole plate on the point that is going to be measured, the MT pauses so the LT can also measure the same point.

The plate hole was clamped into the MT the day before the measurement to be thermally stabilized. The MT is switched on around one hour before starting measurements for an appropriate warm-up. The origin of the MT coordinate system is set on the center of the first hole, as shown in Fig. 1. The measurement strategy consist on first locate the probe near to the center of the hole to be measured. Next, the probe descends to a determined Z-coordinate (all the holes will be measured at the same Z-coordinate) the order of measurement of the four points are: first the point situated on +X with respect to the center, after that the point situated on –X, after that the probes goes to the center and measures the point on located +Y and finally the point on –Y. Once the four points of the hole have been measured the probe goes to the center of the hole, ascends on the coordinate +Z and goes to the next hole to be measured. The holes are measured in spiral as shown in Fig. 1 because it has been simulated that with this strategy the effect of clearance is reduced.

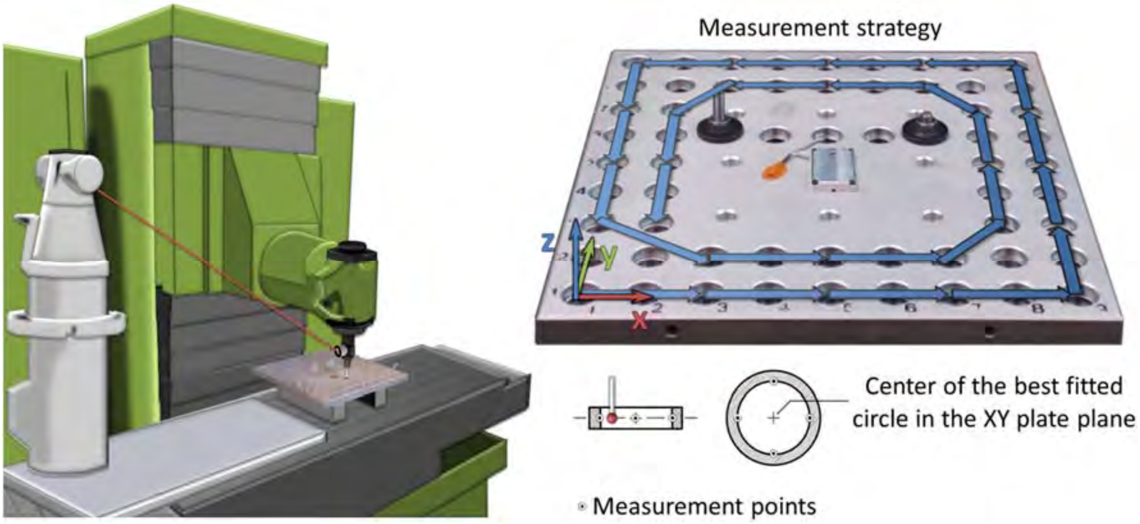

Fig. 1. Measurement configuration and strategy.

With the four points taken the best fitted circle center is calculated in each hole. As the plate was misaligned, it is necessary to rotate the coordinates by multiplying with a rotation matrix:

$$R=\begin{bmatrix}\cos\theta & \sin\theta & 0\\ -\sin\theta & \cos\theta & 0\\ 0 & 0 & 1\end{bmatrix} \tag{1}$$

Where θ is the angle of misalignment between the measured coordinates and to the nominal coordinates. However, as the measurements are going to be compared with its nominal coordinates, which are referred to the plate at 20 ºC, it is necessary to correct the thermal expansion of the plate. For simplicity, a linear behavior is considered starting from the clamping point (which is located on the position X=200 mm, Y=250 mm), according to the equation:

$$d_f = d_0 \cdot \left[1+\alpha_{plate}\cdot\left(T_{plate}-20\right)\right] \tag{2}$$

Where d_0 and d_f are the distance between the clamping point and the center of the hole before and after applying the correction, α_{plate} is the coefficient of thermal expansion of the plate and T_{plate} is the temperature of the plate in ºC at the moment when the hole is being measured.

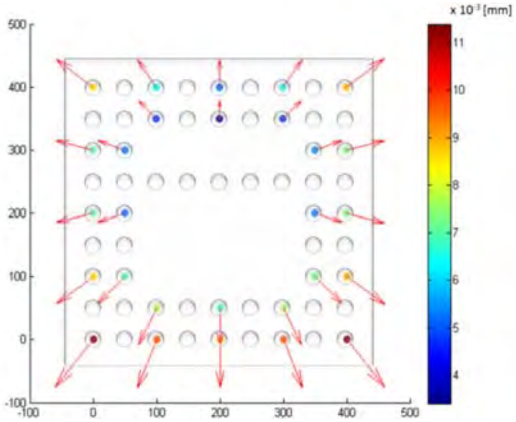

Fig. 2. Correction of the thermal expansion.

As the misalignment and the thermal expansion of the hole plate are not MT errors, they have been compensated to make possible the comparison between the nominal coordinates and the coordinates measured with the MT. Since the measurements are being carried out under quasi-static conditions, the error obtained will be due to the MT geometrical, kinematic and thermally induced errors.

3. Results

The methods and procedures are going to be applied over a 3-axis MT with a XYFZ configuration but can be extrapolated to other cases;

3.1. Simulations

With the nominal coordinates of the calibrated plate, the measured coordinates obtained measuring 28 holes and the equations of the kinematic model; it is possible to develop a volumetric verification to determine the approximation function of error of the system MT+LT.

To obtain the uncertainty, we use the Monte Carlo Method performing simulations varying slightly the input parameters such as LT noise [6]. One thousand test are generated, therefore we have 28000 simulated hole centres with which we have calculated the new 1000 approximation functions of errors. Fig. 3 shows the error distribution of these 28000 points.

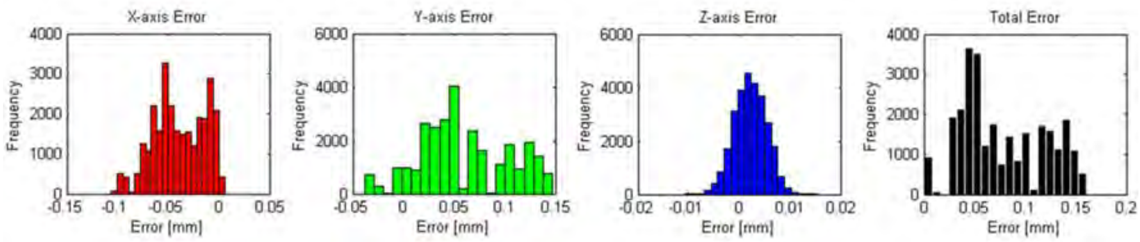

Fig. 3. Error distribution of the simulated mesh before the optimization.

With the 1000 approximation functions of error simulated, non-linear optimization can be used to reduce the MT errors. After applying the optimization compensating the errors, the result obtained are the best fitted coordinates of the holes centres. The error distribution of the 28000 points after optimization can be seen in Fig. 4.

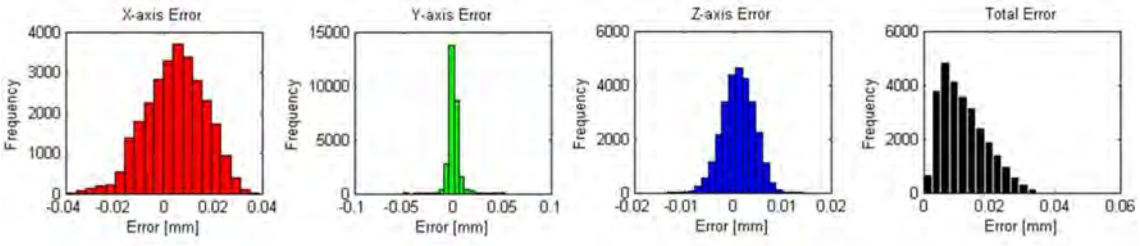

Fig. 4. Error distribution of the simulated mesh after the optimization.

The average error of each hole is considered as a systematic error (b) in that position of the MT workspace, while the standard deviation is part of the uncertainty of the measurement procedure (u_p).

3.2. Uncertainty evaluation

The standard ISO/TS 15530-3:2011 [7] provides an experimental technique for the uncertainty evaluation of CMM measurements. The discussed standard describes the uncertainty evaluation procedure for both parts: experiment and calculation. The expanded uncertainty is calculated as:

$$U = k \cdot \sqrt{u_{cal}^2 + u_p^2 + u_b^2 + u_w^2} \tag{3}$$

Where u_{cal} is the standard uncertainty associated with the uncertainty of the calibration, u_p is the standard uncertainty resulting from the measurement procedure, u_b is the standard uncertainty associated with the systematic error b, u_w is the standard uncertainty resulting from material and manufacturing variations (due to variations of the expansion coefficient, form errors, roughness and elasticity) and k=2 for a coverage probability of 95%.

If the manufacturer do not provide the value of u_{cal}, it can be estimated with the maximum permissible error of the CMM used in the calibration of the plate. In our case, the manufacturer provided that value:

$$u_{cal} = 1.45 + \frac{L}{500} \tag{4}$$

The value of u_p can be calculated in each workspace position as two times the standard deviation of the simulated mesh of points at that position. In our case this value takes values between 4.2 and 15.95 µm, depending on the workspace position.

According to the Guide to the expression of Uncertainty in Measurement (GUM) [8], u_b is calculated as a type A uncertainty, therefore:

$$u_b = \frac{\sigma}{\sqrt{n}} \tag{5}$$

Where σ is the standard deviation of the systematic error b and n is the number of simulated values. The value of u_b is negligible as σ has a small value and n=1000.

The value of u_w has to be estimated. As we have compensated the thermal expansion, our uncertainty due to thermal expansion is related with the possible error that the sensor is committing measuring the temperature of the plate. Assuming that the accuracy of our sensor is ± 0.2 ºC with a rectangular distribution, u_w can be calculated as:

$$u_w = \frac{\Delta L}{\sqrt{3}} = \frac{\alpha \cdot \Delta T \cdot L}{\sqrt{3}} = \frac{24 \cdot 10^{-6} \cdot 0.2 \cdot 400}{\sqrt{3}} = 0.00111 mm = 1.11 \mu m \tag{6}$$

If the MT user is not measuring the temperature of the workpiece and compensating the effect of thermal expansion, this lack of information should be added in this term of uncertainty.

The result of a measurement should be expressed as:

$$Y = y + b \pm U \tag{7}$$

Where Y is the expression of the measurement, y is measured value, b is the systematic error and U is the expanded uncertainty.

Fig. 5 shows the systematic error (b) in every position of the MT workspace.

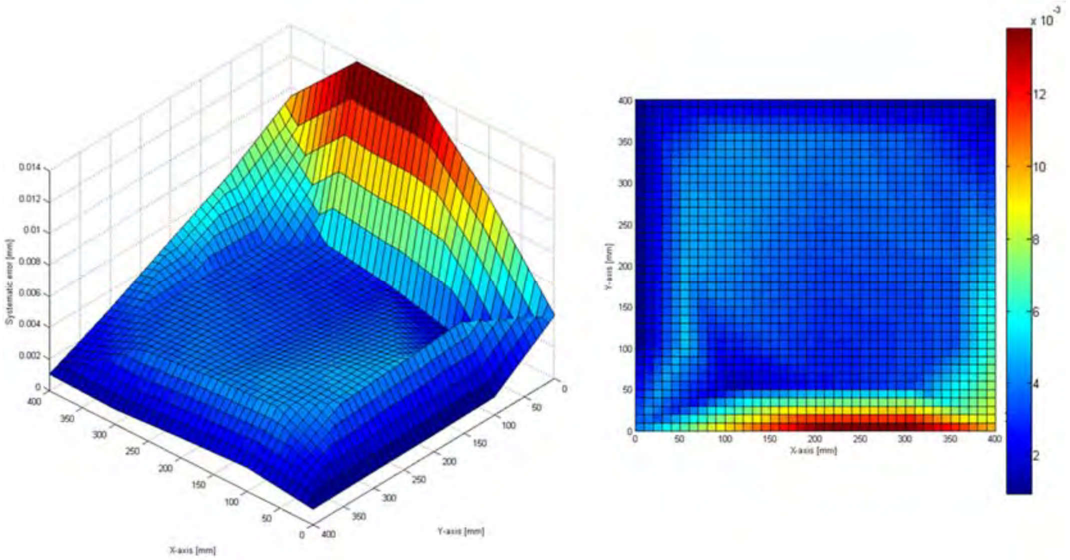

Fig. 5. Systematic error of the workspace.

This systematic error is a residual error that remains on the MT after applying the compensation according to the kinematic model and the approximation functions. Therefore, should be added on the expression of a measurement result with the expanded uncertainty, which value in the workspace is shown in Fig. 6.

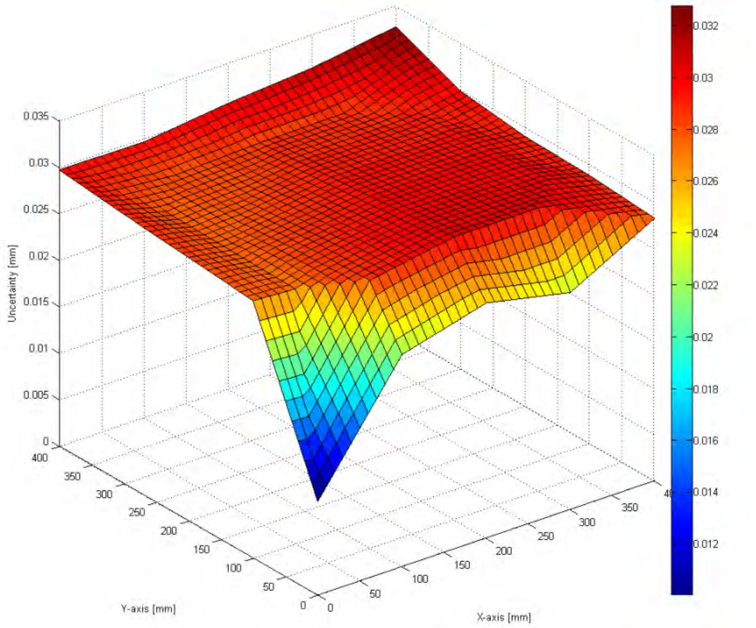

Fig. 6. Expanded uncertainty of the workspace.

In our simulations, the component u_p is the one that has the most influence (around 76.2% of the total uncertainty comes from this component while u_w represents around the 6.5% and u_{cal} the 17.3%). But that is because the temperature was monitored and therefore the uncertainty is reduced, if the user do no monitor the temperature and do not correct the effect of thermal expansion, assuming that temperature of the plate is inside the interval of 20 ± 2 ºC, the u_w component would be greater and would even have the same importance as the u_p component of uncertainty.

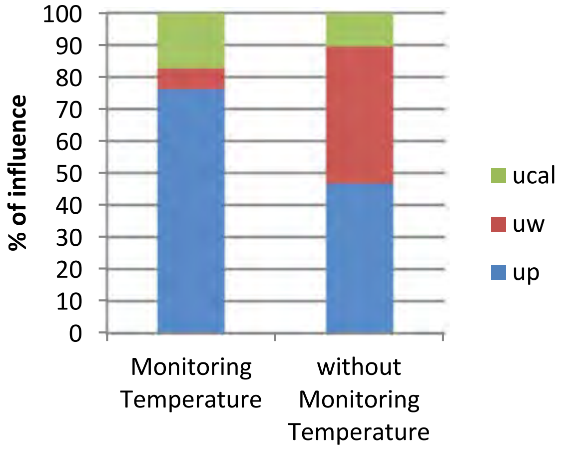

Fig. 7. Percentage of influence of each component of the expanded uncertainty.

The standard uncertainty resulting from material and manufacturing variations can also be reduced by using a calibrated workpiece made of materials with lower coefficient of thermal expansion such as Invar or Zerodur.

4. Conclusions

The capability of a MT as a measuring machine depends on a proper estimation of a measurement uncertainty. With the standard ISO/TS 15530-3:2011 [7] and the indications of the “Guide to the expression of uncertainty in measurements” (GUM) [8], we have estimated the uncertainty area in a delimited area of the MT workspace.

We have determinate a strategy of measurement and we have measured a calibrated object. After performing a volumetric verification the approximation functions of the geometric errors can be calculated and using Monte Carlo Method we have estimated the uncertainty. Applying non-linear optimization the coordinates measured can be corrected; to assure the traceability of the MT the corrected coordinates must be inside the uncertainty volume estimated. In this paper the different components that affect uncertainty have been discussed and calculated for a real milling machine with XFYZ configuration.

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