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Monte Carlo method to machine tool uncertainty evaluation

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Abstract

Currently machine tools are not only a way to make different parts based on material removal processes. These ones can be used as a measurement system too. In this way, overall inspection time is reduced and equipment productivity is increased.
Nevertheless, the use of machine tool probes as measurement tool in manufacturing parts required previous works. Firstly, the machine tool accuracy should be improved, in order to reduce the influence of its geometric errors. This way, volumetric verification based on laser tracker measurement has increased strongly in the last few years, especially in long range machine tools. Secondly, calibration uncertainty should be calculated to provide measurement uncertainty.
This way, the paper presents a new tool able to analyze the effect of different influence verification parameters in calibration uncertainty based on Monte Carlo method. Using real tests carried out on a milling machine and its geometric errors, the influence or laser tracker measurement noise in calibration uncertainty is studied using Monte Carlo method.

Keywords: Volumetric verification; laser tracker; machine tool; uncertainty; Monte Carlo.

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1. Introduction

Machine tool calibration (MT) is defined as the process from which the influence MT geometric errors is obtained. This way, the MT accuracy is increased reducing the influence of these systematic behavior through software compensation.

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Currently there are two different ways to obtain MT geometric errors. First one, determines the influence of each error from each axis in a particular position of the workspace of the MT [1]. Second one, indirect measurement method, obtain the joint influence of MT geometric errors based on multi-axis movement and MT kinematic model [2]. Meanwhile direct measurement provides the real physical behaviour of each error, indirect one provides a join optimum values. However, the relationship between geometric errors obtained using direct measurement is not studied and approximation functions obtained are directly extrapolated to all MT workspace. Similarly, each error needs an own assembly measurement procedure and data treatment; increasing substantially verification time. These are the principal reasons why volumetric verification (VV) based on indirect measurement errors using laser tracer, laser tracker or ball bar as measurement systems, are daily more popular than geometric verification, based on indirect measurement using laser interferometer, levels, etc.

Calibration process result is associated with calibration uncertainty value. It characterizes results dispersion in relation with geometric errors obtained and sources of errors that affect it. This one is considered especially relevant in different manufacturing and quality assurance processes. It is required when the MT is used as measurement system; providing metrological characteristic required to obtain a traceable measurement system.

The International Organization for Standardization (ISO) has developed and published different guidelines for the representation of measurement uncertainty (GUM), such as the UNE-ISO / TR 230-9 [3] standard for measurement uncertainty estimation for machine tool test, or ISO / TS 14253-2 [4], widely accepted. It combines the estimation of the different sources of error and their associated typical uncertainties, to determine the typical uncertainty associated with the overall process. This way, accuracy and metrological characteristic of a MT as measurement system are related to measurement system used, machine tool and calibration conditions. The GUM provides the basic framework for evaluating uncertainty in measurement, but it does not work properly in non-lineal process such as MT calibration based on VV. As errors that affect to VV have a random and probabilistic behavior, Monte Carlo method is recommended to obtain its uncertainty.

This paper presents a new simulation software developed to study how different factors with influence in volumetric verification affect to calibration uncertainty. The software allows the use of different probabilistic error functions (PDFs) to characterize the behaviour of each error source. Within different sources of uncertainty, this paper is focused on the study of laser tracker measurement noise influence. So, using a real milling machine with XFYZ configuration, a LT Leica LT 600 and a probe as measurement system and our own developed software, real tests have been carried out.

2. Comparison of the GUM and Monte Carlo Method to determine the uncertainty of a machine tool volumetric verification process

2.1. Volumetric verification and influence factors

Volumetric verification is based on an intensive process of parameters identification through the kinematic model of the MT. Minimizing the difference between theoretical and real pair of points, through the MT kinematic model, the joint influence of MT geometric errors are obtained. Their behavior are modeled minimizing the mean square volumetric error of the machine (Ev) using non-lineal optimization techniques [2].

As shows Fig. 1, principals' uncertainty sources with influence on machine tool verification are divided in three groups: machine tool, measurement and verification, and measurement system uncertainties.

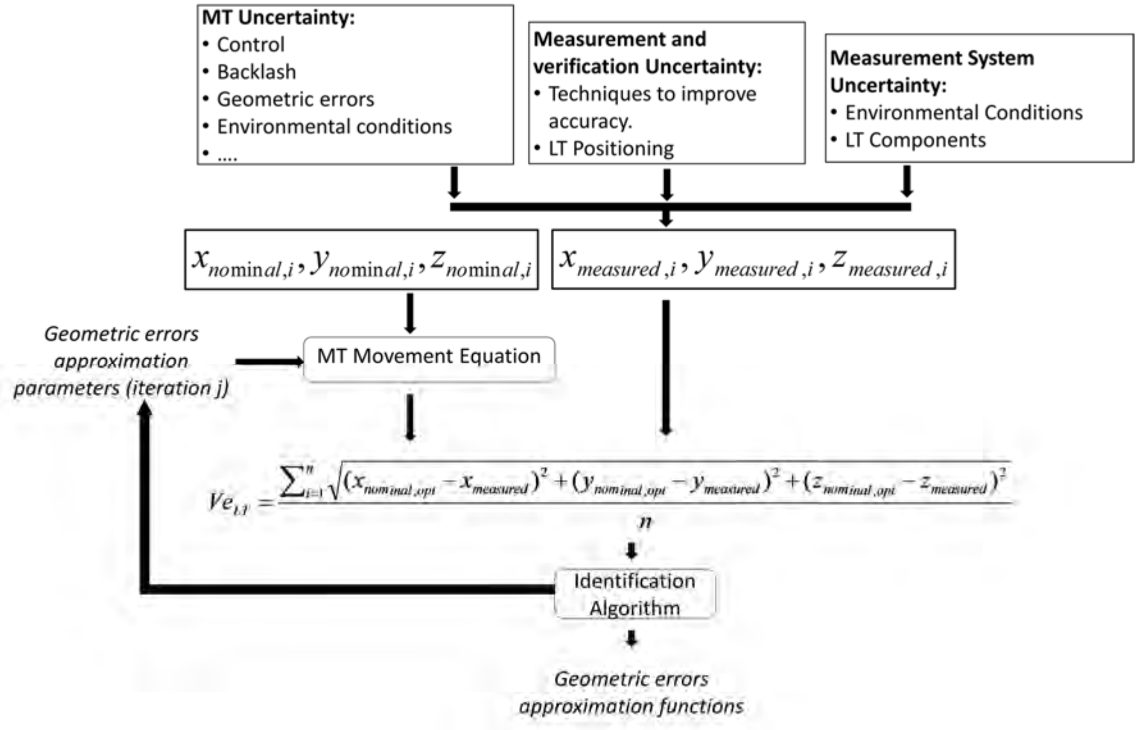


Fig 1. Volumetric verification scheme taking into consideration uncertainty sources.

2.2. Main differences between GUM and Monte Carlo

The Monte Carlo Method (MCM) is a tool that uses the computational capacity of currents computers to simulate a high account of pseudo random numbers. This way, it allows to simulate complex system from a probabilistic point of view [5].

Meanwhile the GUM is focused on evaluate Type A, Type B and combined uncertainties, the MCM uses a large number of samples, with different probabilistic functions, to obtain the final uncertainty distribution (Fig. 2).

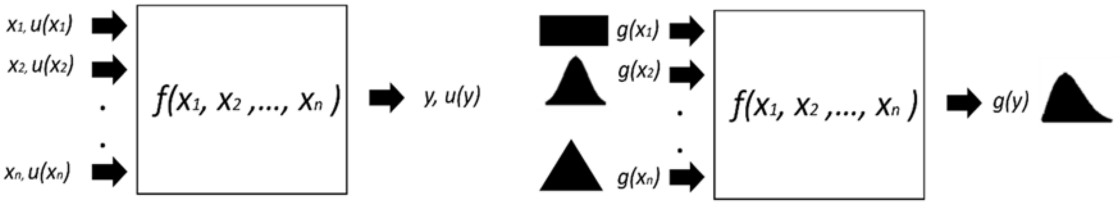


Fig 2. Propagation of uncertainties based on GUM – left – propagation of distribution based on MCM– right.

However, the estimation of uncertainties using GUM is based on assumptions that are not always fulfilled. These adequacy limitations of the GUM are given by:

- The non-linearity of the mathematical model that describes the process. When the model presents strong elements of non-linearity, the approximation made by the GUM approach may not be enough to correctly estimate the uncertainty output.

- Validity of the central limit theorem, which states that the convolution of a large number of distributions has as result a normal distribution. However, the result distribution in different real cases presents an asymmetric behavior invalidating the central limit theorem.
- Expanded uncertainty calculated by the GUM does not always present an analytical solution.
- The input quantities are not symmetrical, or one or more of the input sources are much larger than the others.
- The magnitude order of the output quantity estimate and associated standard uncertainty are approximately the same.

The GUM Supplement 1 provides a sequence of steps to be followed similarly as to what is done in the GUM (Fig. 3).

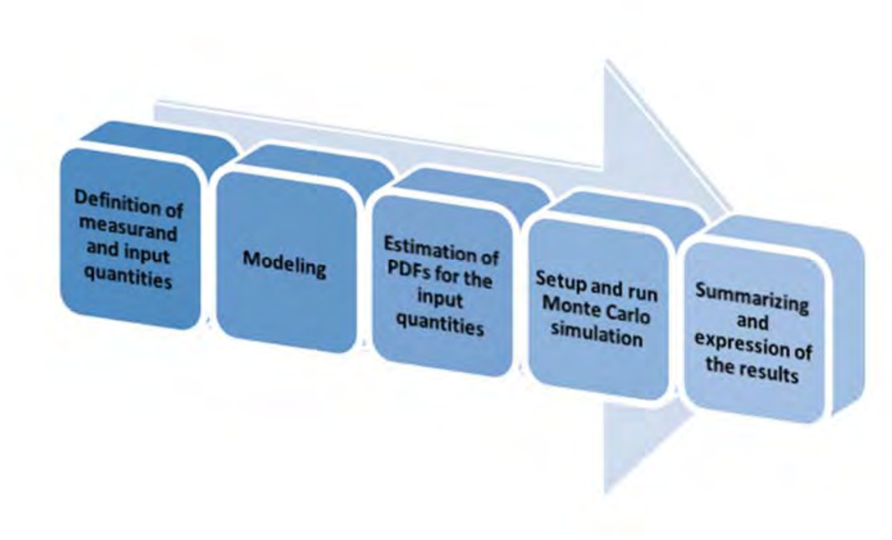


Fig 3. Sequence of steps to used MCM.

3. Methodology and results

First at all, it is necessary to determine and obtain the kinematic of the machine tool to verify. In this case, it's a MT with XFYZ configuration, whose equation of movements that relates the nominal coordinates of the MT with the measured coordinates of the laser tracker through MT geometric errors and MT characteristics is presented in equation 1.

$$\overline{X_{LT}} = \overline{R_{LT}^{-1}} \left(\overline{R_X^{-1}} \left(\overline{R_y} \left(\overline{R_z}\, \bar{T} + \bar{Z}\right) + \bar{Y} - \bar{Z}\right) - \overline{T_{LT}}\right) \tag{1}$$

$\overline{T_{LT}}$ represents the translation vector between the coordinate system of the machine CSO and the laser tracker CSLT.

$$\overline{T_{LT}} = \begin{pmatrix} oX_{LT} \\ oY_{LT} \\ oZ_{LT} \end{pmatrix} \tag{2}$$

$\overline{R_{LT}}$ represents the Olinde-Rodrigues matrix θ between the laser tracker coordinate system and machine tool coordinate system around a unitary vector u = (u_x, u_y, u_z), where $u_x^2 + u_y^2 + u_z^2 = 1$.

$$\overline{R_{LT}} = \begin{pmatrix} \cos(\theta) + u_x^2(1-\cos(\theta)) & u_xu_y(1-\cos(\theta)) - u_z\sin(\theta) & u_xu_z(1-\cos(\theta)) + u_y\sin(\theta) \\ u_xu_y(1-\cos(\theta)) + u_z\sin(\theta) & \cos(\theta) + u_y^2(1-\cos(\theta)) & u_yu_z(1-\cos(\theta)) - u_x\sin(\theta) \\ u_xu_z(1-\cos(\theta)) - u_y\sin(\theta) & u_yu_z(1-\cos(\theta)) + u_x\sin(\theta) & \cos(\theta) + u_z^2(1-\cos(\theta)) \end{pmatrix} \quad (3)$$

$\overline{X_{LT}}$ are the coordinates of a machine point measured with the laser tracker.

$$\overline{X_{LT}} = \begin{pmatrix} X_{LT} \\ Y_{LT} \\ Z_{LT} \end{pmatrix} \quad (4)$$

$\bar{T}$ is the offset of the tool.

$$\bar{T} = \begin{pmatrix} x_t \\ y_t \\ z_t \end{pmatrix} \quad (5)$$

$\overline{R_k}$ represents the rotational error matrix in axis k of the tool with $k = x, y, z$

$$\overline{R_k} = \begin{pmatrix} 1 & -\varepsilon_{z,k} & \varepsilon_{y,k} \\ \varepsilon_{z,k} & 1 & -\varepsilon_{x,k} \\ -\varepsilon_{y,k} & \varepsilon_{x,k} & 1 \end{pmatrix} \quad (6)$$

$\bar{X}$ represents the linear error vector in the X axis of the milling machine.

$$\bar{X} = \begin{pmatrix} -x + \delta_{x,x} \\ \delta_{y,x} \\ \delta_{z,k} \end{pmatrix} \quad (7)$$

$\bar{Y}$ represents the linear error vector in the Y axis of the milling machine.

$$\bar{Y} = \begin{pmatrix} \delta_{x,y} - y \cdot S_{xy} \\ y + \delta_{y,y} \\ \delta_{z,y} \end{pmatrix} \quad (8)$$

$\bar{Z}$ represents the linear error vector in the Z axis of the milling machine.

$$\bar{Z} = \begin{pmatrix} \delta_{x,z} - z \cdot S_{xz} \\ \delta_{y,z} - z \cdot S_{yz} \\ z + \delta_{z,z} \end{pmatrix} \quad (9)$$

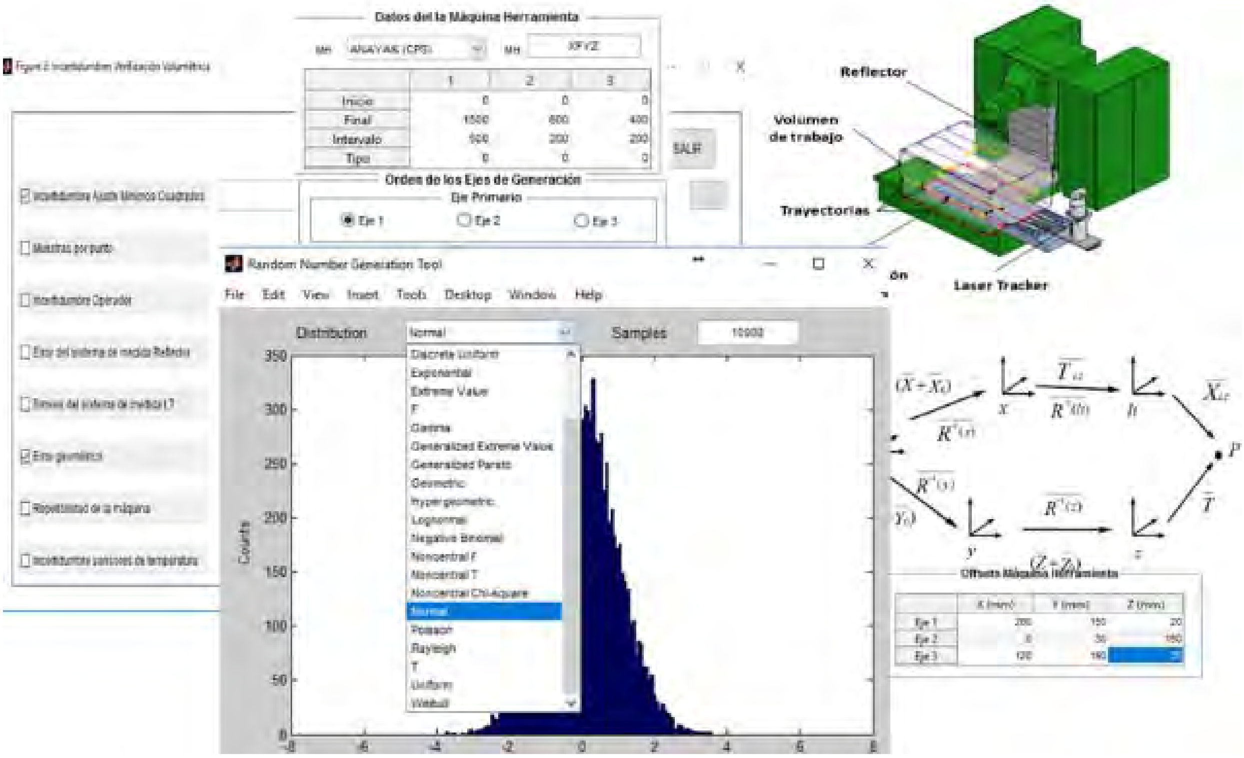
Where $\varepsilon_{x,k}, \varepsilon_{y,k}, \varepsilon_{z,k}$ are three rotation errors of an axis k = x, y, z; $\delta_{k,k}$ is the position error of axis k = x, y, z; $\delta_{k,j}$ with k ≠ j is the straightness error in the k direction; and S_{xy} S_{xz} S_{yz} are squareness errors.

Once the MT equation movement was obtained, it was verified using VV and a laser tracker LEICA LT600 as measurement system. In the same way, it was redone using a probe as measurement system too. At the end of the process, approximation functions that characterize the influences of all MT geometrical errors were obtained.

Although synthetic error generation functions could be used to define the influence of each geometric error, approximation functions obtained in previous verification were used in order to provide real results. Therefore, approximation functions where used as generation function in Monte Carlo tests.

Developed software takes into account all verification process in Monte Carlo´s simulations. It is divided into: MT characteristic and definition parameters in verification, positioning and measurement noise of the measurement systems, techniques and strategies in verification, uncertainty inputs to consider and random number generation for each input of the uncertainty model (Fig. 4).

As influence to study in this tests is the influence of laser tracker measurement noise, only this influence was introduced. That is to say, there is not influence of: MT uncertainty, verification and verification uncertainty, environmental influences are not considered and LT positioning is accuracy known.



	1	2	3
Inicio	0	0	0
Final	1500	600	400
Intervalo	500	200	200
Tipo	0	0	0

☑ Incertidumbre Ajuste Mínimos Cuadrados
☐ Muestras por punto
☐ Incertidumbre Operador
☐ Error del sistema de medida Reflector
☐ Errores del sistema de medida LT
☑ Error geométrico
☐ Repetibilidad de la máquina
☐ Incertidumbre sensores de temperatura

	X (mm)	Y (mm)	Z (mm)
Eje 1	200	150	20
Eje 2	0	30	180
Eje 3	120	180	[illegible]

Fig 4. Developed software modules.

Laser tracker measurement noise was modelled as a normal distribution with 24 µrad to angular encoders and 4 µm ± 0.8 µm/m to radial error. The relationship between laser tracker and MT coordinate system was defined based on a translation vector defined as X = -863.527mm Y = 194.373 mm Z = 677.782 mm and Euler angles (XYZ) = (0.0339 °, 0.0343 °, 59.4652 °). As results obtained should be used later in order to calculate measurement uncertainty based in probe [6], the MT workspace to verify was defined as a small area of the total MT workspace with 0 mm ≤ X ≤ 400 mm, 0 mm ≤ Y ≤ 400 mm, Z = 0 mm. Taking into consideration these dates and approximation functions obtained previously, one thousand tests were generated. In Fig. 5 are presented histograms of initial errors in X, Y, Z coordinates, as well as distance error. Analyzing all test carried out, the average initial volumetric error is 77.39 µm with a standard deviation of 40.91 µm (these values has been obtained in module, as Fig. 1 shows).

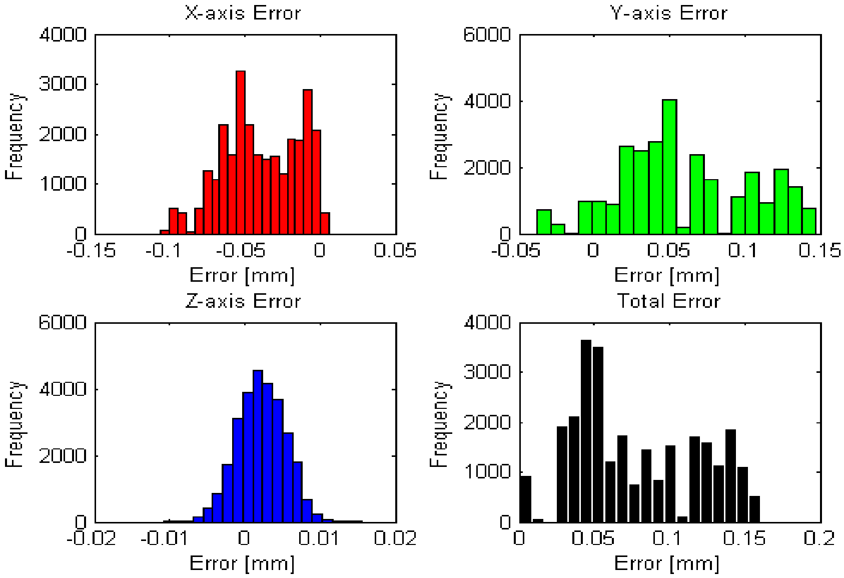


Fig 5. Initial error distribution.

The influence of LT measurement noise in measurement points affect to MT volumetric error and approximation functions obtained after verification process. Therefore, the final error of each point is different for each generated test. Based on Mont Carlo method, the uncertainty of each point after verification process (calibration) can be obtained. A higher number of tests should be required to be sure about PDF calibration uncertainty. Nevertheless, tests carried out are enough to observe uncertainty trend.

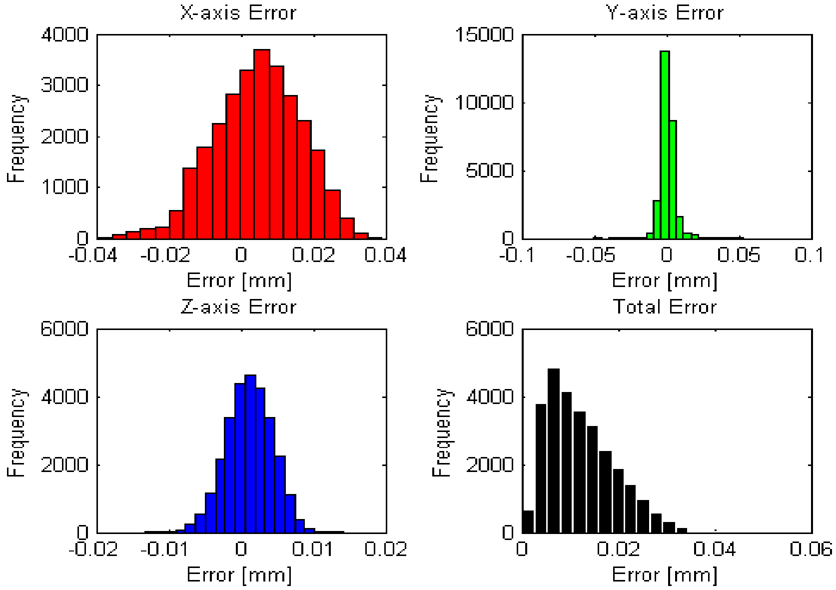


Fig 6. Final error distribution.

As shows Fig. 6 MT volumetric error has been substantially reduced, residual errors are described as normal probability distribution. Providing an average residual error of 12.34 µm and 7.06 µm as standard deviation.

4. Conclusions

MT calibration uncertainty based on volumetric verification using laser tracker as measurement system cannot be obtained using The Guide to the Expression of Uncertainty (GUM). Therefore, Monte Carlo method is required to determine calibration uncertainty.

Monte Carlo method uses the computational capacity of current computers to generate random numbers within different error distribution functions. Real errors functions obtained through volumetric verification allows to study the influence of difference uncertainty sources using the developed software. First tests presented in this paper show that laser tracker measurement noise has a real influence in volumetric verification, providing a calibration uncertainty related only with random errors introduced in measured points. In this way, final volumetric error can be presented as a value defined as residual volumetric error plus an uncertainty value 12.34 µm + 2*7.06 µm. Similarly, developed software allows to calculate the uncertainty of point of the MT workspace used in verification. When the MT is used as measurement system, it is really relevant to determine the measurement uncertainty. It is a quantitative indication of the quality of measurement results, without which they could not be compared between themselves, with specified reference values or to a standard.

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