Uncertainty assessment for on-machine tool measurement: an alternative approach to the ISO 15530-3 technical specification

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Abstract: Touch probes are commonly employed in new machine tools (MTs), and enable machining and measuring processes to occur on the same MT. They offer the potential to measure components, either during or after the machining process, providing traceability of the quality inspection on the MT. Nevertheless, there are several factors that affect measurement accuracy on shop-floor conditions, such as MT geometric errors, temperature variation, probing system, vibrations and dirt. Thus, the traceability of a measurement process on an MT is not guaranteed and measurement results are therefore not sufficiently reliable for self-adapting manufacturing processes. The current state-of-the-art approaches employ a physically calibrated workpiece to realise traceable on-MT measurement according to the ISO 15530-3 technical specification, but it has a significant limitation in that it depends on a physical workpiece to understand the performance of the systematic error contributor (u_b). To this end, the aim of this paper is to propose an alternative methodology for on-MT uncertainty assessment without using a calibrated workpiece. The proposed approach is based on a volumetric error mapping of the MT prior to the measurement process, which provides an understanding of how the systematic error contributor (u_b) performs. An experimental exercise is performed for a medium-size prismatic component according to the VDI 2617-11 guideline, and the results are compared with the ISO 15530-3 technical specification.

Keywords: uncertainty budget; on-machine tool measurement; traceability; uncertainty

1. Introduction

The development of flexible manufacturing processes for high-quality products at low cost is one of the main research objectives in the field of production technology [1]. The quality inspection of high-value components usually takes place on coordinate measuring machines (CMMs), either beside the production line or in an isolated measurement room, so the manufacturing process is interrupted and transportation, handling and the loss of the original manufacturing setup influence the workpiece quality [2] and the overall equipment effectiveness (OEE). The high investment required for a CMM and the above-mentioned limitations show the need for a machine tool (MT) integrated traceable measuring process.

Although on-MT measurement can provide advantages for more flexible and intelligent manufacturing processes, there are also some limitations. The main limitation is that MT time is more expensive than CMM time, so measurements that are executed on an MT should clearly add value to the manufacturing process. Here, it is particularly relevant to determine critical component dimensions and measure them on the MT in order to ensure zero-defect manufacturing processes [3].

The current manufacturing scenario shows that dimensional measurements are already being employed for on-MT measurements at different stages of the manufacturing cycle, mainly because the technology to perform a measurement, either touch-trigger probes (TTPs) or measurement software, are already available on the MT side. There are four potential measurement scenarios where on-MT measurement adds value to the manufacturing process: a) monitoring of the MT geometry performance by employing a calibrated standard; b) workpiece set up on the MT coordinate system; c) in-process measurements to provide correction values for the manufacturing; and d) the performance of a final metrology validation of the finished product for final quality inspection as well as statistical trend analysis of the manufacturing process. Nowadays, depending on the size of the component, traceable on-MT measurement technology readiness levels (TRLs) are at different stages: While large-scale manufacturing processes employ on-MT measurements to reduce the setup time of large components on the MT bed, medium-size aeronautic manufacturers are already performing on-MT measurement for the in-process measurement of high-value components such as aircraft engines and components, close to realising a traceable on-MT measurement.

From a technology point of view, the aim is to use an MT as a CMM, but there are some key differences between a CMM and an MT, mainly because CMMs are designed for measurement purposes and MTs are focused on manufacturing production. The main problem when executing a measurement on an MT is that the machining and measuring processes are performed using the same machine, and some error sources therefore cannot be distinguished if a calibration process is not realised before the measurement execution [4]. This is currently the main limitation to close the calibration chain for on-MT measurement.

Over the years, several standards and guidelines [5–10] have been developed in order to verify the accuracy of either MTs [11–16] or CMMs [6,7], but measurement traceability assessments for on-MT measurements are not as developed as is the case for CMMs. In this scenario, owing to the similarity between CMMs and MTs, some of the methods employed for a correct assessment of uncertainty in CMMs are being adopted for MTs. The general guide for a suitable evaluation of measurement data is given in the ISO Guide 98-3: 2008, on the expression of uncertainty in measurement (GUM) [17]. Three different approaches are considered for an uncertainty assessment on an MT [3]: a) an experimental technique according to ISO 15530-3 technical specification [8]; b) a numerical simulation-based approach, as described in the ISO 15530-4 technical specification [9]; and c) an uncertainty budget method based on the VDI 2617-11 guideline [10].

Several research works have focused on the idea of converting an MT into a CMM. In 2010, Schmitt et al. proposed that a large MT should be employed as a comparator to measure the geometry of large scale components during the manufacturing process [18]. In 2013, Schmitt et al. also presented a study in which a specific workpiece was manufactured and calibrated on a CMM for several on-MT measurement experimental tests [1]. In this regard, Mutilba et al. reported that a research work where a calibrated workpiece was employed to assess the on-MT measurement uncertainty on a real manufacturing process for a medium-size prismatic component [4]. In 2015, Schmitt et al. went a step further, presenting an approach to determine the uncertainty assessment for on-MT measurements according to the VDI 2617-11 guideline; they defined a maximum permissible error (MPE) [7] for MTs to assess the systematic error of the on-MT measurement error budget [2]. Recently, Holub et al. presented a capability assessment for on-MT measurement assisted by an external laser interferometer [19]. Similarly, Sladek et al. reported an interesting approach for the systematic error assessment of a CMM based on the use of a laser tracer for the volumetric error mapping and compensation of geometric errors. It is an online accuracy-estimation solution based on the virtual coordinate measuring machine (VCMM) concept for CMMs [9,20–22].

In this context, this paper presents a methodology to perform traceable on-MT measurements without using a calibrated workpiece, performing the VDI 2617-11 guideline [10]. The approach aims to perform the systematic error (u_b) assessment of on-MT measurements by means of a previous volumetric error mapping of the MT using laser tracer technology.

Finally, an experimental exercise was performed on a three linear-axis medium-size MT. It shows that the uncertainty assessment for a medium-size prismatic component can be performed without using a calibrated workpiece. Results have been compared to the ISO 15530-3 technical specification [8].

2. On-machine tool measurement uncertainty budget

Before presenting the new approach, it is interesting to understand those uncertainty contributors that should be considered for on-MT measurement uncertainty budget. The ISO 15530-3 technical specification explicitly presents four uncertainty contributors that consist of all the systematic and random errors comprising the uncertainty budget for on-MT measurement [8]:

- u_b: Standard uncertainty associated with the systematic error of the measurement process.
- u_p: Standard uncertainty associated with the measurement procedure.
- u_{cal}: Standard uncertainty associated with the uncertainty of the workpiece calibration.
- u_w: Standard uncertainty associated with material and manufacturing variations.

Thus, the standard uncertainty of the measurement system (u_{MS}) is given by the quadrature sum of every uncertainty contributor, according to the formula expressed in Equation 1. In addition, the expanded measurement uncertainty of the measurement system (U_{MS}) is assessed by U_{MS} = k x u_{MS} for a coverage factor of k=2, as expressed in Equation 2. For the systematic error (u_b) contributor, different approaches are employed to assess it. If the measurement result is not corrected by the systematic error (b), the error fully contributes to the uncertainty, so u_b = b. Thus:

$$u_{MS} = \sqrt{u_p^2 + u_{cal}^2 + b} \quad (1)$$

$$U_{MS} = k * u_{MS} \quad (2)$$

With respect to the ISO 15530-3 technical specification, the uncertainty u_p is given by the maximum standard deviation of every measurement performed on the workpiece; therefore, it uses the experimental (type A) approach. The systematic error is defined as the difference between the mean value of the on-MT measurement and the calibrated value, and the calibration uncertainty is given by the workpiece's features calibration on a CMM. Both contributors are evaluated using the type B method. Further, if variations of form errors and roughness owing to fluctuating manufacturing processes and material properties are considered within their required limits, the u_w contribution is considered as insignificant [8]. In this case, u_w is considered negligible, so it is not introduced in Equation 1.

For the VDI 2617-11 guideline, the determination of the on-MT measurement uncertainty is determined using an uncertainty budget. Here, each uncertainty source and its magnitude on the measurement result is considered. In this case, the error sources are as follows [2]:

- The geometric error of the MT and its repeatability.
- Probing system.
- Temperature: MT structure, surroundings, and workpiece.
- Workpiece under measurement: Temperature and clamping.
- Measurement procedure.
- Geometric error mapping technique.

Those error sources comprise systematic and random errors for the on-MT uncertainty budget [23]. The result is the on-MT measurement uncertainty for a 95% confidence level.

Similar to the ISO 15530-3 technical specification, the systematic error contributor (u_b) on the VDI 2617-11 guideline is affected by the following error sources: geometric error of the MT, probing system, workpiece under measurement, measurement procedure, and geometric error mapping technique. The random contributor (u_p) comprises the MT repeatability, touch probe repeatability, and temperature variation for the measurement scenario. For the experimental approach presented below, the measurement procedure and the workpiece under measurement have not been considered for the uncertainty budget because an easy-to-measure medium-size prismatic component was measured. Moreover, negligible deformations occur during the clamping process. In addition, the probing system characterisation and the uncertainty of the MT volumetric error mapping technique are within 2 μm. Thus, the uncertainty budget exercise focuses on major uncertainty contributors. In this manner, the geometric error of the MT is considered as the main error source within the systematic contributor (u_b), and the effect of the temperature on the measurement scenario and MT repeatability are highlighted as the main random error contributors (u_p).

Considering those major uncertainty error contributors, this study adopts the random error characterisation, which performed on the ISO 15530-3 technical specification and which does not require a calibrated workpiece to understand how (u_p) performs. For the systematic error contributor (u_b), Schmitt et al. presented an approach where an MPE value was defined for an MT. Their approach was validated within stable temperature conditions, but they proposed further research for unstable conditions because an unstable status causes gradients inside the structure, and the induced deviations are hard to simulate or predict [2]. Considering such limitations, a volumetric error mapping of the MT is performed immediately before the on-MT measurement process execution for the systematic error characterisation. Thus, the geometric error of each contact point is known, and the systematic error contributor (u_b) can therefore be assessed. This research work does not apply the systematic error value correction, so the error fully contributes to the uncertainty budget, as in Equation 1.

3. Methodology for on-MT uncertainty assessment without a calibrated workpiece

A new methodology is proposed to perform the on-MT uncertainty assessment without a calibrated workpiece:

- For the systematic error contributor (u_b), a volumetric error mapping of the MT is performed immediately before the on-MT measurement. Thus, the geometric error of each point is known for the working volume of the machine, which is the main contributor to the systematic error of the on-MT measurement. Once the on-MT measurement is performed, measurement contact points are registered, and the geometric error of every point is obtained from the volumetric error mapping. Thus, every measured feature is fitted again while considering the geometric error of each contact point. The difference between the feature characteristics before and after the second fitting exercise is the systematic error to be considered on the error budget. Figure 1 shows the flow chart for the systematic error characterisation.

- The systematic error originating from the tactile probe could also be considered for the systematic error contributor (u_b). Thus, as explained by Mutilba et al. [4] if a reliable calibration of the probing system is performed every time the tactile probe is mounted on the MT spindle, this contributor becomes negligible. However, if the calibration process is not executed correctly or if the uncertainty contributor is not sufficiently small (< 1 μm for small MT and < 3 μm for large MT) the tactile probe systematic error should be added to the u_b value according to the square root of the sum of squares.

- The measurement procedure uncertainty (u_p) is performed on the workpiece to be measured on the MT, similar to the ISO 15530-3 technical specification [8]. Thus, the repeatability of the on-MT measurement is performed within the temperature range of the measurement scenario, considering that the temperature variation is critical for this uncertainty contributor. Therefore, several on-MT measurement cycles shall be performed within the complete temperature range of the measurement scenario. For example, consider an eolic hub being machined in a large MT, where the temperature variation on the surrounding air is between 18 °C and 23 °C. The u_P contributor should be assessed by means of repeated measurement cycles (every 15 min) on the workpiece within the working temperature range. Equation 3 shows how to calculate the u_P contributor.

- The u_{cal} contributor is considered as the standard uncertainty associated with the measurement uncertainty on the systematic error characterisation process.

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \qquad u_p = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{3}$$

where:

- $\bar{y}$ = mean value of the measurement result.
- y = measured value.
- n = number of measurement results.

Figure 1 shows the flow chart for the systematic error characterisation.

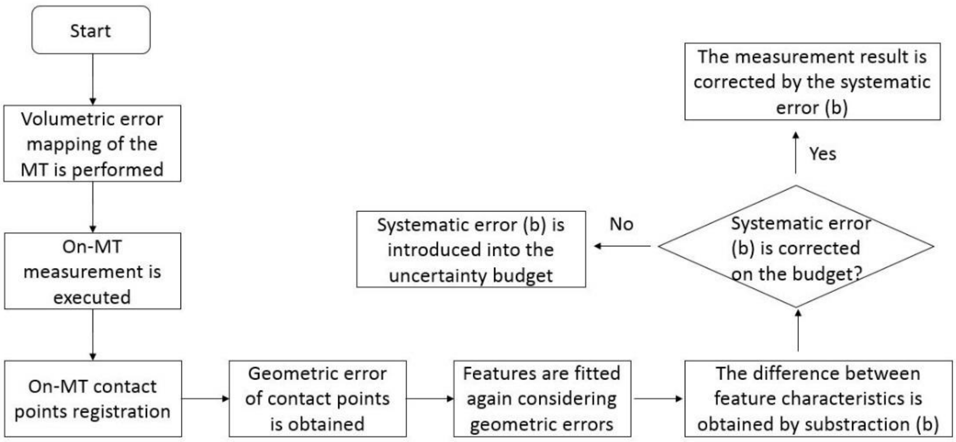

Figure 1. Systematic error assessment methodology.

For the geometric fitting of the measured plane and diameters, three dimensional (3D) and two dimensional (2D) fitting equations have been employed in MATLAB [24]. This fitting exercise considers the geometric error information of each contact point obtained in this case from the volumetric error mapping measurement. Results obtained on each fitted feature are compared to the initial fitting value obtained by the on-MT measurement software, so the difference between both fittings is the systematic error to be considered on the error budget according to the VDI 2617-11 guideline. Equation 4 shows the employed algorithm for circumference fitting; the variation of the radius shows the roundness error.

$$r = \sqrt{(x - x_c)^2 + (y - y_c)^2} \tag{4}$$

where:

- r = circumference radius.
- x,y = measured contact points (geometric error in each point is considered).
- x_c,y_c = circumference centre coordinates (to be obtained).

For the 3D fitting of the plane, Equation 5 shows the algorithm which was employed in this experimental exercise. The least-squares fitting algorithm was employed to compare the flatness error before and after considering the geometric error of the contact points [25].

$$f(x_i,y_i,z_i) = p_1x_i + p_2y_i + p_3z_i + 1 \cong 0 \quad (5)$$

where:

- p = plane feature parameters.
- x_i,y_i,z_i = measured contact points (geometric error in each point is considered)

4. Technology adoption on a machine tool

The presented methodology requires a volumetric error mapping of the MT before performing the on-MT measurement to characterise the geometric error of the MT as the main error source to the systematic error (u_b) of on-MT measurement. In this context, as explained by Nisch et al. [18], there are two main approaches to enable a traceable measurement on MTs: a) the MT geometric error is known at the moment when the measurement is performed through a volumetric error mapping of the MT; and b) an external high precision metrological frame is employed to measure and compensate for the geometric error of the MT in real time [21,22,26,27].

Figure 2 shows the above-mentioned two alternatives a) an MT volumetric error mapping exercise. It shows an integrated multilateration approach reported by Mutilba et al. [30], and b) an external high-precision metrological frame comprised of four tracking interferometers in simultaneous mode.

a) b)

Figure 2. Multilateration approaches for MT error mapping a) integrated approach , and b) external high-precision frame with four tracking interferometers (Both measurements were performed by IK4-TEKNIKER on a ZAYER large MT)

The first approach increases the process capability by a volumetric verification and compensation of the MT, as shown in Figure 2(a). Currently, there are different options for the volumetric error mapping of MTs [28], but they are time-consuming, mainly for large-scale MTs. In this regard, the multilateration approach is suitable for realising such a fast performance. Schwenke et. al. reported an approach to continuously monitor the geometric variation of a large MT on shop floor conditions [29], and recently, Mutilba et al. reported an integrated and automatic volumetric error mapping solution for large MTs which is executed within 30 min [30]. For the proposed experimental approach, a volumetric error mapping of the MT under research was performed using laser tracer NG technology in sequential mode.

The second approach applies an external high precision metrological frame to monitor the tool centre point (TCP) position in real time. This option requires a line of sight between the measuring tracking interferometers and the TCP, which cannot be ensured when the workpiece is on the MT. The current cost of the solution is very high because four interferometers are required simultaneously. However, it offers the possibility of being self-calibrating and represents a scalable measuring solution.

Currently, the first approach is under research, and according to the latest studies, with the continued development of interferometer-based non-contact measuring technology to realise more accurate absolute distance measurements, it will be incorporated into MTs, allowing traceable CMM measurements in MTs [31].

5. Uncertainty budget assessment experimental exercise

An experimental exercise of the proposed methodology was performed using a workpiece replica standard. The obtained results were compared to the ISO 15530-3 technical specification. The workpiece replica standard selected for the experimental uncertainty assessment exercise is defined at the ISO 10791-7:2014 standard [32], and it is referred as a ′Test piece ISO 10791-7, M1-160′. A description of the measured geometry is illustrated in Figure 3.

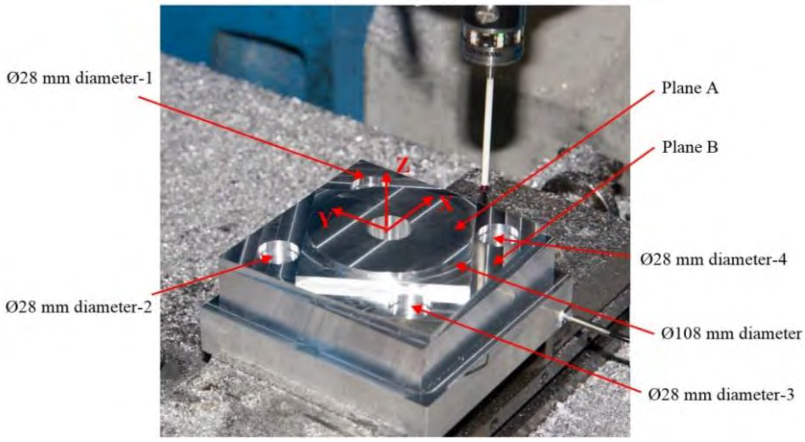

Figure 3. Workpiece replica standard with measured geometry on the experimental test.

A medium-size KONDIA MAXIM MT equipped with a RENISHAW OMP 400 tactile probe and POWER INSPECT on-MT measurement software was selected to run the on-MT measurement experimental test. The MT cutting stroke is: X = 750 mm, Y = 1000 mm and Z = 500 mm. The computer numerical control (CNC) is a 16i-type FANUC controller. For the tactile probe calibration on the MT spindle, a 50 mm-diameter calibrated ring was employed immediately after it was mounted on the MT spindle. Figure 4 shows a) the measured contact points for the experimental on-MT measurement test and b) the measurement scenario on the MT.

a) b)

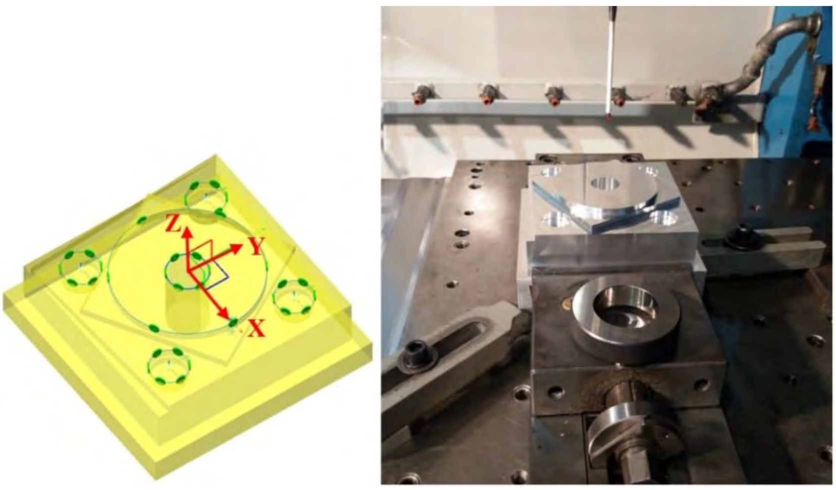

Figure 4. On-MT measurement contact points, a) General overview of the measurement strategy (contact points in green), and b) the measurement scenario where the workpiece and the calibrated ring are shown.

For the systematic error contributor (u_b) assessment, a volumetric error mapping of the MT was performed immediately before the on-MT measurement. To do this, laser tracer technology from ETALON AG was employed [33]. It employs a kinematic model which enables to calculate the geometric error of any point within the measured volume from the volumetric error mapping information, so the geometric error of the on-MT measurement contacts points was assessed in this manner. Figure 5 shows the volumetric error mapping exercise and the measured point grid (in black) of the MT. The laser tracer NG, which is placed on the MT table, measures the distance to the reflector, which is fixed to the spindle, for every point comprising the point grid under the multilateration scheme [33]. It demonstrates the technology adoption of the above-mentioned first approach where a unique tracking interferometer is employed in sequential mode for the MT volumetric error mapping.

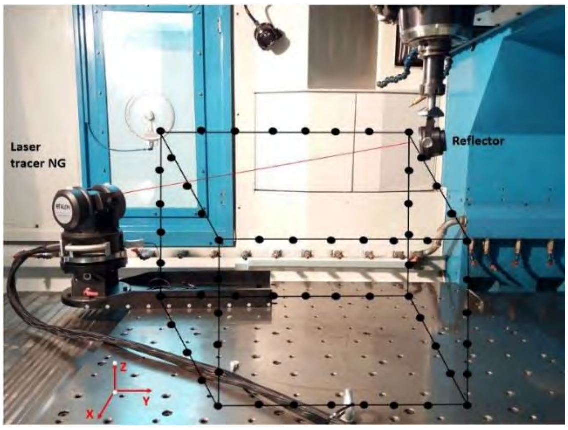

Figure 5. Volumetric error mapping of MT and measured point grid (in black).

The volumetric error mapping measurement was performed under a no-load condition when the temperature on the MT side was 20 °C, with a temperature variation within 0.5 °C.

5.1 On-MT measurement results according to ISO 15530-3 technical specification

The experimental on-MT measurement exercise according to the ISO 15530-3 technical specification is explained in detail in the article: ´Traceability of on-MT measurement: Uncertainty budget assessment on shop floor conditions´ which was reported by Mutilba et al in 2018 [4]. Here, the approach is to employ a CMM-calibrated workpiece replica standard to assess the on-MT measurement uncertainty. Figure 6 shows the absolute value of the systematic error contributor (u_b) assessed using the calibrated workpiece. All of the results are within 8 μm.

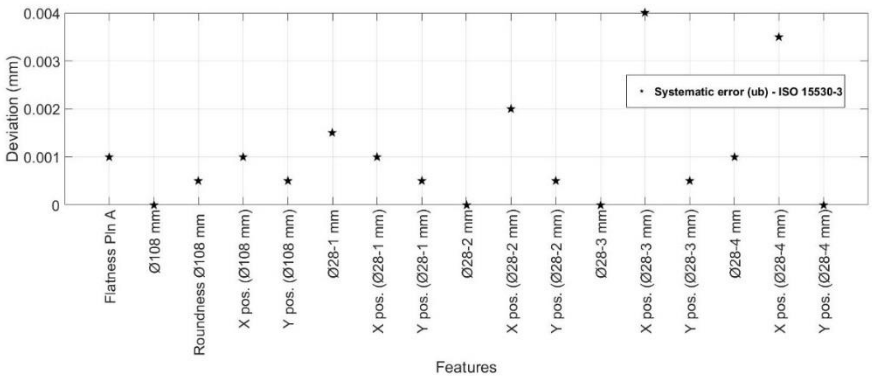

Figure 6. Systematic error (u_b) according to ISO 15530-3 technical specification. [4]

The uncertainty budget of the task-specific uncertainty assessment on shop floor conditions according to the ISO 15530-3 technical specification [4] is shown in Figure 7. The measurement procedure uncertainty (u_p) is on average a few micrometres larger on than the systematic error (u_b) uncertainty, which is within 8 μm for every measured feature. The calibration uncertainty contributor (u_{cal}) is within 2 µm for each feature. Expanded measurement uncertainty results are obtained by Equation 2 for a coverage factor of k = 2, where u_{MS} is given by Equation 1. As previously mentioned, it should be considered that the systematic error (u_b) contributor is not corrected on the uncertainty budget, which significantly increases the expanded measurement uncertainty (U_{MS}) result.

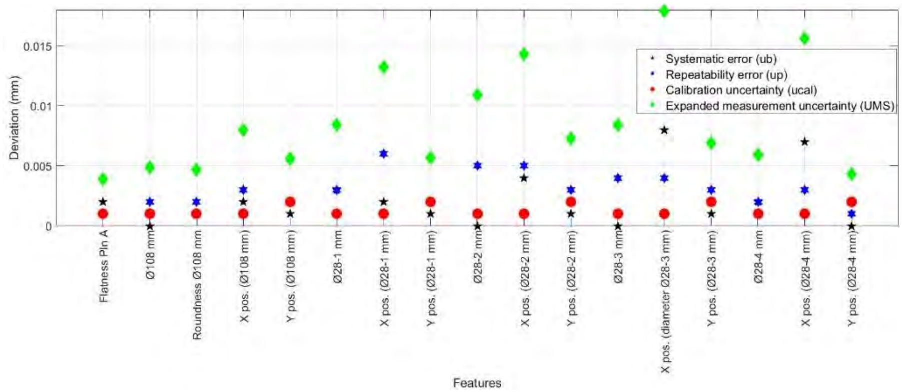

Figure 7. Uncertainty budget according to ISO 15530-3 technical specification. [4]

5.2 On-MT measurement results according to VDI 2617-11 guideline

The main difference for the VDI 2617-11 approach is that a calibrated workpiece is not employed to assess the systematic error uncertainty contributor (u_b) on the uncertainty budget. Thus, a volumetric error mapping of the MT was performed immediately before the on-MT measurement exercise, and the TRAC-CAL software from the company ETALON AG, which includes kinematic models for point-error determination, was used to calculate the geometric error of each contact point for the on-MT measurement process. Figure 5 shows the volumetric error mapping setup on the MT, and Figure 8 shows the 3D deviation result of each measured point comprising the point grid. The simple ETALON kinematic model was employed, and was performed by 17 components of the error, and the results are depicted in a 3D deviation-type plot. The uncertainty for the geometric error mapping measurement is within 1 µm. The volume of the point grid depicted in Figure 8 is similar to the MT cutting stroke, i.e. X = 750 mm, Y = 1000 mm and Z = 500 mm.

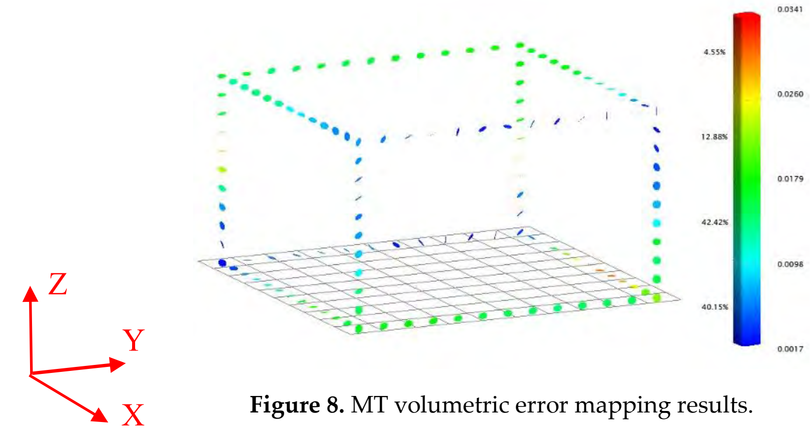

Figure 8. MT volumetric error mapping results.

The MT volumetric error mapping exercise demonstrates that the geometric error is within 20 µm for almost the entire volume of the machine. Moreover, the workpiece replica standard size is 160 mm × 160 mm, which means that the geometric error on the MT side that applies to the on-MT measurement is within 5 µm. The volumetric error mapping process also measures the MT volumetric repeatability; in this case, the MT volumetric repeatability is within 2 µm. This means that either the backlash error or the repeatability itself are within this value.

For the systematic error contributor (u_b) assessment, the proposed methodology depicted in Figure 1 was applied. In addition, a reliable tactile probe calibration was performed prior to the on-MT measurement exercise to avoid systematic errors due to the probe set-up process. The repeatability of the calibrated ring measurement is within 1 µm, which is similar to the MT repeatability. In this manner, it was considered to be within the measurement procedure uncertainty (u_p) on the uncertainty budget. Figure 9 shows a comparison of the systematic error assessment for the ISO 15530-3 technical specification and the VDI 2617-11 guideline. The difference between both approaches is within 1.5 µm.

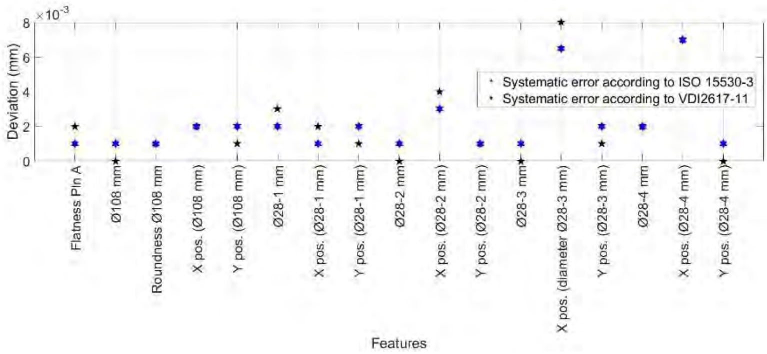

Figure 9. Systematic error (u_b) assessment according to ISO 15530-3 technical specification and VDI 2617-11 guideline.

For the measurement procedure uncertainty (u_p), results obtained from the ISO 15530-3-based experimental test were considered because they do not require a calibrated workpiece. Here, it is crucial to understand the effect of temperature gradients on the results. Thus, the experimental test suggests on-MT measurements immediately after the machining process of the workpiece replica standard and measurements under a no-load condition when the temperature on the MT side and workpiece side is constant at 20 °C. The temperature variation on the on-MT measurement scenario is within 3 °C, and the workpiece temperature increases to 22.5 °C (on average) immediately after the machining process, after which it stabilises to 19.5 °C (on average) after an on-MT measurement acquisition time of 2h. Figure 10 shows the measurement procedure uncertainty (u_p) for each measurement feature, both for measurements executed immediately after the machining process as well as measurements executed under no-load conditions [4].

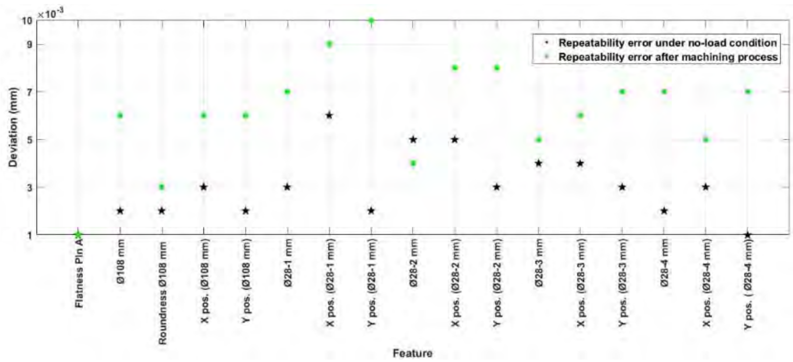

Figure 10. Measurement procedure uncertainty (u_p) results for both approaches. [4]

The measurement procedure uncertainty results (u_p) show differences between the measurement executed under the no-load condition and the measurements executed immediately after the machining process. All of the results show repeatability within 6 µm for the no-load condition, while the maximum repeatability values for the measurements immediately after the machining process are within 10 µm. The form error feature measurement (flatness and roundness) shows better measurement procedure uncertainty results than the scale-related feature measurement (diameter and positioning values) because these features are more sensitive to the measurement scenario temperature variation [34]. Here, factors such as the swarf or dirty surfaces should affect the u_p uncertainty result.

For the uncertainty (u_{cal}) contributor, the volumetric error mapping of the MT also indicates the uncertainty of the volumetric measurement exercise; it is obtained using a Monte-Carlo simulation technique considering the spatial displacement measurement uncertainty for the laser tracer NG, U (k = 2) = 0.2 µm + 0.3 µm/m [33]. The obtained uncertainty contributor (u_{cal}) of the volumetric error mapping is within 1 µm.

Finally, the uncertainty budget of the task-specific uncertainty assessment in shop floor conditions according to the VDI 2617-11 guideline [3] is depicted in Figure 11. Similar to the ISO 15530-3 technical specification, the expanded measurement uncertainty results were obtained using Equation 2 for a coverage factor of k = 2, where u_{MS} is given by Equation 1. For the measurement procedure uncertainty (u_p), the contribution to the uncertainty budget uncertainty results for the no-load condition were considered.

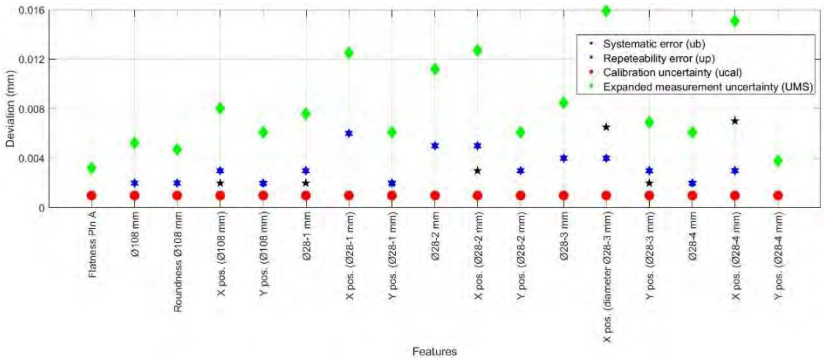

Figure 11. Uncertainty budget according to VDI 2617-11 guideline (no-load condition).

Finally, Table 1 shows the uncertainty budget assessment within the VDI 2617-11 guideline and it is compared with the result obtained according to the ISO 15530-3 technical specification.

Table 1 Uncertainty budget according to VDI 2617-11 guideline and comparison with ISO 15530-3 technical specification. (results in µm)

Feature	u_b	u_p	u_{cal}	u_{MS}	U_{MS} – VDI 2617-11	U_{MS} – ISO15530-3
Flatness Plan A	1.0	0.7	1.0	1.6	3.2	3.9
Ø108 mm	1.0	2.2	1.0	2.6	5.2	4.9
Roundness Ø108 mm	1.0	1.9	1.0	2.4	4.7	4.7
X position (Ø108 mm)	2.0	3.3	1.0	4.0	8.0	8.0
Y position (Ø108 mm)	2.0	2.1	1.0	3.1	6.1	5.6
Ø28-1 mm	2.0	3.1	1.0	3.8	7.6	8.4
X position (Ø28-1 mm)	1.0	6.1	1.0	6.3	12.5	13.2
Y position (Ø28-1 mm)	2.0	2.1	1.0	3.1	6.1	5.7
Ø28-2 mm	1.0	5.4	1.0	5.6	11.2	10.9
X position (Ø28-2 mm)	3.0	5.5	1.0	6.3	12.7	14.3
Y position (Ø28-2 mm)	1.0	2.7	1.0	3.0	6.1	7.3
Ø28-3 mm	1.0	4.0	1.0	4.2	8.5	8.4
X position (Ø28-3 mm)	6.5	4.5	1.0	8.0	15.9	17.9
Y position (Ø28-3 mm)	2.0	2.6	1.0	3.4	6.9	6.9
Ø28-4 mm	2.0	2.1	1.0	3.1	6.1	5.9
X position (Ø28-4 mm)	7.0	2.7	1.0	7.6	15.1	15.6
Y position (Ø28-4 mm)	1.0	1.3	1.0	1.9	3.8	4.3

Experimental results show that the uncertainty budget according to the VDI 2617-11 guideline obtains similar results to what obtained according to the ISO 15530-3 technical specification, where a calibrated workpiece is employed for the purpose. For the systematic error contributor (u_b), the difference between both approaches is within 1.5 µm, which agrees with the accuracy of the volumetric error mapping performance, i.e. roughly 1 µm, and also with the backlash error, which is within the 2 µm result that shows the volumetric repeatability. In addition, the calibration component (u_{cal}) is similar in both cases because of the employed reference standards, whether the calibrated workpiece or the volumetric error mapping solution have a similar uncertainty contributor. For the measurement procedure contributor (u_P), the same raw data is employed.

6. Conclusions and future work

This paper presents an alternative on-MT uncertainty assessment methodology based on the VDI 2617-11 guideline, which could allow scaling traceable on MT measurements to large-size MTs. The current approach, which is based on the ISO 15530-3 technical specification, requires a calibrated workpiece, which is similar to the manufactured part. Therefore, the solution is not very flexible, especially for larger parts, for which it is tedious and expensive. In addition, it also presents the two main alternatives for the adoption of the volumetric error mapping technology to MTs.

An experimental uncertainty budget of on-MT measurement was presented:

- Making a comparison with the ISO 15530-3 technical specification, the systematic error contributor (u_b) on the VDI 2617-11 guideline is shown to be affected by those error sources: the geometric error of the MT, probing system, workpiece under measurement, measurement procedure and the geometric error mapping technique.
- The random contributor (u_P) comprises the MT repeatability, touch probe repeatability, and temperature variation in the measurement scenario. For the experimental approach, the measurement procedure and the workpiece under measurement were not considered in the uncertainty budget because an easy-to-measure medium size prismatic component was measured. Moreover, negligible deformations occur during the clamping process. Furthermore, the probing system characterisation and the uncertainty of the volumetric error mapping technique are within 2 µm. The former is considered within the procedure uncertainty contributor (u_P) and the latter is considered as the u_{cal} contributor.

The experimental exercise which was performed without a calibrated workpiece shows that the obtained results are similar to what was obtained using a calibrated workpiece. For the systematic error contributor (u_b), the difference between both approaches is within 1.5 µm, which is similar to the volumetric error mapping uncertainty, for which the difference is approximately 1 µm, and also with the volumetric repeatability of the MT, which includes the backlash error within 2 µm. Random errors for both experimental approaches are the same because they were obtained on the ISO 15530-3 approach.

In summary, the methodology offers an opportunity to obtain traceable CMM measurements on MTs without employing a calibrated workpiece as long as interferometer-based technology is developed for MT volumetric error mapping and calibration.

The results obtained were validated on a three linear axis medium-size MT owing to machine availability and other practical issues. The future work will focus on scaling the presented methodology to large MTs similar to those used in large-scale manufacturing; the ISO 15530-3 approach is not affordable because a calibrated workpiece similar to the manufactured part is required, which makes the solution difficult and expensive.

In this scenario, this research work is a gateway to large on-MT traceable measurement.

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