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Traceable on-machine tool coordinate measurement through the integration of a virtual metrology frame in large machine tools

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Metrological traceability and micrometre-level measurement uncertainty are the main research challenges towards traceable coordinate measurement on large machine tools. The impact of time- and space-varying thermal conditions on the machine tool structure is the major uncertainty contributor to the uncertainty budget. Aiming to minimise this influencing factor, this research proposes the use of integrated multilateration as a virtual metrology frame in combination with the machine tool controller information to characterise the position and orientation of every coordinate measurement performed by the machine tool. Experimental results demonstrate that measurement uncertainty is within an 18-micrometre range and assess the required metrological traceability.

1. Introduction

While industrial sectors such as aerospace, wind and nuclear power, large science facilities, and shipbuilding demand a zero-defect manufacturing production model for their high-value production processes [1], the manufacturing of large and complex geometric components remains a challenge. In this context, it is a common trend to integrate metrology into production to enable process control and tolerance verification, which can help in making corrections to the manufacturing processes [2].

The integration of on-machine and in-process metrology [3] is being adopted more rapidly for small and medium-sized high-value components than for large-sized components. Usually, for large components, the manufacturing process is interrupted, and quality inspection takes place beside the production line using instruments such as large bridge coordinate measuring machines (CMMs), articulated arms, laser trackers, or photogrammetry [4].

The possibility of performing traceable measurements with machine tools (MTs) is extremely interesting. However, the impact of time and space-varying thermal conditions on the machine tool structure limit the accuracy and traceability of the measurement data obtained with large MTs [5].

This research proposes using integrated multilateration as a virtual metrology frame combined with MT controller information to address thermal effects on the MT structure and achieve micrometre accuracy and metrological traceability in coordinate measurements taken with a large MT. The proposed method involves executing a measurement approach in sequence between the positioning and probing points of the tactile probing process [6]. Initially, the virtual metrology frame determines the MT position and orientation in the positioning point with micrometre accuracy. Then, the MT controller measures the relative displacement between the positioning and probing points, which is typically within a 3 - 10 mm range. This allows for the correction of the positioning point coordinate deviation at the probing point coordinate.

Finally, the practical application of the method is demonstrated by integrating an AT960™ LEICA laser tracker into a ZAYER ARION G™ large MT and performing the presented coordinate measurement approach on a medium-sized CMM-calibrated workpiece.

2. Coordinate measurement on MT

Different approaches have been researched to assess dimensional traceability in the coordinate measurements performed on an MT. The use of dimensional artefacts in combination with the ISO 15,530−3 technical specification has traditionally been applied to ensure metrological traceability for medium-sized components [2]. However, for large components, the previous approach is not feasible since a calibrated workpiece similar to the manufactured component is needed. In this way, two research trends can be envisioned towards traceable coordinate measurements on large MTs: a) the use of the MT as a CMM, and b) the integration of an external measurement instrument or metrology frame into the MT.

The first approach is limited by the MT structure and its constant drift caused by the impact of time and space-varying thermal conditions [7]. An a priori MT error mapping characterization process could help to characterise the MT volumetric positioning error [8], but this approach is not reliable enough for accurate measurements because the MT geometric error is not determined at the moment of the coordinate measurement.

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For the second approach, the state-of-the-art suggests avoiding the MT structure as a metrology frame. Several researchers propose the use of a virtual metrology frame to determine the position and orientation of the touch trigger probe (TTP) at the moment of measurement. Schwenke et al. propose using multiple absolute interferometry measurement lines installed on the MT structure to monitor the MT thermal drift [9]. Wendt et al. developed a portable multilateration scheme consisting of four length measurement instruments, such as laser trackers or laser tracers, that monitor the position and orientation of a retro-reflector mounted at the stylus of a CMM in almost real-time [10]. The coordinate measurement process is realized in a sequence where the measurand is initially measured on a CMM. Then, after removing the measurand from the CMM to avoid collisions, the previously recorded coordinate probing points are characterized by the external metrology frame. In this way, Wiemann et al. demonstrated the realization of this method in a CMM for the calibration of a large involute gear [11].

3. Integrated multilateration as a virtual metrology frame

An integrated multilateration technique was first introduced in [12]. It is similar to the approach presented by Wendt et al. [10], but it suggests using a unique instrument integrated into the MT spindle and several retro-reflectors playing the role of fiducial points, fixed on the MT working volume, to realize the virtual metrology frame [13]. Thus, several improvements are obtained, such as the use of a single measurement instrument, the full automation of the measurement process, and the almost real-time external characterization of the coordinate measurement. Fig. 1 shows the integrated multilateration experimental realization with a LEICA AT960^{TM} laser tracker embedded into the spindle and four wide-angle retro-reflectors fixed to the MT table.

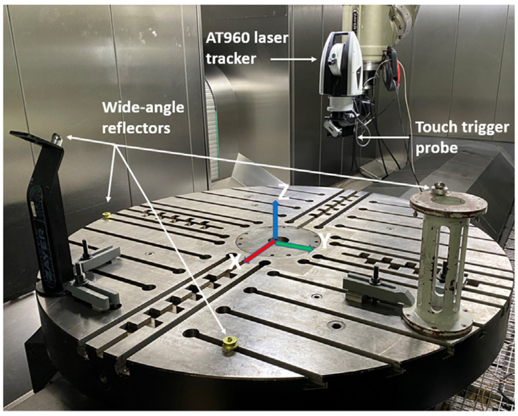

Fig. 1. Integrated multilateration practical realization on a ZAYER ARION G^{TM} large MT.

4. The method for traceable on-MT measurement

As defined by Weckenmann et al. [6], the coordinate probing sequence can be divided into four sequential processes: positioning, probing, measuring, and evaluating. Positioning is the process of bringing the probing system into the measuring range of the workpiece. It defines a static point in front of the probing point, which is usually located between 3 - 10 mm away from the workpiece surface (depending on the measurement plan parametrization). Probing is the process where the TTP contacts the component's surface, and the measurement trigger occurs. It is the point where coordinate measurement is performed and, therefore, the point of maximum interest. However, the dynamic nature of the probing point makes it extremely difficult to externally characterise the MT position and orientation at the moment when the TTP contacts the component's surface.

Considering the probing sequence, the proposed coordinate measurement method is executed in sequence with the probing process. Due to the static condition of the positioning point, the method proposes the realization of the virtual metrology frame to characterise the MT position and orientation error vector at this point. Right after, the relative displacement between the positioning and probing points is obtained by the MT controller.

In this context, the proposed measurement method relies on the assumption that the positioning and probing points, which are only a few mm apart, have an identical error vector in a large MT (several metres of stroke in XYZ). Therefore, the error vector obtained at the positioning point is applied to the probing point to correct the information coming from the MT controller. As a result, the obtained probing coordinate is almost fully characterized by the measurement performed by the virtual metrology frame, considering that the measurement error performed by the MT controller is negligible at such a short distance.

4.1. Initial spatial referencing process

Initially, the measurement method suggests spatial referencing for every instrument that plays a role in the measurement scenario, as shown in Fig. 2. Thus, the integrated multilateration is performed by integrating a laser tracker into the MT spindle and fixing retro-reflectors to the MT table. As explained in [12], the spatial relationship between the laser tracker (T_{01}) and retro-reflectors (T_{0R1} - T_{0R4}) in the MT coordinate system is realized through two sequential best-fit transformations that are performed at four corner points of the MT working volume. After that, a second referencing process is performed to define the spatial relationship between the laser tracker and the TTP in the MT coordinate system (T_{12}). To do that, the TTP centre is physically placed at the MT coordinate system origin (centre of the table on the ZAYER ARION G^{TM}) and the laser tracker coordinate system (CS1) is created by measuring the retro-reflectors (R1 - R4) placed on the MT table. Right after, a controlled motion is performed by the MT table in the X direction, ensuring the line of sight between the laser tracker and the centre of the table. At this known position, the MT coordinate system is measured by the laser tracker attached to the spindle, and therefore, the spatial relationship between both systems (T_{12}) is obtained.

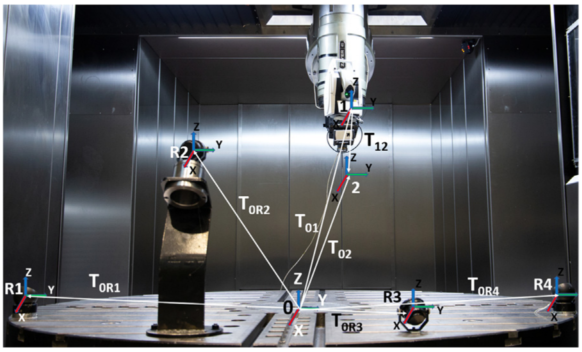

Fig. 2. Illustration of the instruments and their coordinate systems in the measurement scenario.

Fig. 2 shows the spatial relationship between the instruments present in the measurement scenario. It displays the coordinate systems (CS) that define the MT coordinate system (CS0), the integrated laser tracker (CS1), the retro-reflectors (CSR1 - CSR4), and the TTP (CS2).

Once the instrument's spatial referencing is resolved, the coordinate measurement procedure will be executed in a fully autonomous mode.

4.2. Coordinate measurement process

The coordinate measurement process is performed in sequence with the probing process. When the MT reaches the positioning point, the laser tracker embedded into the MT spindle executes the integrated multilateration approach. It does so by pointing and measuring the available retro-reflectors on the MT table (R1 - R4). As a result, the position and orientation of the laser tracker (CS1) are characterised by the external metrology frame. By applying the transform between CS1 and CS2 (T_{12}), the accurate position vector on the TTP

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($\boldsymbol{TTP}_{\text{ipos}}$) is obtained. This result is compared to the TTP position vector given by the MT controller ($\boldsymbol{MT}_{\text{ipos}}$). Therefore, the error vector on the positioning point ($\boldsymbol{e}_{\text{ipos}}$) is determined, as stated in Eq. (1).

At this moment, the communication between the laser tracker controller and the MT Programmable Logic Controller (PLC) allows the laser tracker to send a trigger to the MT to start the probing process. As soon as the TTP touches the component's surface, the MT controller registers the probed position vector ($\boldsymbol{MT}_{\text{iprob}}$). Finally, assuming that positioning and probing points have the same error vector on a large MT (Eq. (2)), the error vector obtained by the external metrology frame on the positioning point ($\boldsymbol{e}_{\text{ipos}}$) is applied to the probing point (Eq. (3)). Therefore, the probing point is characterised by the combination of the external metrology frame information ($\boldsymbol{TTP}_{\text{ipos}}$) and the relative displacement ($\boldsymbol{\Delta}_{\text{iMT}}$) information obtained from the MT controller.

$$\boldsymbol{e}_{\text{ipos}} = \boldsymbol{MT}_{\text{ipos}} - \boldsymbol{TTP}_{\text{ipos}} \tag{1}$$

$$\boldsymbol{e}_{\text{ipos}} = \boldsymbol{e}_{\text{iprob}} \tag{2}$$

$$\boldsymbol{TTP}_{\text{iprob}} = \boldsymbol{MT}_{\text{iprob}} - \boldsymbol{e}_{\text{iprob}} \tag{3}$$

$$\boldsymbol{TTP}_{\text{iprob}} = \boldsymbol{MT}_{\text{iprob}} - \left(\boldsymbol{MT}_{\text{ipos}} - \boldsymbol{TTP}_{\text{ipos}}\right) \tag{4}$$

$$\boldsymbol{TTP}_{\text{iprob}} = \boldsymbol{TTP}_{\text{ipos}} + \Delta_{\text{iMT}} \tag{5}$$

wherein:

$\boldsymbol{e}_{\text{ipos}}$ error vector (XYZ) of the point i at the positioning point
$\boldsymbol{e}_{\text{iprob}}$ error vector (XYZ) of the point i at the probing point
$\boldsymbol{MT}_{\text{ipos}}$ position vector (XYZ) of point i obtained by MT controller at the positioning point
$\boldsymbol{MT}_{\text{iprob}}$ position vector (XYZ) of point i obtained by MT controller at the probing point (triggered by TTP)
$\boldsymbol{TTP}_{\text{ipos}}$ position vector (XYZ) of point i obtained by external metrology frame at the positioning point
$\boldsymbol{TTP}_{\text{iprob}}$ position vector (XYZ) of point i at the probing point
$\boldsymbol{\Delta}_{\text{iMT}}$ Relative displacement vector (XYZ) between positioning and probing points given by MT controller

$$\Delta_{\text{iMT}} = \boldsymbol{MT}_{\text{iprob}} - \boldsymbol{MT}_{\text{ipos}}$$

5. Uncertainty budget and metrological traceability

5.1. *Uncertainty* budget

The general guide for the evaluation of measurement data (GUM) [14] recommends the uncertainty budget approach to describe the different uncertainty contributors and how these input quantities relate to the measurement result. Thus, the proposed measurement method has several major uncertainty contributors: a) the integrated multilateration (virtual metrology frame), b) the MT controller information, and c) the repeatability of the probing system. Additionally, there are other minor contributors to uncertainty, such as the systematic error of the probing system, the MT resolution, or the coordinate measurement procedure, that could be less than 2 µm and therefore considered negligible. Uncertainty related to the initial alignment process is not considered in the uncertainty budget since it is a constant within the transformation matrix.

The uncertainty contribution related to the component under measurement (measurand) should also be considered in the uncertainty budget. For instance, factors such as the effect of temperature and gravity on the measurand, the clamping of the measurand on the MT, or the presence of dirt on the measurand surface at the moment of coordinate measurement can all affect the measurement process of a large component. However, these factors have not been considered in this research.

Table 2 summarises the suggested uncertainty budget. While the contributors b) the MT controller information, and c) the repeatability of the probing system are considered type B contributors [14], the contributor a) the integrated multilateration (virtual metrology frame) is considered a type A contributor. Thus, the integrated multilateration contribution has been assessed through a Monte-Carlo simulation exercise according to the JCGM 101:2008 guide [15]. The MT controller information is estimated by the MT repeatability specification since the MT positioning error does not affect such a small displacement. Finally, the repeatability of the probing system is also considered according to the manufacturer's specifications.

The Monte-Carlo simulation was run with the help of the Spatial analyzer (SA™) metrology software and the available Unified Spatial Metrology Network (USMN) algorithm. Although it is not a pure multilateration algorithm since angle-derived data is still used to some extent, it gives similar results in practice [13]. Moreover, it greatly facilitates the development of a fully autonomous measurement procedure. The simulated MT working volume is X 3000 mm, Y 2000 mm, and Z 1500 mm, and 60 coordinate points are considered within the measurable probing point cloud. For the instruments, four fiducial points are defined on the MT table, one in each table corner, and an Absolute Distance meter (ADM)-based laser tracker is integrated into the MT spindle. The nominal uncertainty related to the instrument length measurement error is U(k = 2) = 10 µm+ 0.4 µm/m [13]. Table 1 shows the mean value for the standard uncertainty [14] obtained at the simulated point cloud.

Table 1
Integrated multilateration simulation results (mean values for the standard uncertainty in the X, Y and Z coordinates, as well as the quadratic sum of those uncertainties). All values are reported in mm.

u_x	u_y	u_z	u_{xyz}
0.0061	0.0045	0.0043	0.0087

Table 2
Uncertainty budget for the proposed on-MT coordinate measurement method.

Standard uncertainty component (u)	Uncertainty contributor	Standard uncertainty (mm)	Probability distribution	Sens. coef. (c)
u_{VMF}	Integrated multilateration	0.0087	Normal	1.0
u_{MT}	MT controller information	0.0020	Rectangular	1.0
u_{PROBE}	Repeatability of the probing system	0.0020	Rectangular	1.0
u_{COORD}	Combined standard uncertainty	0.0091	–	–

Considering that uncertainty contributors are uncorrelated and by applying the law of propagation of uncertainty [14] according to Eq. (6), the combined standard uncertainty for the proposed measurement method (u_{COORD}) is obtained.

The expanded measurement uncertainty (U) was calculated with a 95% level of confidence (k = 2) using Eq. (7) [14]. In summary, the average expanded measurement uncertainty for the proposed on-MT coordinated measurement method is 18 µm based on the simulated measurement scenario.

$$u_{COORD} = \sqrt{u_{VMF}^2 + u_{MT}^2 + u_{PROBE}^2} \tag{6}$$

$$U = k * u_{COORD} \tag{7}$$

wherein:

k coverage factor
u_{COORD} combined standard uncertainty

5.2. *Metrological traceability*

The traceability of the proposed on-MT coordinate measurement method is established based on the property of the integrated multilateration measurements to relate to the International System of Units (SI) definition of the metre, which is the main uncertainty contributor to the uncertainty budget. Thus, the laser tracker traceability is assessed through the instrument calibration process, and the SA™ software, including the USMN algorithm, is compliant with the standards of NPL, PTB, and NIST. The traceability of both the MT controller

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information and the repeatability of the probing system should also be accomplished through the individual calibration of these instruments.

6. Experimental realization

To demonstrate the proposed on-MT coordinate measurement method, an experiment was conducted on a ZAYER ARION G™ large MT. The setup involved integrating a LEICA AT960™ laser tracker into the MT spindle using a customized tool, fixing four wide-angle retroreflectors to the MT table, and using a RENISHAW RMP 600™ TTP for tactile coordinate measurement. The setup can be seen in Fig. 3.

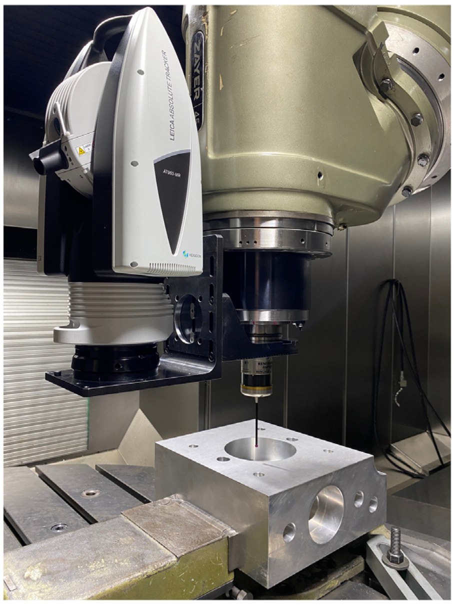

Fig. 3. Experimental realization of the proposed on-MT coordinate measurement method on a ZAYER ARION-G machine tool.

From the perspective of the workpiece, a medium-sized prismatic component was used for the experimental realization of the proposed method on the large MT. The results obtained were compared to the workpiece calibration results obtained from a ZEISS UPMC CARAT 850™ CMM. The measurement uncertainty of the CMM measurement is better than 0.002 mm, as calculated by the ZEISS VCMM™ tool.

For the experimental characterization of the method, the selected dimensional and geometrical tolerances aim to show the ability of the proposed method to correct the coordinates obtained by the MT, performing as a CMM. Thus, the assessed tolerances are the dimensions of the holes available at the upper surface of the workpiece, their positioning error, and the perpencularity between the upper and lateral surfaces. Table 3 shows the experimental results.

The maximum differences between the methods are observed for the "Diameter Ø150 mm" feature. While the difference between the proposed method and the MT raw information is 44 µm, the difference between the proposed method and the calibrated value is 6 µm. Therefore, the results show a clear improvement of the MT raw coordinates through the use of the proposed method for every tolerance, including the positioning error of the holes.

The recorded measurement time is roughly 3 s per measured coordinate, including the time taken to perform integrated multilateration used in determining the positioning point. The initial alignment process may take between 10 and 15 min to complete.

Table 3
Experimental results obtained on the prismatic workpiece. (The temperature was 18.9°C at the moment of measurement). All values are reported in mm.

Tolerance	CMM calibrated result	MT raw result	Proposed method result
Diameter Ø150 mm	150.871	150.821	150.865
Diameter Ø26 mm	26.011	25.980	26.005
Position Ø150 mm	0.131	0.120	0.127
Position Ø26 mm	0.056	0.050	0.054
Perpendicularity between planes	0.016	0.009	0.013

7. Conclusions

The manuscript presents a novel on-MT coordinate measurement method that aims for low-uncertainty and metrologically traceable measurements in large machine tools. The method is based on a virtual metrology frame combined with short displacement length information obtained from the MT controller.

The experimental results demonstrate a clear improvement in the MT raw data information based on the use of the proposed method to correct the coordinates performed by the MT. Although the experiment focused on a medium-sized workpiece, the maximum deviation observed compared to the calibrated value is 6 µm. Future work will focus on performing a complete characterization of the method using a larger workpiece.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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