Achieving traceability of industrial computed tomography

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Abstract

Achieving traceability is crucial for complex measurement techniques, especially for coordinate measuring machines (CMMs). For CMMs using tactile probes, traceability can for certain measurements be achieved using model-based uncertainty budgets. Up to now, uncertainty simulations could be used applicable only for tactile CMM measurements of regular geometries, but are available as an add-on for CMMs of different brands. This procedure is accepted by guidelines and international standards (VDI/VDE 2617-7 and supplement 1 [1] to the GUM). Furthermore, empirical approaches to assess the measurement uncertainty by means of calibrated workpieces or prior knowledge exist or are under development. These approaches can as a matter of principle also be used for CMMs featuring computed tomography (CT). In this paper, the empirical assessment of the measurement uncertainty of the upcoming measurement technology CT [2, 3] will be discussed uniting the present approaches and the current knowledge, with the focus being on the applicability of concepts for users in industry. For this purpose, the influences on dimensional CT measurements are analyzed and evaluated, taking the measurement data of a current industrial micro CT system as a basis.

Keywords: Industrial computed tomography (CT), coordinate metrology, traceability

1. Introduction

The traceability of a measurement means the ability to link the result of a defined measurand to the referred SI unit(s). The practical meaning of this link is that it is possible to make a valid measurement uncertainty statement which usually consists of a specified standard measurement uncertainty and a coverage interval for a certain coverage probability. In coordinate metrology, the measurement results are, as a general rule, to be traced back to the SI unit of length, the meter. For 3D measurements, usually coordinate measurement machines (CMMs) are utilized. An important characteristic of measurands based on CMM measurements is that a large quantity of influence factors contributes to the uncertainty of a measurement. Significant influence factors originate from the environment, the measurement strategy, the properties of the workpiece to be measured, the properties of the measurement system itself and from user interaction. CMMs are complex universal measurement systems which enable various types of measurements to be conducted. Therefore, no unique measurand exists. Finally, some measurands of CMM measurements are multivariate or vector quantities. However, measurement uncertainty statements for CMM measurements have to be strictly task-specific. Furthermore, due to the complex nature of CMM measurements, no general approach exists to make uncertainty statements for all types of measurements. However, the GUM [4] approach can, in the majority, be applied to cases which are relevant in practice.

An upcoming industrial measurement technology are CMMs featuring computed tomography (CT) [2, 3]. While these CMMs offer many advantages, e.g. high-speed measurements, non-destructive volume assessment and high point density, they involve new sources of measurement uncertainty. CT measurements yield a volumetric description of the X-ray absorption of the workpiece under study which is subdivided into small volume cells called "voxels". Thus, studies of the measurement uncertainty have to take both the new and the classical influence factors of CMMs into account. In the following, the measurement uncertainty assessment of CMMs will be briefly discussed for CMMs featuring classical tactile sensors before the discussion will turn to CMMs featuring CT as measurement system.

2. Assessment of the measurement uncertainty for CMM measurements

For CMMs using tactile probes, the traceability of measurements can be achieved for selected measurement tasks by using model-based measurement budgets. Up to now, the simulation of tactile CMM measurements could be used as a tool to assess the measurement uncertainty for regular geometries only (planes, cylinders, spheres, etc.) and is commercially available as an add-on (*VCMM - Virtual CMM*) for different CMMs. This measurement uncertainty assessment procedure is accepted by guidelines and international standards (VDI/VDE 2617-7 and supplement 1 to the GUM [1]). Furthermore, empirical approaches to assess the measurement uncertainty by means of calibrated workpieces (DIN EN ISO 15530-3, ISO/TS 14253-2, ISO/DTS 15530-2 and VDI/VDE 2617-11 draft) exist or are under development.

ISO/TS 15530-3:2004 discusses measurements of a series of parts taken from a production process. Thus, the production-caused dispersion of workpiece properties is considered. For the approach of ISO/TS 15530-3, the handling of systematic errors has to be discussed. The GUM explicitly recommends correcting known systematic errors. If this is not done for whatever reasons, the following equation (1) includes the influence of uncorrected systematic errors to the measurement uncertainty. Recent discussions of the measurement uncertainty formula used in ISO/TS 15530-3 to express the expanded measurement uncertainty show that the influence of the systematic errors is not treated according to GUM with the formula as stated now. As a result, the formula has been rewritten. The correct formula is [5]:

$$U = k \cdot \sqrt{u_{cal}^2 + u_p^2 + u_w^2 + b^2} \quad , \qquad (1)$$

where
- U expanded measurement uncertainty
- k expansion factor (depending on the probability density function of the measurement output quantity; k is usually chosen to be 2 in many practical cases)
- u_{cal} standard calibration uncertainty of the material standard
- u_p standard uncertainty (standard deviation) of repeated measurements
- u_w standard uncertainty from the production-caused dispersion of workpiece properties (e.g. thermal expansion coefficient, form deviation, roughness, etc.)
- b systematic deviation between the mean measurement value and the calibration value

The draft ISO/DTS 15530-2:2008 (document N727) describes a procedure to estimate a task-specific measurement uncertainty from multiple measurements of a workpiece. These measurements are performed in different orientations and locations of the measurement volume. The danger of underestimating this type A uncertainty contribution is being accounted for by the analysis of the effective degrees of freedom of the measurements and by applying an expansion factor for a coverage probability of 95% of greater than 2.

ISO/TS 14253-2:1999 describes how to estimate the measurement uncertainty by a simplified iterative process. ISO/TS 14253-2 is applicable to the case of GPS measurements where all influence factors and standard uncertainties are known. Correlations are taken into account only for the cases of strong correlations or no correlations at all.

The guide VDI/VDE 2617-11 (scheduled as a public draft in 2009), tries to estimate the measurement uncertainty of certain measurement tasks by means of uncertainty balance sheets. The most important input quantity is the characteristics (*MPE* values) of the given CMM. The guide restricts itself, e.g., to tactile single-point probing and regular geometries which have been created by a least-squares fitting, to mention only the most important points.

3. Measurement uncertainty of CMM measurements using computed tomography

For complex measurement techniques - and especially for CMMs using CT - it is important for any uncertainty analysis to define the measurand very clearly. Thus, the definitional uncertainty (VIM, 2008) contributing to the measurand can be decreased by specifying the true quantity value and a reference measurement method to which the CT measurements are to be related. A common means is to define the tactile probing of a surface as reference.

In the case of CT, the measurement process is usually not finished with the tomographic reconstruction. For dimensional measurements, at least a threshold process for the determination of surfaces and a geometric analysis of surfaces follow. Due to the complexity of the whole CT measurement process (e.g. tomographic reconstruction and non-linear physics of X-ray absorption) and the numerous influence quantities, an analytical solution for describing the measurement uncertainty of CT seems to be not appropriate.

CT measurements can yield different types of results (measurands). The result can, e.g. be just a single value (e.g. a diameter), but also vector quantities (location of points or axes) or maps of deviations are possible. Maps of deviations are usually determined by means of actual nominal value comparisons. The analysis of the multi-point surface measurement using CT has been performed on an empirical basis for the CT measurement of an aluminum cylinder head [6]. For this analysis, the influence of varying workpiece properties (esp. the roughness) and uncorrected systematic errors according to (1) have been considered. The work showed that a subvoxel measurement uncertainty of the extracted surface points from a CT data set can be achieved using correction techniques. For further empirical analysis of the measurement uncertainty of CT, the approach of VDI/VDE 2617-8 of cumulating the properties of different samples for covering the influence of workpiece properties can help.

The ansatz of ISO/DTS 15530-2 can be also transferred to CT measurements. While for classical CMMs, multiple measurements within a reasonable area of the measurement volume and in arbitrary orientation make sense for the determination of the measurement uncertainty, the case is different for CT. For classical CMMs, usually no prior knowledge exists about anisotropies of the measurement uncertainty within the measurement volume. Furthermore, the spread of properties within the measurement volume is usually moderate. For CT measurements, a strong orientation dependency of the measurement properties and, in some cases, a location dependency exist. The orientation dependency results from changing X-ray absorption properties in different orientation of the measured workpiece, in combination with limitations and characteristics of the CT system in use. Therefore, measurements in arbitrary orientation will not reflect the properties of the CT measurement system when operated by a skilled operator. Only orientation and location changes of the measured workpiece being within reasonable limits should by applied.

A critical point of the approach of ISO/TS 15530-3 for the use in the field of CT is the missing guidance in the handling of CT specific effects. Thus, CT specific effects have to be analyzed for the individual measurement task.

In the opinion of the authors the VDI/VDE 2617-11 draft and the approach of ISO/TS 14253-2 can both render no satisfying help for the assessment of the measurement uncertainty of CT because in VDI/VDE 2617-11, the influence of the workpiece has not been considered up to now and because, for the application of ISO/TS 14253-2, the knowledge of the standard uncertainties of all influence quantities - which are hard to assess - is required.

The simulation of digital X-ray radiography is an existing working tool. Nevertheless, the simulation of CT measurements requires additional modeling. The main items are the rotation of the part, the tomographic reconstruction, the threshold process to achieve surfaces and its subsequent analysis. It is important to stress that for simulations in order to obtain the measurement uncertainty, the simulation must describe the measurement task adequately, i.e. the simulated measurement process has to be complete and its results have to be validated. Due to the complexity of the CT measurements, only very few attempts to calculate the measurement uncertainty from simulations are reported [7]. Up to now, simulations suffer from the incompleteness of the influence factors and from being not validated. In addition, the presented results are based on nominal assumptions. Therefore, the empirical approach seems up to now to be the only possibility to assess the measurement uncertainty of CT in the next years.

4. Experimental results

In the following, results from micro CT measurements of a micro spur-gear will be presented. The gear made from steel features the following parameters:

Table 1. Gear parameters [7], current analysis parameters and view of the micro gear under study.

No. of teeth	14
Normal modul m_n	0.12 mm
Pressure angle α_0	20°
Addendum modification coefficient x	0.12
Base circle radius r_b	0.789 341 mm
Helix angle β_0	0°
Tip diameter d_a	2.0 mm
Face width b	1.0 mm
Reference circle radius r_0	0.840 mm

Micro spur-gear with tactile measured flanks and 3 holes on mounting base (2 visible)

Analysis parameters of measurement:	
Tooth No.	1, 5, 8, 12
Flanks	left and right
Radius / length of roll foot r_{SAP} / $l_{\alpha SAP}$	0.845 mm / 0.301 605 mm
Radius / length of roll head r_{EAP} / $l_{\alpha EAP}$	0.985 mm / 0.589 208 mm
Reference for the height of measurement	-0.05 mm (related to the datum face of the gear artifact)
Measurement range in height	0.7 mm

Micro CT measurements have been performed using a CT system of BAM with the following parameters:

Table 2. Parameters of micro CT measurement.

Voltage	Filtering	Voxel size	Detector size	Reconstruction	Data binning	Surface extraction
80 kV	0,25 mm Cu	3,6 µm	2048 x 2048	Feldkamp	no	adaptive

In total 6 independent CT measurements have been recorded. Surface data has been created from the CT raw volume data by an adaptive threshold process using Volume Graphics *Studio Max 2.02*. The quality of surfaces has been leveled for optimal processing resulting in polygon data sets with 1.51 millions triangles for each set. The applied level of quality of surfaces is about 0.7 µm worse than the “best measurement capability” of the CT system applied. The CT data has been corrected for first order scaling errors by correcting the nominal voxel size with the known diameter of the core hole of the gear (assessed by tactile micro CMM measurements). This is a common procedure which is applied for industrial CT systems, too.

Tactile reference measurements have been performed using a Carl Zeiss *F25* CMM dedicated for measurements of micro parts. Even if the error behavior for real workpieces measurements of micro CMMs are focus of current research, the manufacturer stated characteristics of MPE_P = 0.3 µm and $MPE_E = 0.25\ \mu m + 1.5 \cdot 10^{-6} \cdot L$ (according to ISO 10360-2) indicate that this CMM is definitely more precise than the micro CT system under study. In a previous work [8] similar reference measurements have been used to analyze the gear measurement capabilities of micro CT. In this work the capability of micro CT to assess the gear as a sculptured surface measurand and the resulting measurement errors are the main topics.

The tactile measurements now have been performed using a probe tip of about 0.12 mm diameter. The measurements have been accomplished with the software Zeiss *Calypso 4.6.08* and Zeiss *Gear pro 3.5.06*. While *Calypso* has been used for setting up a local workpiece coordinate system, the measurements of 8 flanks of 4 teeth have been made with *Gear pro*. Each tooth flank has been sampled with single points probing resulting in a point cloud of about 640 points. In total two independent measurements of the 8 flanks have been recorded. The analysis of the tactile measurements has been done twice:

1. In contrast to standard gear measurements the assessed data has been exported from Gear pro to get the tip radius corrected contact points of the tactile probing.
2. The core functionality of *Gear pro* has been used to assess the gear parameters of the micro gear under test (see Table 1).

The registration of the CT data and of the tactile measured point clouds has been accomplished by a step by step procedure. First of all the surface extracted from the CT volume data has been created by Volume Graphics *Studio Max* in a coordinate system which is formed by the cylinder of the gear core hole (primary alignment), the top plane of the gear (origin of coordinate system) and a circle in one of the three cylinders inserted in the mounting base pointing roughly in direction of tooth No. 1 (secondary alignment, see view in Table 1). For creating this coordinate system reference geometries cylinder, plane and circle have been fitted to the CT volume data. For the final alignment of the extracted CT surface data and the tactile reference data similar reference geometries cylinders and planes have been fitted (to the CT data) and constructed (to the tactile CMM data). The final alignment then is performed by a restricted Gaussian best fit with Geomagic *Studio 10 SR1 (64bit)* where after a match of pair of reference geometries (pair cylinder axis CT surface – z-axis of tactile data and pair plane CT surface – xy-plane through origin of tactile data) only a rotation around the z-axis is unrestricted. For each CT data set finally an actual nominal comparison is calculated with Geomagic *Studio*. The result of the actual nominal comparison is the local difference of the tactile reference and the CT measurement. This can be interpreted as the measurement error of the CT measurement. Figures 1 and 2 show the resulting histograms of all measurement errors.

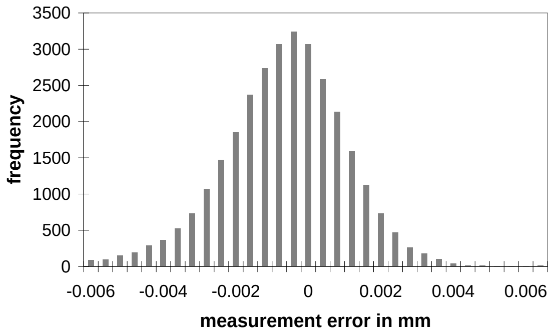

Fig. 1. Histogram of (signed) measurement errors (incl. all 6 CT measurements)

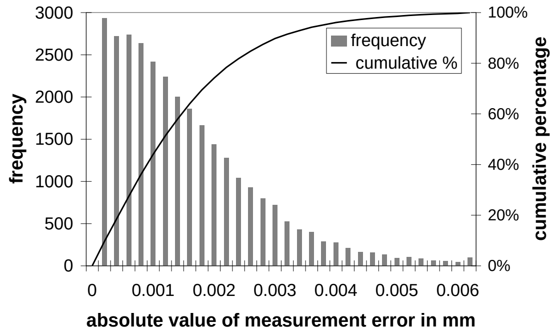

Fig. 2. Cumulative histogram of absolute values of measurement errors (incl. all 6 CT measurements)

95% of all absolute error values are less 0.0037 mm. For the analysis of this result the small sample size of 6 CT measurements has to be kept in mind. For a balanced result the observed value is corrected using the t-distribution (see ISO 14253-2 or [4]). Thus, a value of 1.3*0.0035 mm = 0.0048 mm is estimated to be characteristic for describing a 95% coverage interval of all absolute errors. For a further analysis of the measurement uncertainty the uncertainty of the reference measurements and the contribution of the workpiece properties in principle have to be included, but due to the size of the observed errors of the CT system, these terms do not increase the empirically assessed value significantly. Thus, the value of 0.0046 mm can be a first measure of the measurement uncertainty of micro CT measurements of the micro gear under study. It shows that a one voxel measurement uncertainty of micro CT measurement can be achieved even for measurements of sculptured surfaces.

5. Conclusion

Analytical methods to determine the measurement uncertainty of CMMs featuring computed tomography (CT) are currently out of reach as a closed model of the whole CT measuring process does not exist. The simulation of the measurement uncertainty of these CT systems seems to be possible and can also yield information about the properties of inner geometries, but requires a validation of the correctness of the simulated measurement process. First simulation approaches have been presented in the past, but suffer from the early state of the procedures and the incompleteness of the budget. In this paper, we analyzed the existing empirical approaches for the assessment of the measurement uncertainty with a view to their applicability in the field of CT and tried to unite and evaluate the present knowledge. First results for the measurement uncertainty of micro CT measurements of a micro gear, deduced from a series of 6 CT measurements, are presented. The results are valid in a strict sense only for the objects under study and are limited by the statistics of the measurements, but they can at least give an estimate of the measurement uncertainty of micro CT measurements. The results show that a one voxel measurement uncertainty can be achieved also in the field of micro CT for well-conditioned measurement tasks. The finalization and validation of the findings and the transfer of the results to similar objects will be one of the coming tasks.

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