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Assessment of the measurement procedure for dimensional metrology with X-ray computed tomography

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Abstract

X-ray computed tomography (CT) is a promising technology for quality assurance of industrial parts. However, computed tomography for dimensional metrology is a complex and indirect measurement procedure, whose results depend on a variety of influencing factors. To ensure that a measurement is traceable back to the basic SI units, a statement about the measurement uncertainty has to be given together with the actual measurement result. A generally accepted method for uncertainty evaluation is the use of calibrated workpieces. However, the influencing factors throughout the measurement procedure that contribute to the uncertainty are not quantified individually and remain unknown. The quality and reliability of the measurement, expressed in measurement uncertainty, hereby depends on hard- and software as well as user-set scan parameters. Not only scan parameters, such as current, tube voltage or exposure time, can influence the measurement results, but also surface determination and geometrical evaluation of the measured features add to the measurement uncertainty.

In this contribution, the measurement procedure for metrological computed tomography is assessed and influencing factors throughout the different steps in the measurement procedure are identified as well as quantified. The approach is used to analyze the data quality of different measurements with a test object. The CT data are compared to tactile calibration data of the object and an experimental uncertainty evaluation is given.

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Keywords: metrology; computed tomography; measurement uncertainty; quality

1. Introduction

X-ray computed tomography (CT) is a promising technology for quality assurance of industrial parts. The possibility to visualize and measure inner and outer structures non-destructively makes computed tomography a unique method, especially for parts where conventional tactile or optical metrology come to their limit, for example at undercuts or internal details [1, 2]. On the other hand, computed tomography is a complex and indirect measurement procedure, which depends on a variety of influencing factors. To ensure that a CT measurement is traceable back to the basic SI units, a statement about the measurement uncertainty has to be given together with the actual measurement result. Three methods for assessing the task specific uncertainty for CT measurements are currently under discussion: Assessment by model equations analytically calculated according to the Guide to the Expression of Uncertainty in Measurement (GUM) [3], Monte Carlo simulations [4] or empirical methods, namely the uncertainty evaluation by use of calibrated workpieces according to ISO 15530-3 [5]. The third approach is generally accepted and already established for CT measurements [6, 7]. In this method, calibrated workpieces are repeatedly measured under the same conditions. To ensure traceability, tactile coordinate metrology is commonly used as reference method for calibration.

According to VDI/VDE 2630 [8], the expanded measurement uncertainty can be expressed as:

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$$U = k\sqrt{u_{ref}^2 + u_p^2 + u_w^2 + b^2} \quad (1)$$

with $k = 2$ as coverage factor for a confidence level of 95%; u_{ref} as standard uncertainty for tactile reference measurements; u_p standard uncertainty of the measurement procedure performed by computed tomography; u_w as standard uncertainty of the workpiece due to thermal expansion and b as the systematic error (bias) of the measurement, which is treated as random error and thus squared and added under the radical [9].

A separate indication and correction of the systematic error, which is suggested in GUM [3], is not performed in this case. This is due to the fact that in computed tomography measurement many unknown error sources contribute to the measurement, but cannot be distinguished and quantified easily [cp. 7, 10].

2. Influences on Measurement Uncertainty in CT

Generally, at experimental determination of the measurement uncertainty according to the above formula, an overall estimation of the uncertainty related to the measurement procedure is done. The influencing factors that contribute to the uncertainty are not quantified individually and remain unknown.

These influencing factors during the measurement process occur at different steps along the measurement procedure and will be described shortly. This description is not exhaustive, further reading can be done e.g in [1].

The measurement procedure can be divided into four steps, namely the acquisition of multiple x-ray images within 360° of rotation of the measured part, the reconstruction into 3D volume data, which might also include data filtering and artefact reduction algorithms, the subsequent thresholding procedure and the data evaluation according to a chosen measurement strategy, which includes the fitting of geometry primitives to the measurand.

The uncertainty during the acquisition of x-ray images depends on one hand on properties of the hardware used for the components, such as the stability of the x-ray tube, positioning errors of the (rotatory) axes and detector response but on the other hand also on the user, who sets scan parameters including voltage, current, position etc., thus e.g. influencing focal spot size and magnification. After the acquisition process, the reconstruction takes place, which is largely user-independent.

Afterwards, thresholding and evaluation operations on the reconstructed 3D volume are performed. Here, the user influence is significantly higher, due to the fact that one has options to decide about the settings for thresholding and the subsequent measurement strategy.

Especially the thresholding is important, because this operation defines the interface between the workpiece and surrounding air or between materials of different densities in the case of multi-material. A fast and simple approach is to use the so-called ISO50-threshold, which is obtained from the histogram of the volume greyvalues [cp. 1]. As more accurate thresholding strategy, especially for noisy scans or multi-materials, a locally adaptive threshold is used instead, which gives significantly better results. Thresholding hence forms the basis for all following steps during dimensional measurements, because it provides the data set to which the geometric primitives in the subsequent data evaluation are fitted. Depending on the surface of the workpiece or its form deviation, the fitting strategy, such as number and position of fitting points, can influence the measurement result and its related uncertainty.

The estimation of measurement uncertainty in CT has been an emerging field of investigations by many researchers. The work from *Dewulf et al.* discusses uncertainty sources for length measurements based on the GUM [11].

Several experimental studies on uncertainty budget have been performed using a calibrated reference workpiece [6, 7, 12, 13], which – according to Formula (1) – just take into account the standard uncertainty of the measurement procedure as a whole, not assessing individual contributions.

A simulative study on the influence of the threshold determination has been done by *Lifton et al.* [14], while *Mueller et al.* [10] performed an experimental investigation on the measurement strategy itself, focusing on comparing different software packages for the evaluation including adaptive thresholding and polygonal mesh-conversion of the surface.

In this paper, the aim is to experimentally quantify different contributions to the uncertainty of the measurement procedure with a special focus on user influence in thresholding and evaluation operation. Even when using adaptive thresholding, the user can define multiple thresholding parameters, which in turn can influence the measurement result. To separate machine-inherent systematic and random errors as well as user influence, the repeatability and reproducibility of the CT scans are investigated as well. Here, the repeatability is defined as the variation of measurement results of consecutive scans performed under the same conditions, hence describing the variance of the measuring machine. To assess reproducibility, i.e. the behavior under changing conditions, scans were performed at different times, in between which the object was taken out by the user and repositioned on the rotatory table.

3. Experimental methods

3.1. Test Object

The test object used in this study consists of three ruby spheres with a nominal diameter of 2mm each attached to carbon fibre rods, which are fixed to a PVC plate by thread (Fig. 1 (a)). The PVC plate just serves as fixation and is not scanned. The ruby spheres were chosen due to their simple and well defined geometric features with low manufacturing inaccuracies with a form deviation smaller than 0.13 µm. The assessed measurands (Fig. 1 (b)) are the diameters of the spheres (D1, D2, D3) as well as their 3D distances to one another (d1, d2).

a) b)

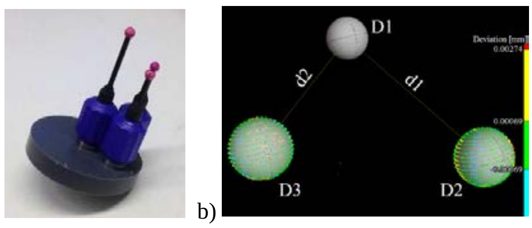

Fig. 1: (a) Test object; (b) Evaluated measurands

In comparison to the ruby spheres, the carbon fibre rods have a lower density, thus enable an easy distinction between rod and sphere in the 3D volume.

Note that the sphere diameters depend on the chosen threshold, while the distance between the sphere centers can be measured threshold-independently. Hence, it can be distinguished between error sources in the scan that can lead to deviations in the voxel size and thus contribute to both diameter and distance deviations, and errors that occur due to the thresholding operation and affect only the sphere diameters.

3.2. CT Scan

Two sets of CT scans were performed with identical scan parameters. All CT scans are done on a Zeiss Metrotom 800 device with a sealed 130kV microfocal x-ray tube with tungsten target. The CT has a 1536 x 1920 pixel flat panel detector, with CsI-szintillator and a pixel size of 127 µm x 127 µm. The source-detector distance is 800 mm. No prefilter was applied. The scan parameters are shown in Table 1. The CT scanner uses a built-in compensation of focal spot drift with a calibration object, which was scanned every 64 projections. No additional correction of the scale error was performed. Even though, this correction does not necessarily lead to a complete compensation.

Table 1. Used scan parameters in the CT measurement

	Unit	Value
Voltage	kV	130
Current	µA	60
Integration time	ms	1000
Magnification	--	9,52
Voxel size	µm	13
Focal spot size	µm	8
Number of Projections	--	1550
Gain	--	2.5

The CT scans were performed in a temperature controlled environment with a temperature of 20±0.3°C. Before the measurements, the tube was turned on for about two hours for a warming up phase.

The first set of scans comprised 25 successive scans. To exclude user influences during the scan, all scans were performed in an automated manner, such that no user interaction took place in between the single measurements. This set of scans is used to assess the repeatability of the measurement result.

In order to assess reproducibility, an additional set of ten scans was performed, where the parts were scanned in different days and the specimen was manually repositioned on the rotatory table for each scan. All other scan parameters were kept constant (Table 1).

3.3. Thresholding and evaluation strategies

The threshold determination as well as the subsequent data analysis was performed with VGStudio Max 2.2.

Five different strategies for threshold determination were chosen (Fig. 2). Strategy 1 uses the automatic ISO50% threshold, while strategies 2 to 4 use adapted thresholding starting from the ISO50% value with different search distances, namely 2 voxels (strategy 2), 4 voxels (strategy 3) and 8 voxels (strategy 4). In the 5th strategy, the user sets the threshold according to his visual impression of the volume data.

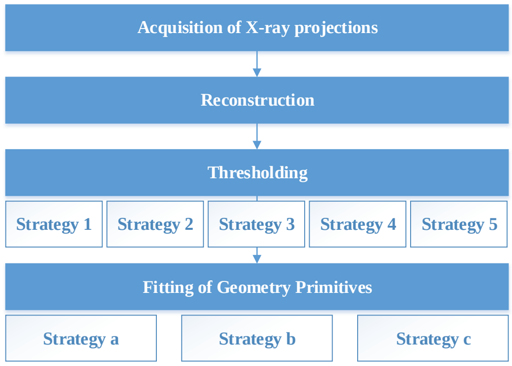

Fig. 2: Compared measuring strategies

In addition, the subsequent evaluation strategy was varied, namely using (a) 1,000, (b) 10,000 and (c) 50,000 surface points for fitting the geometry primitive of a sphere to all three diameters. In each strategy, a Gaussian fit was applied.

To identify the influences of the thresholding and evaluation strategy as well as the experience of the user, one reconstructed 3D volume was chosen on which the operations with all different strategies were performed. Each threshold operation in combination with each geometry fitting was performed by five different users, from a beginner to an experienced CT user.

3.4. Calibration uncertainty

The calibration uncertainty is calculated from tactile reference measurements with a scanning probe head. The used coordinate measuring machine (CMM) was a Zeiss Prismo with a length measurement deviation of MPE_E (3D) = (1.2 + L/350) µm (L in mm) according to ISO 10360-2 [16]. In total, 25 measurements with two operators where performed in a controlled laboratory with a room temperature of 20±0.5°C. The measurements were done with a tip stylus in scanning mode. Due to the geometry of the part, the probing was only performed on the upper hemi-spheres.

The expanded calibration uncertainty U_{ref} is determined according to ISO 15530-3 [5] with

$$U_{ref} = k\sqrt{u_i^2 + u_p^2 + u_w^2} \quad (2)$$

Where k is again the coverage factor (k=2 for a confidence level of 95%) and u_i the standard calibration uncertainty of the CMM, which is calculated using the MPE_E:

$$u_i = 0{,}5MPE_E \quad (3)$$

u_p is the standard uncertainty from the 25 repeated measurements with the CMM and u_w is temperature-related standard uncertainty of the workpiece. To determine its value, a thermal expansion coefficient of 5.5 x 10^{-6} K^{-1} for ruby is used. The shaft of the ruby spheres is made from thermofit CFRP, thus its contribution to the thermal expansion can be neglected. The lower plate is made from PVC, but contributes only to the deviations in the spheres' distances, not the diameters.

4. Results

4.1. Thresholding and evaluation strategy

Fig. 3 shows that the thresholding operation mainly contributes with a systematic error. Depending on the chosen thresholding strategy, a differently large offset of the measured diameter to the reference value is visible. The ISO50% threshold (strategy 1) shows the highest deviation with approximately 18.5 µm. The user-to-user variation on the other hand only has an impact in a manual choice of the threshold (strategy 5), such that the data analysis step shows a good repeatability. In addition, even with manual choice, a relatively good agreement with the adapted thresholding operation can be achieved, but the large variance of the results shows that this strongly depends on the individual user.

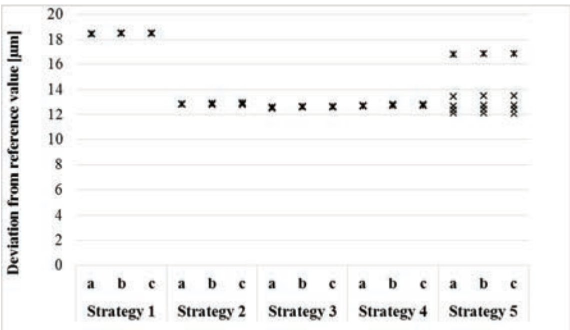

Fig. 3: *Results for D1 (diameter of sphere 1). The same data set was evaluated five times for each strategy.*

A different number of fitting points seem to give a slightly more accurate calculation of the diameter. Nevertheless, there is almost no difference between using 10,000 or 50,000 fitting points, showing that if a minimum amount of points is exceeded, a stable result can be expected.

It is noticeable, though, that the diameters are overestimated, while the distances are underestimated (Fig. 4). However, this underestimation is below 1.3 µm, which lies in the range of the expanded calibration uncertainty (Table 2).

These results confirm, that the measurement of the diameters is affected by the measurement strategy, while the distances are more stable with respect to threshold errors. In strategy 2, strategy 3 and strategy 4, the automated threshold operation as well as the adapted threshold operation yield the same results for four users, while the results of the fifth user differ. This might due to the fact that this – unexperienced - user did not comply with the agreed procedure for the evaluation. Even though, the deviations are below 0.1 µm and thus do not contribute significantly.

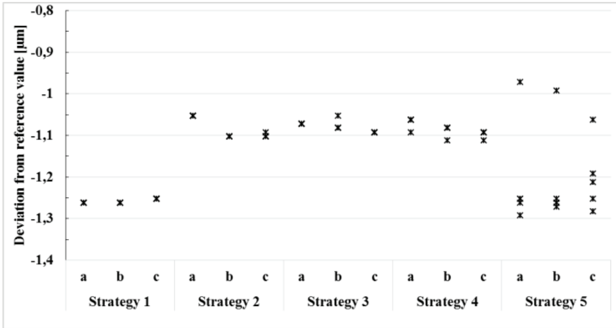

Fig. 4: Results for d1 (3D distance between sphere 1 and sphere 2). The same data set was evaluated five times for each strategy.

4.2. Repeatability and Reproducibility

To evaluate the two sets of scans for repeatability and reproducibility, thresholding and fitting strategy 3b, which showed the lowest bias, was chosen.
Fig. 5 shows the variation of the results of the 25 repeated scans for the three measured diameters. It can be seen that the values are spread at the maximum 1.3 µm around a mean deviation of 12.75 µm for diameter D1. For D2 and D3, the values are even lower. In addition, the results surprisingly do not show any drift throughout the time lapse. Hence, temperature related effects due to continuous operation of the x-ray tube, such as focal spot movement, do not influence the measurement results significantly.

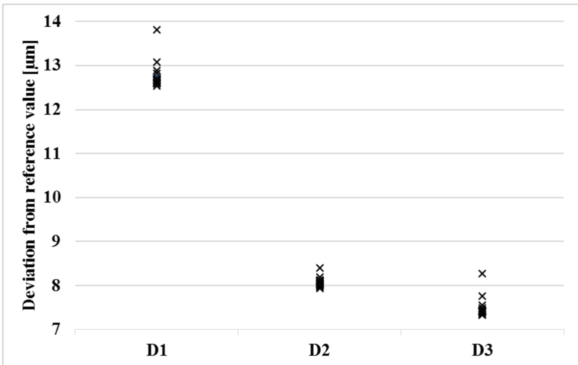

Fig. 5: Results of the 25 repeated scans for each measured diameter, evaluated with strategy 3b

In addition, the data were evaluated with strategy 3a. Fig. 6 shows the difference between the measurands evaluated with strategy 3a and 3b for all 25 scans. The deviation in most cases lies in between ±0.1 µm, with two exceptions. The mean deviation for each measurand is even lower. Hence, the difference can be neglected.

The ten reproducibility scans show a higher variance of the results (Fig. 7). Two effects account for this variation: Different positioning of the specimen on the rotatory table leads to additional artefacts in some scans, because the specimen was not optimally inclined. In addition, movement throughout the scan because of less stable fixation of the specimen resulted in movement artefacts for some scans, which lead to local influences on the surface.

Overall, CT scanning achieved high measurement repeatability. The standard uncertainties of the measurement procedure u_p lie between 0.23 µm (D3) and 0.35 µm (d2) (Table 2).

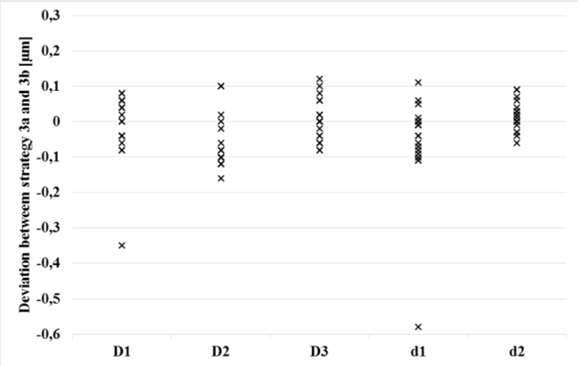

Fig. 6: Deviation between strategy 3a and 3b for the 25 repeated scans

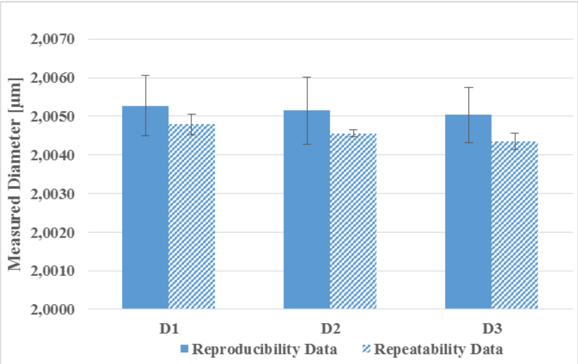

Fig. 7: Mean diameters and corresponding standard deviations of the repeated and reproduced scans

Table 2. Uncertainty contributions of the repeated measurements in µm

	D1	D2	D3	d1	d2
U_{ref}	1,21	1,21	1,21	1,23	1,23
u_p	0,25	0,28	0,23	0,25	0,35
u_w	0,00	0,00	0,00	0,01	0,01
b	13,24	8,66	8,17	-0,87	-2,03

4.3. Measurement Uncertainty

The estimation of the uncertainty was based on the ten reproduced scans. The expanded uncertainty U (k=2) is shown in Fig. 9. While the sphere distances show only an expanded uncertainty of 2.2 µm (d1) and 4.3 µm (d2), respectively, the uncertainty of sphere diameter 1 accounts to 26.5 µm (D1). It can be observed that the main contributor to the uncertainty is the bias of the CT scans (cp. Table 2). This also applies for the two sphere distances d1 and d2, which both show comparably small deviations below 5 µm.

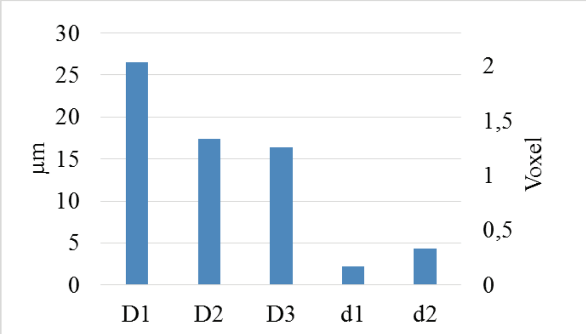

Fig. 8: Expanded uncertainty U at 95% confidence level for each measurand expressed in µm and voxels

Because the distances d1 and d2 are independent of threshold and interpolation errors, this small bias can be related to scan-inherent effects, such as the scale error caused by focal spot movement or axis misalignment. However, this does not explain the large bias of the diameters, especially in diameter D1, which shows a more than 1.5 times higher offset as the other two sphere diameters D2 and D3. A possible cause may be the different position (height) of the spheres on the rotatory table, such that different scaling of upper (D1) and lower spheres (D2, D3) occurs. This might be a non-uniform scaling due to the cone beam, which is not or only partly corrected on the detector. A similar effect for a sphere bar is reported in [11], mentioning a misalignment of the rotation axis as possible cause.

5. Discussion

With standardized procedure, reliable and repeatable measurement evaluation strategies can be achieved, also with unexperienced users. Even for simple geometries, an ISO50-threshold should be avoided, because it leads to an increased systematic error. On the other hand, the number of fitting points has a very small effect on the investigated geometries. For components with small form error the number of surface points does not play a major role. Nevertheless this result cannot be generalized, workpieces with e.g. higher form deviation might give different results.

Even though all measurands show a bias, the scale error is not the dominating effect, because of the performed compensation during the scan. Other error sources should be investigated, especially focused on thresholding, such as the starting value for the adaptive thresholding. In addition, a local effect on the diameters cannot be ruled out. Still, it has to be considered that the results deduced in this study cannot be generalized to other kinds of workpieces with different geometric features.

Furthermore, the comparability of tactile and CT data can be questioned. Different strategies, especially number and location of surface points can lead to different results, especially because in the tactile measurement only the upper hemisphere was probed.

If systematic effects resulting in the bias can be compensated as suggested in the GUM [3], the measurement uncertainty can be reduced significantly. This however requires an expert knowledge on the used computed tomography, the measurement tasks and the contributing quantities during scan and evaluation, which remains challenging.

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