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Traceability investigation in Computed Tomography using industry-inspired workpieces

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Abstract

This paper concerns an investigation of the accuracy of Computed Tomography (CT) measurements using four industry-inspired workpieces. A total of 16 measurands were selected and calibrated using CMMs. CT measurements on industry-inspired workpieces were carried out using two CTs having different metrological performance. Different scanning strategies and parameters were selected between two CTs in order to better understand the impact of the operator. The quantification of the measurement uncertainty for CT measurements was also achieved using two different approaches. Metrological compatibility between CTs and between CTs and CMMs was finally assessed using the E_n value concept.

Keywords: Computed Tomography; Metrology; Measurement Uncertainty;

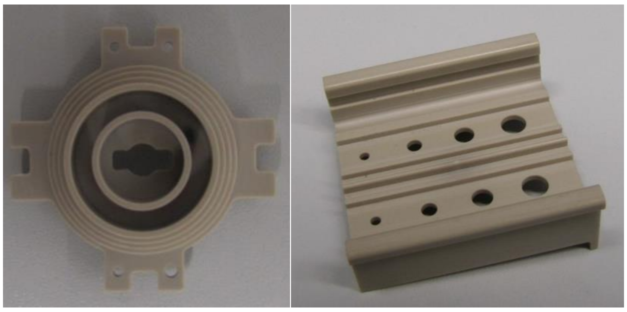
1. Introduction

Small components are increasingly used in innovative industrial products. Such parts are extremely complex and demand elaborate measurement strategies and multiple setups. Computed Tomography (CT) provides a new tool for coping with this complexity, establishing a holistic dimensional metrology on a workpiece [1, 2]. The use of X-rays as a sensor allows penetrating a large variety of materials and enables a complete surface measurement of small and internal features, which would be inaccessible using other measuring instruments. Just by scanning a workpiece once, high information density can be obtained, reducing the amount of measurements required as well as increasing the reliability of measurements. In addition, during CT scanning, no physical interaction with the parts takes place, avoiding workpiece deformations and costs associated with design and manufacturing of dedicated fixturing systems. These are significant advantages over traditional coordinate measuring machines (CMMs). However, the use of CT for dimensional measurements does not provide the same level of accuracy as it is the case with a CMM. This study reports performance of two CTs in measurement of different workpieces with difference measurands and materials. Special attention was paid to quantifying measurement uncertainty and the metrological compatibility between CTs and CMMs.

2. Workpieces

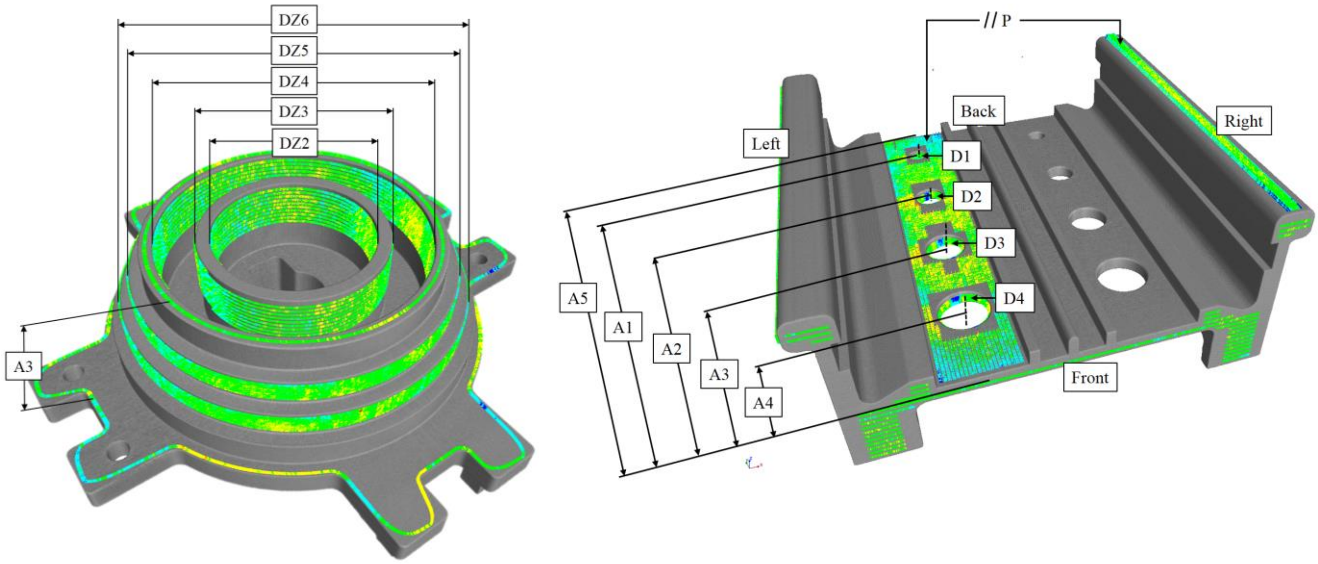
Figure 1 shows the two kinds of workpieces used in this work. The first workpiece, coded as stepped cap [3], consists of five coaxial cylindrical surfaces of different sizes. The second workpiece, coded as ED housing [3], includes multiple measurands for length measurement and diameter measurements with size ranging from 2 mm to 5 mm. The ED housing takes inspiration from a typical housing of electronic devices. The two kinds of workpieces were considered within this work in two different material configurations, namely polyether ether ketone (PEEK) and aluminium alloy (Al).

For the stepped cap, five diameters DZ2 (12 mm), DZ3 (14 mm), DZ4 (20 mm), DZ5 (24 mm) and DZ6 (26 mm) are defined as the inner and outer diameters of the depicted cylinders (Figure 2(a)). In addition, the length A3 (8 mm) is measured between two parallel planes created on two flat surfaces. For the ED housing, the diameters D1 (2 mm), D2 (3 mm), D3 (4 mm) and D4 (5 mm) are defined as diameters of cylinders (Figure 2(b)). The lengths A1 (8.5 mm), A2 (18.5 mm), A3 (28.5 mm), and A4 (38.5 mm) are measured between the plane created on the front flat surface and the respective bore axes and the length A5 (43.5 mm) is measured between two parallel planes created on the front and back side of the workpiece. The parallelism P is measured between the two parallel planes created on the top right surface and the surface with the bores on the left side.



(a) (b)

Figure 1: (a) Stepped cap, and (b) ED housing. The pictures show the two selected workpieces made of PEEK.



(a) (b)

Figure 2: Definition of measurands and visualization of the (tactile) sampling path for the stepped cap (a) and ED housing (b).

3. CMM Measurements

The calibration measurements for the stepped cap and the ED housing were performed on a Carl Zeiss O-Inspect 322 with a stated specified maximum permissible error for length measurements E_{MPE} = (2.4+L/150) µm (L in mm). The measurements were performed in a temperature controlled laboratory (20±0.5°C). To achieve comparable results between the CMM and CT measurements, a very high number of measuring points were used for all measurands (e.g., diameter DZ2 is estimated through scanning about 37,000 points in a helical path). The decision to take a very high number of measuring points was motivated by the fact that the physical interaction between tactile sensor/surface and tomographic sensor/surface differs, mainly due to the high density of points measured by CT and to the morphological filtering by the tactile probe [4]. The measured points were fitted using the least-square method (Gauss-fit). To reduce this tactile filtering of the surface roughness, for the stepped cap, a 0.25 mm diameter ruby probe was used and for the ED housing, both a 0.25 mm and a 1.5 mm diameter ruby probe were used. On the downside, the measuring time was quite high. The tactile measurements were considered as reference measurements throughout the present work. The expanded measurement uncertainty for the calibration process of stepped cap and ED housing was estimated based on VDI/VDE 2617 Part 11 [5], which is in accordance with GUM [6], using the associated expanded uncertainty:

$$U_{cal} = k \cdot \sqrt{u_{qual}^2 + u_p^2 + u_\alpha^2 + u_T^2 + u_{Rz}^2 + u_{\Delta L_X}^2} \quad (1)$$

where u_{qual} is the standard uncertainty of qualifying the stylus against a spherical standard. The contribution of the measurement result u_p is quantified through the standard deviation of the repeated measurements, where n is the number of

repeated calibration measurements (20) and $\bar{y}$ is the arithmetical mean of the measurement results. The standard uncertainty through the coefficient of thermal expansion u_α considers the average measured temperature during CMM measurements. According to VDI/VDE/DGQ 2618 Part 1.2 [7], a minimum standard deviation of the thermal expansions can be assumed as 20 % of the value ($\alpha_{PEEK} = 17 \cdot 10^{-6}$ K^{-1}, $\alpha_{Al} = 23.6 \cdot 10^{-6}$ K^{-1}) with a rectangular distribution. In addition, the temperature related uncertainty u_T is taken into account, again assuming a rectangular distribution. The influence of the surface roughness is represented by the mean value of the averaged roughness $R_{z,mean}$ determined by measuring the roughness of the workpieces three times with a MAHR Perthometer available at wbk (Table 1). The statement $R_{z,mean}/2$ generally gives an upper limit to the observed uncertainty effect of the roughness [8, 9], which is included in the uncertainty u_{Rz} with a rectangular distribution.
The uncertainty contributions $u_i(y)$ are obtained by taking into account the distribution factor b_i, which represents the shape of the distribution function (normal distribution b_i = 0.5, uniform distribution $b_i = 1/\sqrt{3} \approx 0.58$, type B estimation), and a sensitivity coefficient c_i, representing the partial derivatives of the model function of the individual influence quantities [5, 6]. Except for the repeatability, the contributions were all evaluated using type B evaluations. The uncertainty contributions were all considered to be independent of each other.

	ED housing		Stepped cap	
	PEEK	Aluminium	PEEK	Aluminium
$R_{z,mean}$ in µm	2.5	1.3	9.1	1.1

Table 1: Average roughness $R_{z,mean}$ of the workpieces.

To estimate the geometrical errors of the CMM for the distances and diameters $u_{\Delta LX}$, the length-dependent component of the E_{MPE} was used as an upper limit for the geometrical errors ΔL, taking into account the nominal size of the inspection characteristic (diameter or distance). A normal distribution was assumed. For the parallelism feature, the uncertainty contribution $u_{\Delta Lp}$ was estimated according to VDI/VDE 2617 Part 11 [5]. The expanded calibration uncertainties with their respective uncertainty contributions are stated in Tables 2-5.

Uncertainty contribution	**Measurands**					
	DZ2	**DZ3**	**DZ4**	**DZ5**	**DZ6**	**A3**
u_{qual}	0.4	0.4	0.4	0.4	0.4	0.4
u_p	1.7	1.4	1.7	0.4	0.4	4.5
u_{Rz}	0.3	0.3	0.3	0.3	0.3	0.3
u_α	0.0	0.0	0.0	0.0	0.0	0.0
u_T	0.1	0.1	0.1	0.2	0.2	0.1
$u_{\Delta LX}$	0.0	0.0	0.1	0.1	0.1	0.0
U_{cal} *(k=2)*	3.6	3.0	3.6	1.4	1.4	9.1

Table 2: Expanded calibration uncertainty for aluminium stepped cap. All values are in µm.

Uncertainty contribution	**Measurands**					
	DZ2	**DZ3**	**DZ4**	**DZ5**	**DZ6**	**A3**
u_{qual}	0.4	0.4	0.4	0.4	0.4	0.4
u_p	1.6	1.1	1.8	0.6	1.0	1.5
u_{Rz}	2.6	2.6	2.6	2.6	2.6	2,6
u_α	0.0	0.0	0.0	0.0	0.0	0.0
u_T	0.1	0.1	0.1	0.1	0.1	0.0
$u_{\Delta LX}$	0.0	0.1	0.1	0.1	0,.1	0.0
U_{cal} *(k=2)*	6.3	5.8	6.5	5.5	5.7	6.1

Table 3: Expanded calibration uncertainty for PEEK stepped cap. All values are in µm.

Uncertainty contribution	**Measurands**									
	P	**A1**	**A2**	**A3**	**A4**	**A5**	**D1**	**D2**	**D3**	**D4**
u_{qual}	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
u_p	2.3	0.7	1.2	1.6	1.0	1.0	0.3	2.0	0.5	0.4
u_{Rz}	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
u_α	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
u_T	-	0.1	0.1	0.2	0.3	0.3	0.0	0.0	0.0	0.0
$u_{\Delta LX}$	0.0	0.0	0.1	0.1	0.1	0.2	0.0	0.0	0.0	0.0
U_{cal} *(k=2)*	4.7	1.8	2.6	3.4	2.4	2.5	1.3	4.1	1.5	2.0

Table 4: Expanded calibration uncertainty for aluminium ED housing. All values are in µm.

Uncertainty contribution	Measurands									
	P	**A1**	**A2**	**A3**	**A4**	**A5**	**D1**	**D2**	**D3**	**D4**
u_{qual}	0,4	0,4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
u_p	2.4	2.2	2.1	2.1	2.0	1.8	8.7	8.9	8.7	8.3
u_{Rz}	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
u_α	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
u_T	-	0.0	0.1	0.1	0.2	0.2	0.0	0.0	0.0	0.0
$u_{\Delta LX}$	0.0	0.0	0.1	0.1	0.1	0.2	0.0	0.0	0.0	0.0
U_{cal} $(k=2)$	5.0	4.8	4.6	4.6	4.4	3.9	17.5	17.9	17.4	16.6

Table 5: Expanded calibration uncertainty for PEEK ED housing. All values are in µm.

4. CT Measurements

The measurements of the stepped cap and the ED housing were conducted using two CT systems of the types Zeiss Metrotom 800 at wbk and NIKON 225 at DTU. The scanning parameters are listed in tables 7 and 8 for the stepped cap and the ED housing, respectively. The choice of the scanning parameters reflects the structural differences between two CTs used in this work. Zeiss Metrotom 800 is a low energy CT while NIKON 225 is an example of high energy CT. The measurements conducted on NIKON 225 involved an online reference object, named CT crown, in order to establish traceability of measurements and to perform scale error correction (Figure 3). The scanning parameters were selected by two different operators according to their own experience. The workpieces were all mounted in a low absorption fixure made of polystyrol. The workpieces were scanned without being repositioned in order not to modify the fixture stiffness over the scanning time. The two CTs were both warmed up in order to reduce vertical and horizontal X-ray focus drifts as much as possible. A total of 20 scans were performed for each workpiece at wbk, while a total of 4 scans were conducted for each workpiece at DTU. The cabinet temperature was sampled during the CT measurements in order to detect any deviation from the reference temperature of 20 ºC. The CT data sets were subsequently evaluated with the inspection software VG Studio Max 2.2. A local-adaptive threshold method was used for the surface estimation. In order to have comparable data, the same alignment procedure and the same measurement strategy as for the tactile measurements were applied. Macro programs were used, such that the influence of the operator was reduced.

Parameter	Unit	Stepped Cap			
		PEEK (wbk)	Aluminium (wbk)	PEEK (DTU)	Aluminium (DTU)
Tube Voltage	kV	130	130	150	200
Current	µA	120	200	90	200
Integration Time	ms	1000	1000	1000	1000
Voxel Size	µm	33.85	40.15	45	45
No. of projections		1550	1550	1300	1300
Frames per projection		1	1	4	4
Prefilter	mm	/	0.25 (Copper)	2.5 (Aluminium)	2.5 (Aluminium)

Table 6: CT scanning parameters for the measurement of the stepped cap.

Parameter	Unit	ED housing			
		PEEK (wbk)	Aluminium (wbk)	PEEK (DTU)	Aluminium (DTU)
Tube Voltage	kV	130	130	150	200
Current	µA	200	300	90	200
Integration Time	ms	1000	1000	1000	1000
Voxel Size	µm	41.73	42.52	45	45
No. of projections		1550	1550	1300	1300
Frames per projection		1	1	4	4
Prefilter	mm	0.25 (Copper)	0.50 (Copper)	2.5 (Aluminium)	0.25 (Tin)

Table 7: CT scanning parameters for the measurement of ED housing

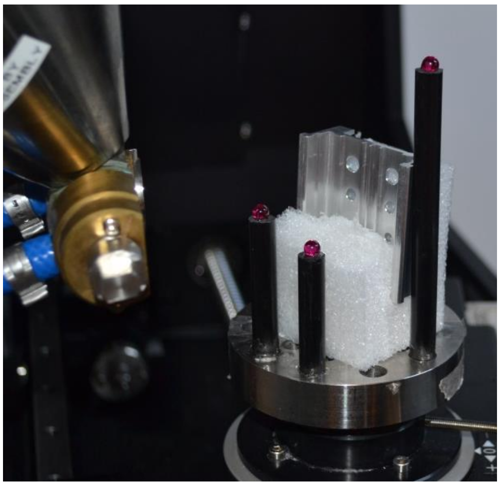


Figure 3: Setup for CT measurements at DTU (aluminium ED housing and CT crown as online reference object)

Measurement uncertainties for the CT measurements carried out at wbk were estimated according to VDI/VDE 2630 [4], as follows:

$$U_{CT,wbk} = k \cdot \sqrt{u_{cal}^2 + u_p^2 + u_w^2 + u_T^2 + b^2}. \tag{2}$$

Measurement uncertainties for CT measurements conducted at DTU were estimated following ISO 14253-2 [10]. The formula for uncertainty estimation for CT measurements is given by equation (3):

$$U_{CT,DTU} = k \cdot \sqrt{u_{crown}^2 + u_{tran}^2 + u_p^2 + u_T^2 + u_{noise}^2 + u_{datum}^2} \tag{3}$$

where k is the coverage factor at a confidence level of 95%, (k=2); u_{cal} is the standard uncertainty of the tactile reference measurements and u_p is the standard uncertainty from measuring process based on the CT measurements of the respective workpiece. The influence of the workpiece u_w can have various causes due to variations in material and production. In this study, the uncertainties of the thermal expansion coefficient (CTE) and of the surface finish of the workpieces were considered to quantify u_w; u_T is the evaluation of standard uncertainty due to the temperature variability; u_{crown} is the standard uncertainty of the CT crown, stated in the calibration certificate, u_{tran} is the standard uncertainty due to the correction that was quantified as the maximum standard deviation of the sphere-to-sphere distances used for the correction. This uncertainty was quantified to be 0.5 µm; u_{noise} is the standard uncertainty due to the noise based on the sphericity of two spheres of the CT crown. The deviation with respect to the reference values were assumed as the noise contribution. u_{datum} is the uncertainty contribution due to the repeatability of the datum system, based upon experience.
In contrast to the measurements at DTU, no scale error correction was performed at wbk. As a consequence, it was decided to include the bias b into the uncertainty calculation [5, 11].

The expanded CT uncertainties with its uncertainty contributions are stated for every workpiece in the Tables 9-12.

Mean values in mm	**Measurands**					
	DZ2	**DZ3**	**DZ4**	**DZ5**	**DZ6**	**A3**
$\bar{y}_{CT,wbk}$	11.9826	13.9988	19.9862	24.0009	26.0010	7.9969
$\bar{y}_{CT,DTU}$	11.9765	14.0010	19.9881	24.0016	25.9948	7.9969
$\bar{y}_{CMM}$	11.9829	13.9970	19.9862	23.9942	25.9941	7.9946
Uncertainty contribution in µm						
u_{cal}	1.8	1.5	1.8	0.7	0.7	4.5
u_p	0.3	0.6	0.3	1.0	1.0	0.3
u_w	0.3	0.3	0.3	0.3	0.3	0.3
u_T	0.4	0.5	0.7	0.8	0.9	0.3
$b_{wbk\text{-}CMM}$	0.3	1.8	0.0	6.7	6.9	2.3
$b_{DTU\text{-}CMM}$	6.4	4	1.9	7.4	0.7	2.3
$U_{CT,wbk}$ $(k=2)$	3.8	4.9	4.0	13.8	14.2	10.2
$U_{CT,DTU}$ $(k=2)$	10.0	10.0	10.0	10.0	10.0	10.0

Table 8: CT uncertainty for aluminium stepped cap.

Mean values in mm	**Measurands**					
	DZ2	**DZ3**	**DZ4**	**DZ5**	**DZ6**	**A3**
$\bar{y}_{CT,wbk}$	11.9894	13.9921	19.9964	24.0078	26.0089	7.9984
$\bar{y}_{CT,DTU}$	11.9840	13.9940	19.9960	23.9950	25.9947	7.9966
$\bar{y}_{CMM}$	11.9903	13.9859	19.9963	23.9982	25.9991	7.9969
Uncertainty contribution in µm						
u_{cal}	3.1	2.9	3.2	2.7	2.8	3.1
u_p	0.6	0.4	1.1	1.1	1.3	0.3
u_w	2.6	2.6	2.6	2.6	2.6	2.6
u_T	0.3	0.3	0.4	0.5	0.6	0.2
$b_{wbk\text{-}CMM}$	0.9	6.2	0.1	9.6	9.8	1.5
$b_{DTU\text{-}CMM}$	6.3	8.1	0.3	3.2	4.4	0.3
$U_{CT,wbk}$ $(k=2)$	8.5	14.8	8.7	20.8	21.2	8.7
$U_{CT,DTU}$ $(k=2)$	10.0	10.0	10.0	10.0	10.0	10.0

Table 9: CT uncertainty for PEEK stepped cap.

Mean values in mm	**Measurands**									
	P	**A1**	**A2**	**A3**	**A4**	**A5**	**D1**	**D2**	**D3**	**D4**
$\bar{y}_{CT,wbk}$	0.0316	8.4890	18.4918	28.4820	38.4785	43.4729	1.9663	2.9714	3.9663	4.9668
$\bar{y}_{CT,DTU}$	0.0338	8.4791	18.4760	28.4813	38.4690	43.4732	1.9555	2.9515	3.9527	4.9550
$\bar{y}_{CMM}$	0.0247	8.4824	18.4808	28.4871	38.4783	43.4709	1.9555	2.9535	3.9570	4.9597
Uncertainty contribution in µm										
u_{cal}	2.4	0.9	1.3	1.7	1.2	1.2	0.7	2.0	0.8	1.0
u_p	1.5	6.3	8.0	1.9	1.7	1.9	1.2	1.7	1.6	1.2
u_w	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
u_T	0.0	0.3	0.6	1.0	1.3	1.5	0.1	0.1	0.1	0.2
$b_{wbk\text{-}CMM}$	6.8	6.6	11.0	5.1	0.2	2.1	10.8	17.9	9.4	7.1
$b_{DTU\text{-}CMM}$	9.1	3.3	4.8	5.8	9.3	2.3	0.0	2.0	4.3	4.7
$U_{CT,wbk}$ $(k=2)$	14.7	18.3	27.3	11.7	5.0	6.8	21.8	36.2	19.1	14.6
$U_{CT,DTU}$ $(k=2)$	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0

Table 10: CT uncertainty for aluminium ED housing.

Mean values in mm	**Measurands**									
	P	**A1**	**A2**	**A3**	**A4**	**A5**	**D1**	**D2**	**D3**	**D4**
$\bar{y}_{CT,wbk}$	0.0379	8.5107	18.5133	28.5153	38.5169	43.5244	1.9464	2.9544	3.9543	4.9748
$\bar{y}_{CT,DTU}$	0.0338	8.5101	18.5086	28.5104	38.5108	43.5129	1.9440	2.9530	3.9546	4,9691
$\bar{y}_{CMM}$	0.0333	8.5068	18.5086	28.5112	38.5111	43.5169	1.9640	2.9714	3.9707	4.9898
Uncertainty contribution in µm										
u_{cal}	2.5	2.4	2.3	2.3	2.2	2.0	8.8	9.0	8.7	8.3
u_p	3.1	0.3	0.3	0.4	0.4	0.3	0.6	0.6	0.6	0.8
u_w	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
u_T	0.0	0.2	0.5	0.7	0.9	1.1	0.0	0.1	0.1	0.1
b_{wbk}	4.6	4.0	4.6	4.1	5.7	7.5	17.7	17.0	16.4	15.0
b_{DTU}	0.5	3.3	0.0	0.8	0.3	4.0	20.0	18.4	16.1	20.7
$U_{CT,wbk}$ $(k=2)$	12.3	9.4	10.5	9.7	12.6	15.7	39.5	38.5	37.2	34.4
$U_{CT,DTU}(k=2)$	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0

Table 11: CT uncertainty for PEEK ED housing.

5. Comparison and discussion

Figure 4 shows the measurement results for all workpieces considered within the work. The y-axis represents the bias of the CT measurements to the average CMM values. The error bars depict the expanded uncertainties. These results are reported after scale error and temperature correction. It can be seen from the figure that a good agreement between CMM and CT results was obtained for most measurements. Inner and outer measurands show the same level of accuracy, suggesting that image artefacts were fully minimized. As a general consequence, the wall thickness does not influence the dimensional accuracy in this investigation.

The comparability of the results was checked by calculating the $|E_n|$ values, according to ISO/IEC 17043 [12] (Equation (4)) with $\bar{y}_{M,1}$, $\bar{y}_{M,2}$ the mean values of the measuring machines and $U_{M,1}$, $U_{M,2}$ the associated expanded uncertainty.

$$E_n = \frac{\bar{y}_{M,1} - \bar{y}_{M,2}}{\sqrt{U_{M,1}^2 + U_{M,2}^2}} \tag{4}$$

In all but one case the $|E_n|$ values between the CTs and CMM were smaller than 1, showing a very good agreement between the results. The only $|E_n|$ value larger than 1 occurred at the diameter D4 of the PEEK ED housing ($|E_n| = 1.07$) between the CT at

DTU and the CMM. Because the bias was added squared under the root, the expanded uncertainty of measurement of the CT at wbk were generally higher, causing smaller |En| value in comparison with DTU.
Through the comparison of the CMM and CTs, noticeable deviations were noticed for the bore diameters of the ED housing made of PEEK. Both wbk and DTU results differ from the CMM measurement in the range of 15 µm to 20 µm. Due to the deviation of the CMM, an investigation on the change (drift) of the workpiece or CMM over time since the calibration was carried out. Therefore, about 5 months after the initial calibration, another series of measurements for the PEEK ED housing was perfomed again on the Zeiss CMM and additionally on a Werth Video Check HA 400 (E_{MPE} = (1.5+L/500) µm (L in mm)).

Mean values in mm	**Measurands**			
	D1	D2	D3	D4
$\bar{y}_{CMM,\ initial}$	1.964	2.971	3.971	4.990
$\bar{y}_{CT,wbk}$	1.946	2.954	3.954	4.975
$\bar{y}_{CT,DTU}$	1.944	2.953	3.955	4.969
$\bar{y}_{Werth}$	1.945	2.952	3.952	4.970
$\bar{y}_{CMM,current}$	1.944	2.950	3.947	4.967

Table 12: Mean values of the bore diameters of the PEEK ED housing including the recalibration measurements.

The measurements were repeated three times with the initial CMM, showing acceptable deviations compared to the first tactile measurement series. The deviations range from 0.4 µm to 4.3 µm for all workpieces but for the bore diameters of the PEEK ED housing. The drift of the diameters of the PEEK ED housing accounts for 20 µm to 23 µm. The measurements with the Werth CMM confirm these results (Table 12). The results of the tactile recalibration measurements hence were similar to the CT results (maximal deviation of 5 µm).
Several factors can possibly account for the deviations to the first set of CMM measurements. First, there is the possibility of a mismeasurement (e.g. outlier) caused by contamination or erroneous qualification of the probes. Second, there is the influence of the production and material. The manufacturing of the PEEK workpieces is generally more difficult, possibly resulting in higher geometrical errors and not removed burrs. An investigation of the cylindricality of the bores of the PEEK and aluminium workpieces showed similar results for both materials, ranging from 0.20 mm to 0.30 mm, but small burrs were visible on the PEEK ED housing. This may also explain the relatively high calibration uncertainty of the bore holes. Another influence is the dimensional stability. The shape of the ED housing may have changed over the time, resulting in a dimensional change in the diameters. This effect was assumed to be negligible because most of measurands were found to be similar over time as well as PEEK stepped cap, which was manufactured using the same raw material, appeared to be dimensionally stable during the period of this work.

6. Conclusion

In general, it has been shown that CT measurements performed under different scanning conditions and different machines are in good agreement. Except for the small bores, the two methods of uncertainty evaluation for the CT measurements also mostly lead to similar uncertainties in the range up to 16µm. The high drift between the initial CMM measurements of the small bore holes of the PEEK ED housing and the later CT and CMM measurements results in an overestimation of the CT uncertainty, if the bias is included in the evaluation. In future, the workpieces should be recalibrated after some time, to evaluate if the effect of workpiece drift further occurs.

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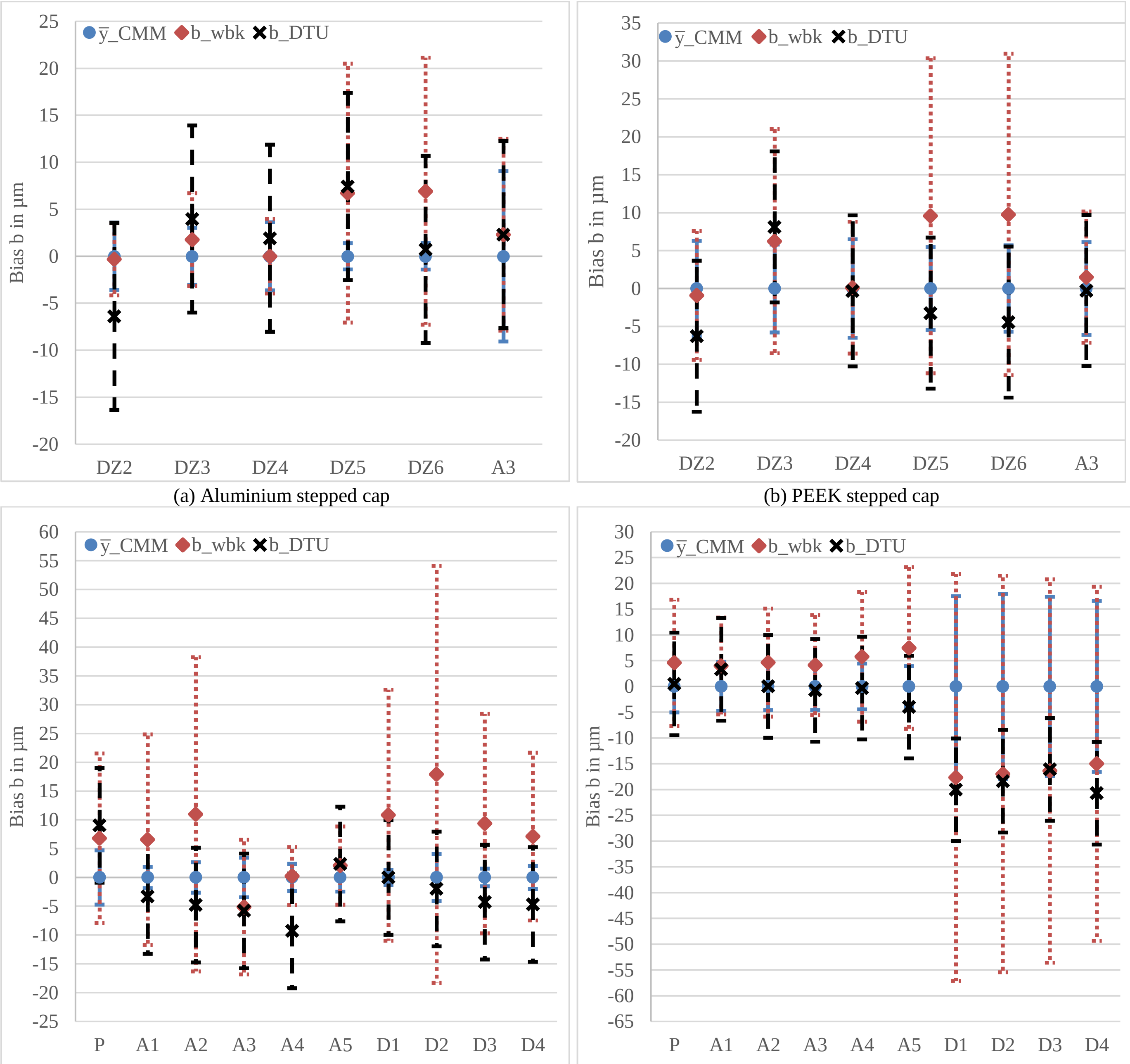

(a) Aluminium stepped cap

(b) PEEK stepped cap

(c) Aluminium ED housing

(d) PEEK ED housing

Figure 4: Comparison of the measuring results from the two CTs and the CMM: the bias b from the CMM value is shown. The error bars represent the expanded uncertainties.

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