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METAS-CT: Metrological X-ray computed tomography at sub-micrometre precision

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Abstract

X-ray computed tomography (CT) is becoming increasingly popular in dimensional metrology [1]. Therefore, research projects are being carried out to put CT measurements on a solid metrological foundation, *i.e.* mitigate error sources and establish traceability [2,3]. Furthermore, we developed a high-resolution CT system, called METAS-CT, to meet the requirements of precision engineering [4]. Here, we present the developed METAS-CT system and report on measures that were implemented to improve the precision of unidirectional CT measurements to the sub-micrometre level. The instrument is capable of measuring parts smaller than 4 mm with a resolution of about 1 µm. A key element of METAS-CT is an interferometric measurement system that enables the machine geometry to be monitored and compensated online with the goal to generate accurate and traceable dimensional CT measurements. Furthermore, cooling systems have been implemented to absorb the heat generated by the different components and keep the system stable for scan times of more than 10 hours. In conclusion, a microtechnology use case will be presented.

Industrial X-ray computed tomography, dimensional metrology, high-resolution, microtechnology, micro-parts, additive manufacturing

1. Introduction

X-ray computed tomography's (CT) unique ability to penetrate through materials and visualise internal structures, renders it a powerful tool for combined dimensional and defect analysis. It is thus becoming increasingly popular and accepted in dimensional metrology. However, establishing metrological traceability is still very challenging due to a large number of error sources. Thus, a simple, straightforward approach for task-specific measurement uncertainty is still lacking [1,5]. The principle of CT for verification of geometric dimensioning and tolerancing (GD&T) is depicted in figure 1: Radiographs of the workpiece are recorded from different angles, usually by rotating the workpiece. A 3D representation is reconstructed from those radiographs, whereafter the object surface is determined by a segmentation step. Finally, dimensional measurements can be taken by fitting geometric primitives to a subset of surface points.

Our high-resolution CT machine, called METAS-CT, was built to contribute to metrological CT research and provide a CT machine tailored for small parts, few millimetres in size [4]. It is comprehensively characterised, enabling us to quantify different error sources. Currently, research projects that investigate questions concerning metrological traceability [2] and explore applications, *e.g.* for additive manufacturing [3], are being performed. The challenge that high-resolution CT poses is that scan times scale non-linearly with the desired structural resolution. For example doubling the resolution, theoretically increases CT scan times 16 fold, *e.g.* from 30 min to 8 h. This poses high demands on CT machine stability and/or requires appropriate compensation algorithms.

In this paper, we discuss the high-resolution metrological CT, METAS-CT, in detail, including measures taken to improve the performance, and conclude the paper with a use case in microtechnology.

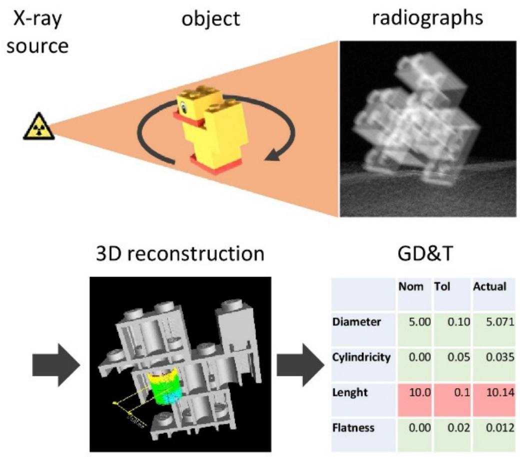

Figure 1. Principle of X-ray computed tomography (CT) for verification of geometric dimensioning and tolerancing (GD&T): Radiographs of the workpiece are recorded from different angles and reconstructed into 3D volume data that is used for dimensional measurements.

2. METAS-CT: A high-resolution metrology CT

2.1. CT system overview

METAS-CT is tailored for dimensional measurement of workpieces a few millimetres in size (figure 2). It consists of a high-resolution X-ray tube and flat-panel detector (see reference [4] for details). An accurate and stable positioning system based on air-bearing linear and rotary axes ensures small guideway errors [6]. All heat sources within the radiation-shielded cabin are managed by METAS-CT's temperature control system to ensure long-term stability. It comprises air conditioning, three individual water cooling circuits and 30 calibrated temperature sensors. The sensor signals are used for monitoring as well as to numerically compensate for thermal expansion.

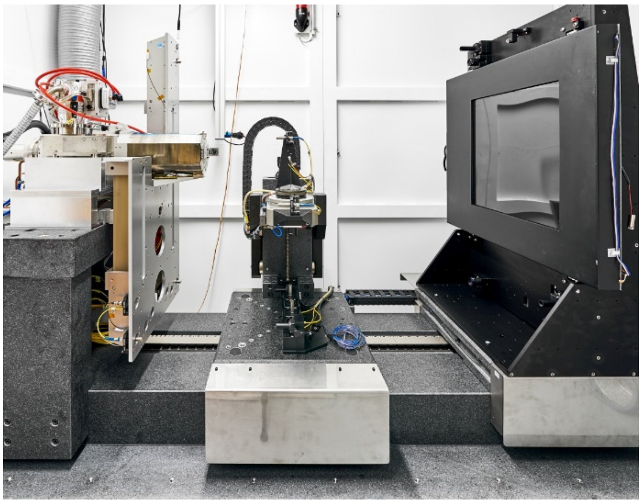

Figure 2. METAS-CT, a high-resolution metrology CT system tailored for dimensional measurements for precision engineering: The X-ray tube is visible on the left, the rotary stage for the workpiece in the middle, and the flat-panel detector on the right. The L-shape metrology frame, to which sensors of the CT geometry measurement system are attached, is mounted close to the X-ray tube.

2.2. CT geometry measurement system

Knowing the geometrical arrangement of the CT machine, *i.e.* the relative position of the X-ray source spot, the axis of rotation and the detector plane, is critical in order to obtain accurate CT data. A static CT geometry can be parametrised using seven degrees of freedom (DoF) [7]. However, when assuming a dynamic CT geometry, *e.g.* due to drift, nine DoF are required [8]: Three translational DoF for the X-ray source and three translational and three rotational DoF for the X-ray detector. This under the assumption that the X-ray source, *i.e.* the focal spot, is a point and the detector has a planar active surface with isotropic pixels. The former can be complied by operating the X-ray tube at appropriate parameters to keep the focal spot size below the voxel size. The latter did not hold and was corrected separately as described in reference [9].

To measure the CT machine geometry, a system consisting of eight interferometers, five optical straightness sensors, three optical position sensors, and the rotary axis encoder is employed. As shown in figure 3, all measurements are taken relative to a metrology frame. Besides the source - rotary axis distance (SRD) and the rotary axis - detector distance (RDD), which determine the magnification, all straightness and angular deviations of the detector and the rotary axis are measured as well. The system measures 25 DoF in total that are condensed into the CT system's 15 DoF in the machine coordinate system; 3 DoF for the X-ray source, 6 DoF for the rotation axis and 6 DoF for the flat-panel detector. By transformation into a CT coordinate system, with the origin defined by either the rotary axis or the detector, this reduces to 9 DoF. In order to establish the positions of the components relative to each other, a radiographic calibration, employing a calibrated multi-sphere standard, is required [8]. This procedure is limiting the accuracy of the whole CT geometry measurement and is still being improved at this time. Finally, the measured deviation from the ideal CT geometry for each radiograph is then provided to the reconstruction algorithm to compensate for it.

2.3. Reference measurements

Multi-sphere standards are common reference objects for performance evaluation of dimensional CT systems. Since the unidirectional measurement between sphere centres is very robust towards common CT artefacts, such as beam hardening, they are ideal to assess the geometrical accuracy of the CT, *i.e.* drift and scaling errors. They, however, are not suited to assess task-specific measurement uncertainties, because they represent a best-case scenario [10]. To determine the maximum achievable accuracy, two multi-sphere standards, one with 21 ruby spheres arranged in a cylindrical volume of Ø 4 mm x 1.8 mm (METROTOM Check nano [11]) and one with 17 steel spheres in a volume of Ø 25 mm x 20 mm (METAS-MSS-Alu [8]), were employed. CT scans with voxel sizes of, respectively, 1 µm and 7 µm for the Ø 4 mm and the Ø 25 mm standards were recorded. The sphere centres were determined by fitting spherical primitives to the CT data. Subsequently, the unidirectional sphere centre-to-centre distances were calculated, globally scale-corrected and compared to high-accuracy tactile reference data from the METAS µCMM [12] ($U_{\mu\mathrm{CMM},k=2} = 0.14\ \mu\mathrm{m}$). As shown in figure 4, the scale-corrected deviations were within $\pm(0.3\ \mu\mathrm{m} + 2 \cdot 10^{-5} L)$, where L is the measured length.

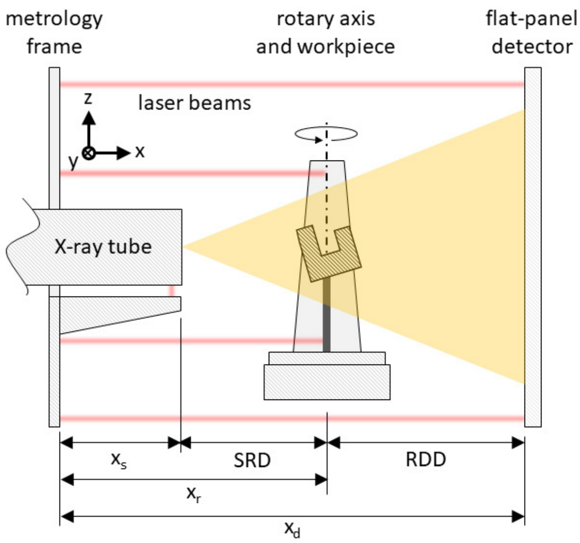

Figure 3. Oversimplified representation of the METAS-CT measurement system: The positions of the X-ray source, the rotary axis, and the flat-panel detector are measured relative to a metrology frame using interferometers and optical position sensors. Thereof, the source - rotary axis distance (SRD) and rotary axis - detector distance (RDD) can be derived.

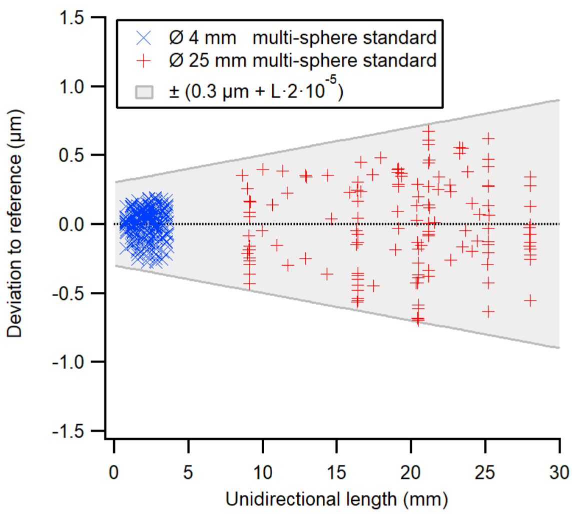

Figure 4. Unidirectional sphere centre-to-centre distances measured on the metrology computed tomograph METAS-CT (scale corrected data).

3. Microtechnology use case

3.1. Glass test workpiece

The test workpiece (figure 5), kindly provided by the *Association Suisse pour la Recherche Horlogère* (ASRH), was microfabricated from glass using the FEMTOPRINT® technology. Its total length is about 15 mm, its width 6.6 mm, and its thickness 0.2 mm. Its fragile nature makes tactile calibration challenging or even impossible for certain features. Therefore, it is an excellent example for the application of dimensional CT.

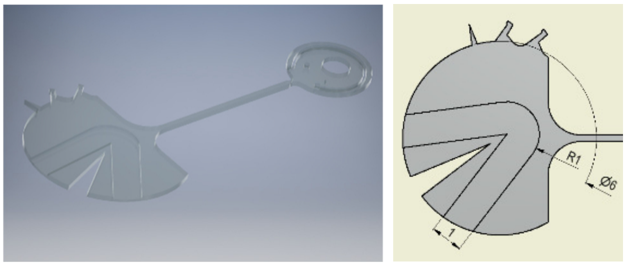

Figure 5. CAD of the glass test workpiece: a microfabricated test workpiece (length: 15 mm); the features analysed in this paper are indicated in the drawing on the right.

3.2. CT measurement uncertainty

To asses a task-specific measurement uncertainty for dimensional CT is challenging due to the large number of error sources, which non-intuitively influence the final measurement results. The measurement uncertainty estimation approaches can be split into two major groups: simulation based and reference object based. Simulations can either be based on physical [13,14] or ray-tracing models [7]. The reference object based approach, either relies on calibrated workpieces very similar to the measured ones, termed substitution method [15,16], or on machine specifications [17–19]. Whereas employing simplified numerical models or machine specifications is very straightforward and quick, they tend to over- or underestimate the measurement uncertainty, because certain sources of error are neglected. Methods that cover all influences, such as physical models or the substitution method, are complex and very time consuming; either because many simulation iterations or measurement repetitions are required. Therefore, as a pragmatic solution, we suggest a hybrid approach that relies on measurements of a calibrated reference object and a single simulation of the workpiece under investigation, based on physical models. Whereas CT scans of reference objects cover the intrinsic accuracy, limited by the geometry and stability of the CT machine, the simulation covers influences by X-ray - material interactions, *e.g.* beam hardening, and the measurement and analysis process. The reference object measurement was performed as described in section 2.3, whereby the uncertainty of the tactile calibration u_{ref} and the deviations of the unidirectional measurements, representing the process uncertainty u_p, were considered. The simulation was performed in aRTist 2 [20] and yields systematic deviations b between the nominal CAD value and the one from the simulation for each feature. Since the simulation employs a polychromatic X-ray spectrum, it accounts for beam hardening effects and flat-panel detector efficiency. Furthermore, systematic deviations from the reconstruction, surface determination and analysis algorithms are also considered. Finally, the workpiece's thermal expansion $u_{w,t}$ and fit point standard deviation from the measured feature $u_{w,s}$, affected by surface roughness, form deviation and noise in the data, is also taken into account.

The measured features are located on the larger disk of the test workpiece to enable tactile reference calibration. They include the outer diameter of the disk and the groove radius and width (see figure 5). Their CT measurement uncertainty budgets are shown in table 1 and were calculated according to [21]: $U_{CT,k=2} = k\sqrt{u_{ref}^2 + u_p^2 + u_{w,t}^2 + u_{w,s}^2 + b^2}$.

For the circular features, the fit point deviation $u_{w,s}$ is the dominant measurement uncertainty contribution. In contrast, the groove's uncertainty is mainly determined by the process uncertainty u_p and the systematic deviation b. Whereas the workpiece influence $u_{w,s}$ cannot be altered, we expect to reduce u_p further in the future; it is emphasised that for this measurement only a static CT geometry compensation was performed due to the stage of development of the CT machine. As expected for such short measurement lengths, the influence of the thermal expansion $u_{w,t}$ is negligible. The systematic deviations b, determined by simulations, might be reduced in the future by X-ray beam filtering, beam hardening corrections and software optimisation. They, however, were rather low in this specific case due to the light material and small object size. In less ideal conditions, such as larger, denser and/or multi-material workpieces, they can become the dominant measurement uncertainty contribution.

Table 1. CT measurement uncertainty budget for measured features on the test workpiece.

Uncertainty contribution	Outer Ø 6 mm	Inner radius 1 mm	Groove width 1 mm
u_{ref} (µm)	0.07	0.07	0.07
u_p (µm)	0.58	0.58	0.58
$u_{w,t}$ (µm)	0.02	0.00	0.00
$u_{w,s}$ (µm)	1.88	1.00	0.40
b (µm)	0.35	0.46	0.59
$U_{CT,k=2}$ (µm)	4.00	2.49	1.84

3.3. CT measurement and results

The test workpiece was CT scanned on METAS-CT employing a helical scan trajectory with a voxel size of 1.8 µm. The data were reconstructed in Siemens CERA and analysed using VG Studio MAX. The workpiece surface was determined using the local gradient method, *i.e.* the *advanced surface determination*. 1000 fit points were evenly distributed along the geometric primitives using the *smart expand* algorithm in VG; points lying further away than 3 σ were removed.

A representation of the CT data of the test workpiece is shown in figure 6. Figure 7 shows the comparison between the µCMM and METAS-CT results, with the µCMM as the reference. All results agree within their task-specific measurement uncertainties. All other features on the test workpiece were also characterised. However, they lack a tactile reference measurement, due to the fragile nature of the beam connecting the two disks.

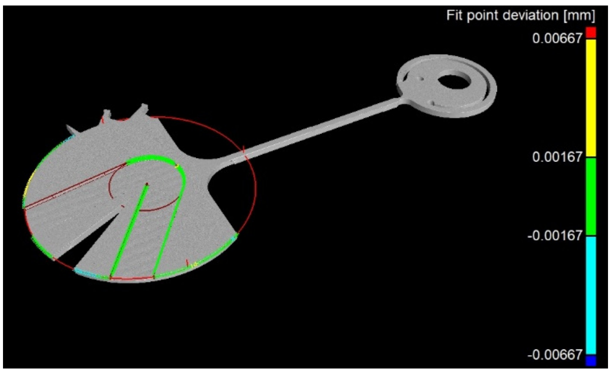

Figure 6. CT data of the glass test workpiece. The used fit points of the three measured features are colour coded according to the deviation scale.

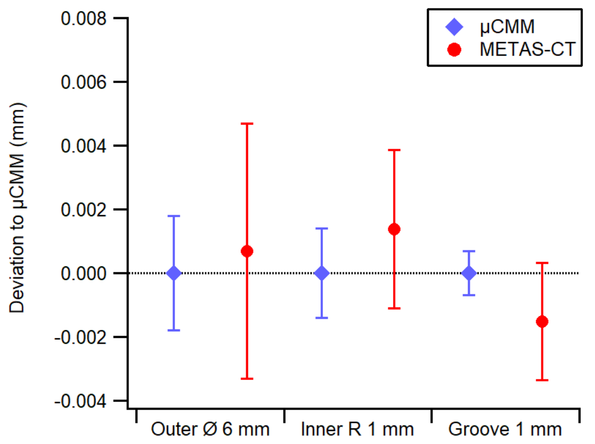

Figure 7. Deviation between METAS-CT and the μCMM (reference) for the measured features on the glass test workpiece.

4. Conclusions

We presented a high-resolution metrology CT, METAS-CT, and evaluated its performance. With the discussed improvements, task-specific measurement uncertainties of about 1 µm will come within reach for small workpieces. In comparison, state-of-the-art CT measurement uncertainties usually range from a few up to tens of micrometres [13,16,18].

Future work on the instrument will include additional improvements of the calibration procedure of the CT geometry measurement system and X-ray energy dependent corrections [22]. Furthermore, there is plenty of room for improvement concerning the correction of CT artefacts, such as beam hardening, and quantify their influence on dimensional measurements. A simulation-based Monte-Carlo measurement uncertainty estimation will be developed within the framework of the EMPIR research project AdvanCT [2]. In addition, quality assurance of additive manufacturing (AM) processes using CT is gaining in importance. This includes AM powder characterisation (size, morphology, air inclusions), workpiece porosity and surface roughness analyses, and dimensional measurements [3].

Acknowledgments

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References

[1] Zanini F and Carmignato S 2019 X-Ray Computed Tomography for Dimensional Metrology *Metrology. Precision Manufacturing* ed W Gao (Springer, Singapore) pp 1–48

[2] EMPIR 17IND08 AdvanCT - Advanced computed tomography for dimensional and surface measurements in industry https://www.ptb.de/empir2018/advanct/

[3] H2020 MANUELA - Additive Manufacturing using Metal Pilot Line https://manuela-project.eu/

[4] Bircher B A, Meli F, Küng A and Thalmann R 2017 Towards metrological computed tomography at METAS *euspen's 17th International Conference & Exhibition* (Hannover, Germany)

[5] Leach R, Carmignato S and Dewulf W 2018 *Industrial X-Ray Computed Tomography* (Cham: Springer International Publishing)

[6] Bircher B A, Meli F, Küng A and Thalmann R 2018 Characterising the Positioning System of a Dimensional Computed Tomograph (CT) *MacroScale - Recent developments in traceable dimensional measurements* (Espoo, Finnland)

[7] Ametova E, Ferrucci M, Chilingaryan S and Dewulf W 2018 A computationally inexpensive model for estimating dimensional measurement uncertainty due to x-ray computed tomography instrument misalignments *Meas. Sci. Technol.* **29** 065007

[8] Bircher B A, Meli F, Küng A and Thalmann R 2019 CT geometry determination using individual radiographs of calibrated multi-sphere standards *9th Conference on Industrial Computed Tomography (iCT 2019)* (Padova, Italy)

[9] Lüthi M, Bircher B A, Meli F, Küng A and Thalmann R 2020 X-ray flat-panel detector geometry correction to improve dimensional computed tomography measurements *Meas. Sci. Technol.* **31** 035002

[10] Bartscher M, Sato O, Härtig F and Neuschaefer-Rube U 2014 Current state of standardization in the field of dimensional computed tomography *Meas. Sci. Technol.* **25** 064013

[11] Weiß D, Kimmig W, Lonardoni R, Ilzhöfer M, Krenkel M and Kuhn C 2019 Verifying the measurement accuracy for X-ray cone-beam CT scans of objects smaller than 5 mm diameter *9th Conference on Industrial Computed Tomography (iCT 2019)* (Padova, Italy)

[12] Küng A, Meli F and Thalmann R 2007 Ultraprecision micro-CMM using a low force 3D touch probe *Meas. Sci. Technol.* **18** 319–27

[13] Wohlgemuth F and Hausotte T 2018 Development of a virtual metrological CT for numerical measurement uncertainty determination using aRTist 2 *tm – Tech. Mess.*

[14] Helmecke E, Fleßner M, Kaufmann M, Staude A and Hausotte T 2016 Numerical measurement uncertainty determination for dimensional measurements of microparts with CT *6th Conference on Industrial Computed Tomography (iCT 2016)* (Wels, Austria)

[15] Schmitt R and Niggemann C 2010 Uncertainty in measurement for x-ray-computed tomography using calibrated work pieces *Meas. Sci. Technol.* **21**

[16] Müller P, Hiller J, Dai Y, Andreasen J L, Hansen H N and De Chiffre L 2014 Estimation of measurement uncertainties in X-ray computed tomography metrology using the substitution method *CIRP J. Manuf. Sci. Technol.* **7** 222–32

[17] Dewulf W, Kiekens K, Tan Y, Welkenhuyzen F and Kruth J-P 2013 Uncertainty determination and quantification for dimensional measurements with industrial computed tomography *CIRP Ann. - Manuf. Technol.* **62** 535–8

[18] Jiménez R, Torralba M, Yagüe-Fabra J A, Ontiveros S and Tosello G 2017 Experimental approach for the uncertainty assessment of 3D complex geometry dimensional measurements using computed tomography at the mm and sub-mm scales *Sensors (Switzerland)* **17**

[19] Villarraga-Gómez H, Lee C B and Smith S T 2018 Dimensional metrology with X-ray CT: A comparison with CMM measurements on internal features and compliant structures *Precis. Eng.* **51** 291–307

[20] Bellon C, Deresch A, Gollwitzer C and Jaenisch G 2012 Radiographic Simulator aRTist : Version 2 *18th World Conference on Nondestructive Testing* (Durban, South Africa)

[21] Klauenberg K, Wübbeler G and Elster C 2019 About not Correcting for Systematic Effects *Meas. Sci. Rev.* **19** 204–8

[22] Illemann J, Neuschaefer-Rube U, Bartscher M and Bate D 2018 Determining spectrum-dependent source and detector positions in cone-beam CT *8th Conference on Industrial Computed Tomography (iCT 2018)* (Wels, Austria)