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Measurement accuracy in X-ray computed tomography metrology: Toward a systematic analysis of interference effects in tomographic imaging

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ABSTRACT

In this paper an investigation of interference effects leading to limitations of metrological performance of X-ray computed tomography (CT) used as a coordinate measuring technique is presented. Using reconstruction data, image quality metrics, and calculations of artifact formation, a deeper understanding and explanation of the physical and technical limitations of CT used in dimensional metrology is given. This is demonstrated in a case study using a simple hollow cylinder made of steel as a test object and calibration measurements from a tactile coordinate measuring machine (CMM). Two different threshold determination strategies for surface computation are applied. Within the study it is also shown that CT image properties, threshold determination strategies, and systematic and random measurement errors must have a definite correlation. As a conclusion it is recommended to focus more strongly on the correlation of local CT image quality and data evaluation operations in order to reduce systematic errors in surface computation and to increase repeatability of dimensional CT measurements.

1. Introduction

X-ray tomography (CT) is a type of imaging technique, enabling the reconstruction of 2D and 3D images of objects from various materials. Non-destructive material testing and characterization using different kinds of industrial CT scanners are two well-established fields of application [1]. Alongside, during the last 10 years CT has been successfully established in dimensional and geometrical metrology as a tool for first sample inspection and geometrical tolerance verification of industrial components for a fast product development and quality assurance [2–5]. Besides the variety of application fields, CT measurements in general and dimensional CT measurements in particular are rather complex. Dimensional measurements have to be traceable to the meter unit and the uncertainty must be stated in order to reliably decide if an industrial component is within or outside specification [6,7]. It is well-known in dimensional CT that effects from image scaling, image artifacts, unsharpness and noise in connection with non-optimal threshold and data evaluation strategies result in systematic measurement errors and limit repeatability of CT measurements [8–10,2]. Several authors have shown in detail within research studies the impact of image artifacts, artifact compensation and threshold methods as well as other effects linked with CT scan parameters (image quality) on the result of CT measurements by uncertainty evaluations using experimental and simulated data [11–15,9,16,17]. Furthermore, DeWulf et al. studied uncertainties in voxel size determination and edge detection on length measurements [18] and Carmignato [19] and Angel et al. [20] demonstrated by an international comparison the metrological performance of CT scanners using calibrated samples and industrial components. In simulation studies it was shown that there is a definite correlation of CT image quality and systematic measurement errors [21,9,17]. However, it is still a major problem to make sure that these effects and influences are compensated or at least minimized so that (primarily) random error contributions determine measurement uncertainty. In contrast to the mentioned studies the focus of the present work goes a step further in the sense that systematic effects and its impact on thresholds and surface accuracy, respectively, using reference data are investigated, taking into account the physics of CT image formation on the basis of analytical models. A hollow cylinder made of steel is used as measuring object and an analysis of systematic

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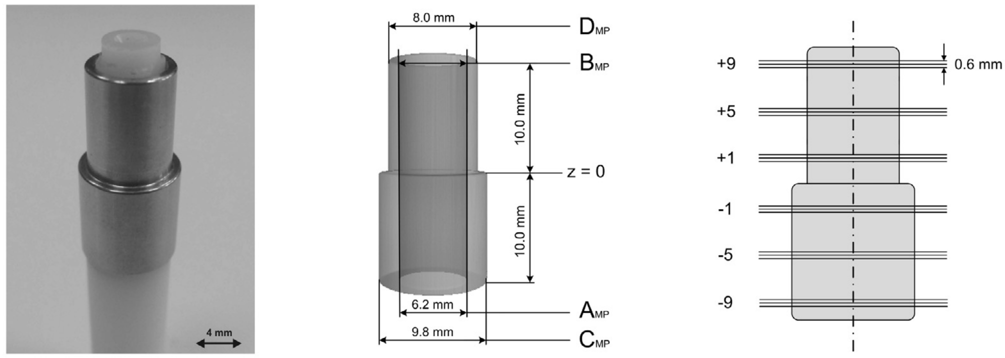

(a) Test object (b) Features (c) Positions

Fig. 1. Hollow cylinder test object (a). The nominal dimensions and features to be measured are indicated in (b). At 12 measurement positions a cylinder element is fitted using 3 circle measurements in each case (c).

effects is performed using reconstruction images, pre-knowledge from characterization measurements, image quality characteristics, and reference values from tactile calibration measurements. It is demonstrated how a systematic analysis can be performed in such a way that both a deeper understanding of CT image formation and hence a reduction of measurement errors can be achieved. The paper is organized as follows. At first, Section 2 deals with materials and methods in terms of a description of the used test object, measurands, calibration measurements, and CT scan settings. In Section 3, effects on CT measurements are analyzed. Simple image quality metrics are then used to establish a correlation between local image quality and threshold errors. Two threshold strategies are selected and described in Section 5. The measurement strategy and the results of the measurements are presented and discussed in Section 6. The paper ends with conclusions based on the results obtained and suggestions to further work.

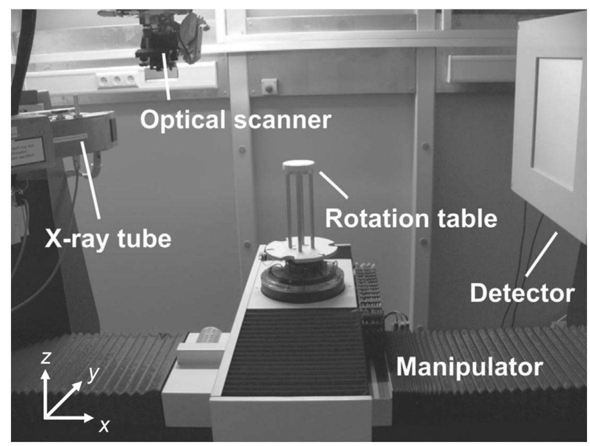

Fig. 2. Micro CT scanner *Tomolibri®*.

2. Materials and methods

2.1. Measuring object and definition of measuring tasks

A hollow cylinder made of stainless steel (X20Cr13) is used as test object. This test object has been already used in several studies [22–24]. Due to its rotation symmetry and simplicity, influences on image formation can be studied in a more systematic and better way as if complex shaped objects were used. Relatively high photon energy must be applied for penetration and interferences, in particular from beam-hardening and scatter radiation on CT image quality, are expected. A photography of the object, its nominal dimensions and the inner and outer geometrical features A_{MP}, B_{MP}, C_{MP}, D_{MP} are shown in Fig. 1(a) and (b). The measurement tasks consist of the determination of the diameters and the coaxility of inner and outer cylinders at 12 positions. In each height the inner and outer diameter of the object is measured using the compensation element *cylinder* consisting of three circles within a total height of 0.6 mm. Fig. 1(c) illustrates the measurement positions.

2.2. Calibration procedure using a tactile CMM

The calibration measurement was performed on a Zeiss UPMC 1200 CARAT in an accredited calibration laboratory. For each circle 40 measuring points were used which gives 120 measuring points per position in total. The least-square method was used to fit a cylinder element into the circles at each position. A probing ball with 0.8 mm in diameter was used. The task-specific calibration uncertainty was calculated using the *Virtual Coordinate Machine* [25], where a temperature of 20 °C ± 0.1 °C in the measuring room, a thermal expansion coefficient of $\alpha = 10.5 \cdot 10^{-6}\,\mathrm{K}^{-1}$ with a standard uncertainty of $u_\alpha = 1.0 \cdot 10^{-6}\,\mathrm{K}^{-1}$, and roughness value of $R_z = 1.7\,\mu\mathrm{m}$ were taken into account. Uncertainties were calculated for diameter and coaxiality measurements.

2.3. CT system and scan parameters

The micro 3D CT system *Tomolibri®* was used to perform the CT scans. Fig. 2 shows a picture of the scanner. The used coordinate system is indicated. The opening angle of the cone-beam is 15° approximately. Technical specifications and results of characterization measurements carried out at the scanner can be found in [10]. Table 1 gives the used scanning and reconstruction parameters. For the 3D reconstruction a derivate of the *Feldkamp* algorithm is used [26].

3. Systematic and random effects

In this section, effects resulting in systematic measurement errors and limited reproducibility are analyzed. Fig. 3 illustrates the typical workflow of dimensional CT based on sub-voxel accurate surface (contour) computation and 3D coordinate measurements on the closed surface of a CT model. Systematic effects from the imaging process result in errors of sub-voxel coordinates leading to systematic surface contour (boundary) errors, which result in 3D coordinate measurement errors and finally in a systematic error of the result of the dimensional CT measurement. Local (adaptive)