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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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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).

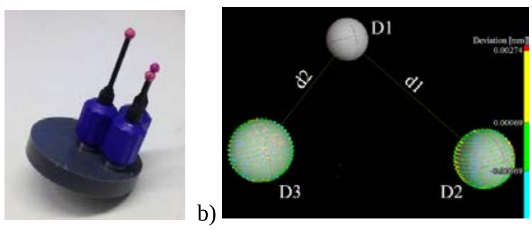
a) b)


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