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ASSESSMENT OF MEASUREMENT UNCERTAINTY CAUSED IN THE PREPARATION OF MEASUREMENTS USING COMPUTED TOMOGRAPHY

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Abstract − X-ray Computed Tomography (CT) is the latest innovation in manufacturing metrology as it offers several opportunities which are not possible with conventional tactile or optical measurement devices: The volumetric which is gained from a CT measurement represents – in contrast to other principles in manufacturing metrology – not only the surface but even the entire volume of the object which allows the analysis of conventionally not accessible features. Due to this fact current research work is concerned with the determination of the task-specific measurement uncertainty for CT measurements as it is an important parameter describing the quality and the reliability of measurement results. This paper presents research work focused on the determination of influences which can be controlled by the machine operator in the preparation of the measurement data acquisition and evaluation, like the magnification of the workpiece, the number of projections taken, or the position and orientation of the workpiece. After the quantification of these influences a task-specific measurement uncertainty budget according to GUM has been calculated. These results can either be used to compare the user-controllable influence to the influence of the machine components on measurement uncertainty or as guidance for the operator to reduce uncertainty in preparation of measurements.

Keywords: Computed tomography, manufacturing metrology, measurement uncertainty

1. INTRODUCTION

X-Ray computed tomography (CT) is a rather new technology in manufacturing metrology as the first devices designed specifically for metrological purposes came to the market after the year 2000. Before that time CT scanners for medical purposes had been adopted, especially for non-destructive testing of safety critical components in aviation like rotor or turbine blades. As the technology showed its capability for the inspection of casted metal parts, even the first measurements for estimating defects like pores or bubbles, were carried out. Developments that increased the accuracy of CT systems, e.g. by developments in X-Ray components like X-Ray tubes or detectors, the use of this technology in manufacturing metrology made sense. The incorporation of manufacturers known from CMM metrology assured the traceability of CT systems and made the use of CT as a measurement device possible. Today modern CT scanners facilitate the acquisition of complex shaped workpieces like plastic housings or connectors used in automotive industry, so the application of CT becomes more and more widespread. As a result the estimation of influences is quite important to qualify and ease the use of this modern technology in manufacturing metrology, e.g. for initial sample testing.

Research work in the field of computed tomography in manufacturing metrology is focused on the estimation of the task-specific measurement uncertainty as it is an important parameter describing the quality and the reliability of the measurement results. Others deal with the qualification of this innovative technique in industrial application, like the estimation of the capability of the measurement process or device and the dealing with material mix, e.g. for the inspection of multi-material workpieces like electronic components [1].

2. PREVIOUS INVESTIGATIONS

2.1 Influences on CT measurements

As the CT measurement process is quite complex and therefore difficult to model for e.g. Monte Carlo simulations or analytic calculations, today it is only possible to analyze the CT measurement uncertainty according to GUM with the help of calibrated reference workpieces for specific measurement tasks. In practice this means the user has to qualify the capability of a measurement device using a typical range of workpieces [2].

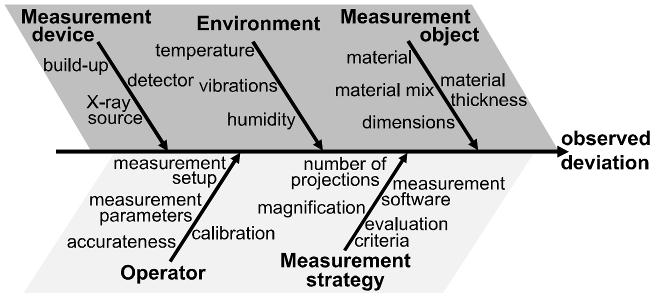

Fig. 1. Influences on CT measurements.

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Fig. 1 shows some influences on CT measurements which result in measurement deviations. Some of them are known from other coordinate measurement techniques where others are CT-specific. The last ones are the focus of interest of different research projects. This work dealing with the estimation and quantification of CT related influences was up to now mainly focused on the modeling of CT components like X-ray sources, detectors or the configuration of the measurement device itself. Other publications were focused on the influence of the measurement object, e.g. its surface roughness or its geometry [3] [4].

2.2 User influence on CT measurements

When it comes to measurements with today's modern CT measurement devices the user is typically not able to choose the different machine components himself as these choices have been done by the manufacturer. As a result the analysis and understanding of the CT components is vital for setting up measurement devices as it has great influences on the possible accuracy of the device and the achievable measurement uncertainty. So typically the manufacturer tries to increase the possible accuracy as much as possible – always keeping in mind the desired choice of measurement objects, e.g. he decides whether the system is suited for large and heavy engine blocks or small and light-weight plastic connectors.

While the operator of the measurement device has no influence on the used components, he influences the measurement uncertainty of his CT measurements. The control software of the CT offers several parameters for data acquisition, like radiation energy, detector integration time, magnification, orientation of the measurement object, etc. As the choice of these parameters is mainly influenced by the experience of the operator, it is important to determine how much he influences the observed deviations and such the measurement uncertainty. This information may even be used in the preparation of CT measurements to predetermine the measurement uncertainty and such the possible accuracy.

Previous investigations and publications showed that the position of the measurement object has great influence on the quality of the volumetric model and such the deviations observed. Especially the orientation to the rotation axis and the X-ray beam have been investigated and identified as main influences mainly due to scattering artifacts. As in today's CT devices flat panel detectors in conjunction with cone beam sources are used the position of the workpiece in the beam (center or border position) and on the detector are to be observed and their influence on the measurement has to be estimated.

The parameter "orientation of the workpiece" has great influence in the preparation of CT measurements and in conjunction with the choice of the measurement parameters, e.g. radiation energy (voltage, current), magnification, detector pixel binning to increase the image intensity or number of projections, the operator here influences the achievable accuracy and as such the uncertainty of the measurements results.

3. MEASUREMENTS OF INFLUENCES

3.1. Investigated influences

The investigations described in this paper are focused on the following influences the operator typically decides during the preparation of a measurement:

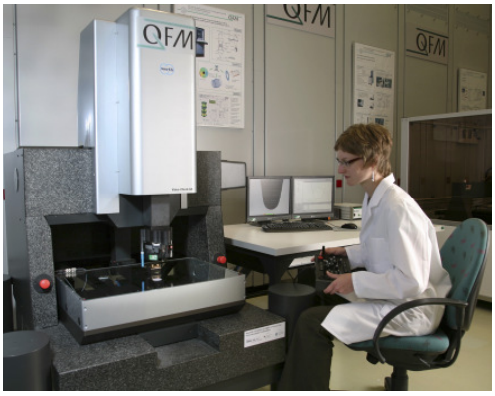
- Orientation of the workpiece
- Magnification (different voxel sizes)
- Number of projections or angle increment between the radiographs

For all investigations it is assumed that the operator chooses the correct radiation energy, i.e. the measurement object is clearly imaged with sufficient contrast.

The orientation of the workpiece is known to have influence on the measurement deviations as previous publications showed that especially due to scattering artifacts surface parallel to the X-ray beam are not images as well as those surfaces oriented perpendicular to the beam. Another fact which has not been investigated in detail up to now is the influence of the position of the workpiece on the detector screen and if deviations are larger if the measurement object is radiated at the edges of the X-ray beam [5].

The magnification is – according to intercept theorems – given by the ratio of the source-object distance and the source-detector distance. It results in different voxel sizes, so higher magnifications reduce the observed deviations and as such the measurement uncertainty. Typically larger measurement objects can only be measured with reduced magnification as the workpiece has to fit always on the detector area. The use of raster tomography is a possible solution for this problem but it increases the necessary measurement time. In practice the user has to choose between more accurate measurements and longer measurement time or less accuracy but faster acquisition time.

The number of projections or the angle increment between two projections is responsible for the time needed for the measurement data acquisition. As a result of it users in industry try to reduce the amount of projections to speed up the measurements. According to signal and system theory, for better accuracy of the volumetric model more projections are to be preferred (Nyquist-Shannon sampling theorem). Preparatory work showed the influence on the deviations observed but with more than 800 projections the results could only be increased by less than 10%.



rence measurements

3.2. Reference measurements

For the estimation of user-controllable influences a ball bar has been used as a reference workpiece. Different features can be evaluated at this workpiece, here the focus is on the measurement of the sphere diameters and the distance of their centers, see fig. 3. For CT measurements the diameter is threshold dependent which allows the assessment of the algorithm used in the evaluation software. The distance of the sphere centers is threshold independent which gives information on other influences.

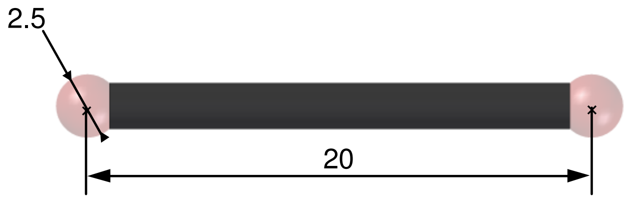


Fig. 3. Ball bar artefact used for investigations.

This artifact has been measured with the optical CMM Werth VideoCheck UA. The resulting values for the diameters and the distance of the sphere centers are listed in table 1 below. These values are used to calculate the deviations of the CT measurements by leaving out the manufacturing deviations of the artifact.

Table 1. Reference values of ball bar.

Feature	Value in mm
Diameter sphere 1	2.5074
Diameter sphere 2	2.4913
Distance of sphere centers	19.8953

3.3 CT measurements

For the investigations a Werth TomoCheck CT scanner has been used, its parameters are listed in table 2. All measurement parameters were set using values gained from hands-on experience. This guarantees the practical usefulness when the results from this investigation will be transferred too practical application – either in the laboratory or industry.

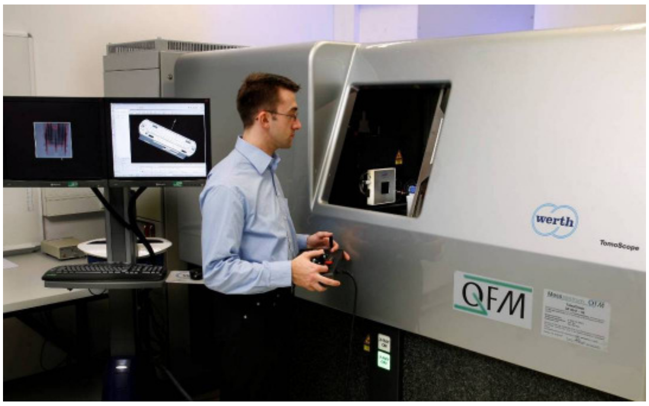


Fig. 4.Multisensor CT Werth TomoCheck 200 3D

Table 2. Specification of Werth TomoCheck.

Parameter	Value
Measurement range	height = 200 mm, diameter = 90 mm
X-ray source	micro focus source V_{max} = 130 kV I_{max} = 300 µA
Detector	1024 × 1024 pixels pixel size 50 µm
Magnification	pre-calibrated, 1×-10×
Manipulator axes	air beared, scale resolution 0.1 µm
Additional sensors for multisensor measurements	image processing, fiber probe, low-force probe, Foucault laser

The ball bar has been measured in different orientations with the parameters described above. The orientations were chosen following ISO 10360-2 but as CT measurements are rotation-symmetrical, the necessary positions can be reduced from six to three, see fig. 5. Additionally the workpiece was placed in inverse orientation, i.e. the bar was flipped over, and the measurements were repeated to determine systematic errors.

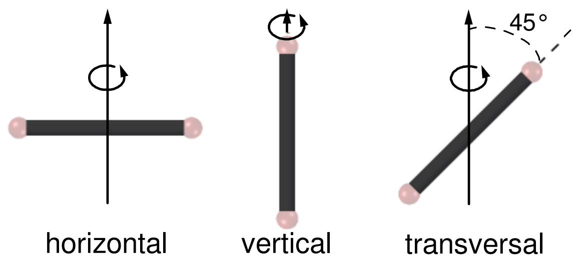


Fig. 5. Orientations of the ball bar.

The aim of this approach was to estimate the influence of the orientation and the position of the workpiece in relation to the detector and the X-ray cone beam. The inverse measurement helps to find out if there is an isotropic or anisotropic behavior, i.e. a preferential direction, e.g. caused by distortion of the detected radiographs due to imperfections or a false calibrated detector. Staggering artifacts have been minimized by placing the workpiece center of gravity on the rotation axis, see fig. 5. Otherwise it would rotate during the measurements and such the 2D projection on the detector would show a moving ball bar which causes deviations during reconstruction.

Table 3. Measurement parameters for ball bar measurements.

Measurement parameter	Value
Acceleration voltage	100 kV
Current	150 µA
Integration time	250 ms
Magnification	1×, 2×
Number of projections	1600

4. CALCULATION OF MEASUREMENT UNCERTAINTY

The measurement uncertainty for the measurement of the sphere center distance has been calculated according to GUM, see fig. 6. To simplify the calculation a basic linear model of the CT measurement process comprising only the investigated influences was used.

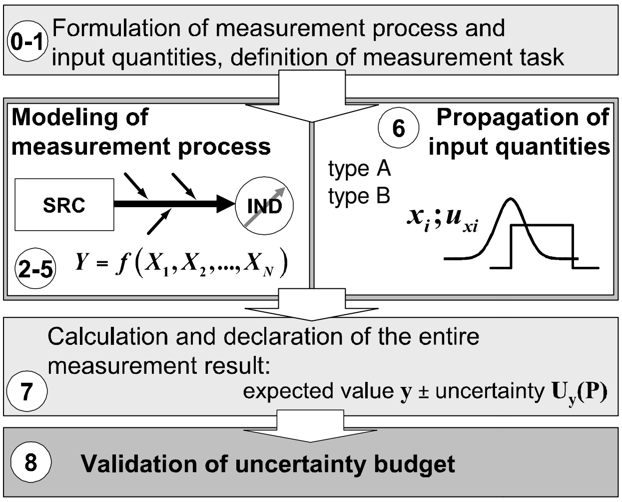


Fig. 6. Determination of the measurement uncertainty according to GUM.

4.1 Model of the measurement process

In order to simplify the calculations the linear model of the CT measurement process described in [6] was used and adopted for the here discussed influences. The resulting analytic model can such be described using (1).

$$X_{IND} = h(Y, \delta Y, X1, \ldots X_i, \Delta X_{IND}, \delta X_{IND}) \quad (1)$$

with X_{IND}: indicated value
Y: measurand
δY: deviation of measurand embodiment

The equation has to be inverted which leads to the equation (2) used for the calculation of the measurement uncertainty.

$$Y = Y_{IND} - X_{Pos} - X_{Mag} - X_{Proj} \quad (2)$$

with X_{Pos}: Influence of the workpiece position/orientation
X_{Mag}: Influence of the magnification
X_{Proj}: Influence of the number of projections

4.2 Estimation of influences

The measurement data have been analyzed using a design of experiments to quantify the expected value and the appropriate uncertainty for each influence factor. As the number of measurements is limited due to minimize the measurement time, a rectangular distribution is assumed as probability density function (PDF). More knowledge from repeated measurements will increase the knowledge and such the PDF may change to better represent the measurement results. Fig. 7 shows the volumetric model of the ball bar, the fit points (about 1,000 per sphere) are color-coded to show their deviation from the Gaussian-fitted sphere. The form deviation, i.e. the distance between the fit points and the Gaussian sphere varies from 0.02 mm or less up to 0.07 mm and is mostly dependent on the voxel size of the volumetric record.

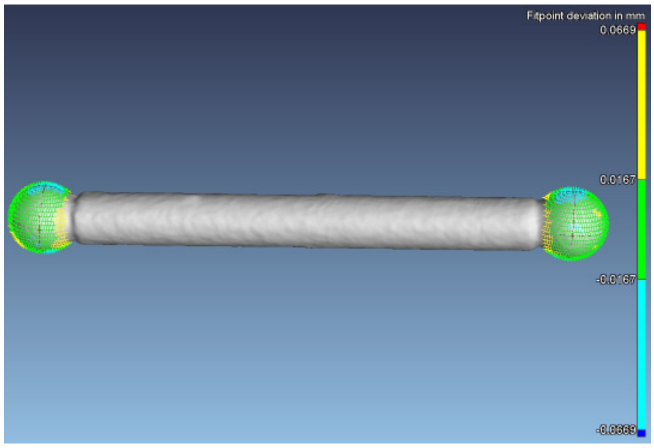


Fig. 7. Analyzed volumetric model of the ball bar.

The measurements showed that the magnification which influences the voxel size in the reconstructed volumetric model has influence on the observed deviations. Smaller voxels enhance the measurement results so typically the operator should try to use the highest possible magnification which is typically limited by the size of the measurement object as the object has to fit the detector area.

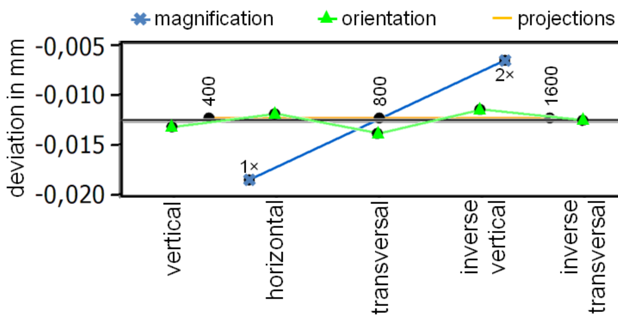


Fig. 8. Measurement results classified by influences

Figure 8 shows the results for each influence factor and each chosen setting: It can be seen that the number of projections has less influence than expected. A larger image stacks increases the quality of the reconstructed data set but lengthens as well the necessary measurement time. As more than 800 projections reduce the deviations by less than 5% it seems sufficient to use 800 projections or less depending on the tolerances to be observed. As a result of it the measurement executes faster and the costs for it are reduced due to less machine time.

The positioning of the workpiece in the measurement volume is vital for the quality of the measurements. Artifacts caused by the orientation of the workpiece, e.g. by wobbling, have to be avoided.

The magnification is the most important influence here, so the operator should always choose it as high as possible which is typically influenced by the size of the workpiece. But modern CT devices offer the possibility of virtually expanding the detector area ("raster tomography") which allows the acquisition of large parts with high magnification.

As a result the entire measurement result for the measurement of the sphere center distance can be expressed by (2):

$$Y = (19{,}8449 \pm 0{,}0236)\,mm \quad k_p = 2.5 \tag{3}$$

However this result only incorporates the influences mentioned above and is as such not to be generalized. It does contain all significant influences on the measurement process like the device itself, environment, workpiece etc. Nevertheless it shows that the operator has a significant influence on the measurement process

5. CONCLUSIONS

The estimation of the task-specific measurement uncertainty of CT measurements is suitable for the quantification of the quality of these measurements. As X-ray computed tomography is a quite new technology in manufacturing metrology, the estimation of influences helps in understanding and improving this technology. As some results dealing with the influences of CT hardware components have already been published the development is quite vivid. However in practical application the user-influenced uncertainty is important and as such it has to be quantified. This paper describes some of these parameters and they have been used to calculate the operator influenced measurement uncertainty using a basic linear model. In future Monte Carlo simulations will help to join the different results to express the task-specific measurement uncertainty in detail.

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