Measurement uncertainty evaluation of an X-ray computed tomography system

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Abstract

X-ray computed tomography (XCT) systems are already well established in the field of non-destructive testing and material characterization, but they are currently not fully accepted in the field of dimensional metrology, since there is still a lack of international standards. Measurement results obtained without specifying the measurement uncertainty are incomplete for metrological applications. For this particular reason, the measurement uncertainty has been determined for a selected specimen from automotive industry, representing a typical measurement task for coordinate metrology by XCT. In addition, the influence of the system stability regarding axis stability, focal spot drift and thermal stability has been analysed. The objective of this work was to estimate a task specific uncertainty for XCT measurements according to an approach described in the guideline VDI/VDE 2630-2.1. The feasibility of the recommended procedure has been evaluated in terms of repeatability and reproducibility conditions, leading to a measurement system analysis regarding accuracy and precision. In addition, the practicability of a fast uncertainty determination has been tested. The system stability is evaluated by a stationary ruby sphere mounted at the non-rotating part on the rotary stage and by a pair of steel wires mounted directly on the tube housing. Moreover the temperature in the measurement room and the temperature rise of the X-ray tube itself has been tracked through the entire measurement time. Results for repeatability conditions show that the uncertainty in measurement is within the sub-voxel region for all measures, with few exceptions. User influence could be minimized by defining a systematic procedure for dimensional measurements with XCT systems leading to traceable measurement results. Furthermore, the correction of systematic errors by calibrated features has been investigated. Reference measurements have been done by a tactile coordinate measurement machine. This correction leads to remarkably better expanded uncertainties and subsequently to improved process suitability, since systematic errors are the main contributor for uncorrected measurement results of XCT.

Keywords: X-ray computed tomography, measurement uncertainty, metrology, VDI/VDE 2630-2.1

1. Introduction

Quality control and non-destructive testing are important tasks to satisfy industrial requirements regarding components safety, reliability and quality. In the case of quality control coordinate metrology is a well-established method for the verification of dimensional and geometrical tolerances. The state of the art is tactile coordinate measuring machines (CMMs), which enable tactile surface determination with high accuracy and traceability, but at the cost of time consuming measurements. X-ray computed tomography (XCT) systems are well established in the field of non-destructive testing and provide fast measurement results, but they are currently not fully accepted in the field of dimensional metrology, since there is no international standard. Detecting a surface with different types of sensors yields inevitably differences of measurement points, which will be reflected in different measurement results. Characteristics of measurement methods must be taken into consideration for a comparison of these results. In XCT a variety of parameters are influencing the measurement result. The measuring system, the specimen, the task and environmental conditions can cause problems during performance evaluations of XCT systems. An overview of the state of the art in industrial XCT for dimensional measurements as well as strategies for accuracy and system evaluations of XCT systems are given in [1,2].
Measurement results without specifying the measurement uncertainty are incomplete for metrological applications [3], a determination of measurement uncertainty of the RayScan 250 E XCT system has been performed. Standards in the field of dimensional metrology by XCT are not fully established or they are currently under development. State of the art guidelines, like VDI/VDE 2630 [4-6], are describing fundamentals and definitions, variables influencing measurement results and recommendations for XCT dimensional measurements. According to VDI/VDE 2617-8 [8] approaches such as simulations (VDI/VDE 2617-7 [7]), uncertainty evaluation by use of calibrated specimens (DIN EN ISO 15530-3 [9]) or uncertainty budgets according to the “Guide to the Expression of Uncertainty in Measurement” (GUM) [3] are applicable to determine the measurement uncertainty. DIN EN ISO 15530-3 describes a method for determining the uncertainty of measurements using calibrated work pieces. According to VDI/VDE 2630-2.1, this method is applicable for coordinate measuring systems (CMS) based on XCT. Due to a number of influencing factors caused by the XCT-system or by the inspected part itself only a task-specific measurement uncertainty can be determined. The specimen inspected within this work is representing a typical measuring task for coordinate metrology by XCT. It has been chosen to perform an uncertainty evaluation according to DIN EN ISO 15530-3. Moreover, the feasibility of a fast approach for uncertainty determination was analysed.

The selected specimen made of plastic is a typical part from automotive industry. In the field of automotive industry non-destructive testing is important for quality assurance. Due to more complex geometries examination of internal structures of assemblies is getting more and more important, but increasingly difficult. XCT techniques are used to measure internal distances or the internal wall thickness of complex castings and areas which are often inaccessible for optical scanners or conventional tactile coordinate measurement machines. Furthermore, XCT enables the possibility to scan specimens of any surface, shape and material up to a certain density and thickness penetrable by X-rays. As a matter of fact the variety of influencing quantities, especially those of a specimen itself hinder the determination of a measurement uncertainty valid for different material compositions, which would be necessary to provide traceable results. To provide complete measurement results for metrological applications the expanded uncertainty for different measurands has been determined conforming to standards. In addition, the system stability regarding temperature, focal spot size and axis movement has been analysed to provide further information about systematic factors affecting the measurement uncertainty [10].

2. Experimental

2.1 Tactile Reference Measurements

The specimen used for the evaluation of measurement uncertainty concerning XCT data is a plastic housing from the automotive industry, representing a typical work piece for metrology tasks in XCT. Accessible geometries have been calibrated by the use of a tactile coordinate measurement machine type Wenzel LH 65 at the laboratory of Delphi Automotive Systems Austria. The maximum permissible error (MPE) of the CMM of

$$MPE = 1.9 \mu m + \left( \frac{L}{350 \text{ mm}} \right) \mu m$$

is valid for the entire measurement range. The alignment of the specimen has been done in a stepwise process including pre-alignment and fine adjustment steps for defining the origin of the
coordinate system. For uncertainty determination certain (accessible) features (see Figure 1, left) have been calibrated including the diameters and distances of holes in horizontal and vertical direction, the wall thickness of the floor area at certain points, the wall-thickness of the ribs beside the plug pins and the length and width of the specimen at given positions.

Figure 1. Calibrated features (left) and measurement setup (right)

2.2 X-ray Computed Tomography Setup

The RayScan 250 E system is a cone beam XCT system with two X-ray sources, covering a large measuring range and allowing the inspection of parts ranging from micro-objects such as small plastic parts to macro-objects such as big casting parts. The XCT system is suitable for the detection of faults as well as for dimensional measurement and reverse engineering. This study is focusing on the dimensional measurement capabilities of the 225 kV micro-focus X-ray source (Viscom XT9225 DED) with a tungsten reflection target. The detector is an amorphous silicon detector type Perkin Elmer XRD 1620 AN14 CS with a pixel pitch size of 200 µm and an image size of 2048x2048 pixels, based on scintillator flat panel technology. The projection data is reconstructed by a standard filtered-back projection, provided by RayScan.

Two independent measurement series consisting of consecutive XCT-scans of one calibrated work piece allows determining measurement uncertainties. The measurement setup (see Figure 1, right) consists beneath the calibrated specimen also of a stationary ruby sphere mounted at a non-rotating part of the turntable for focal spot tracking and two calibrated ball bars with different length scales for the calibration of the voxel size. Thermocouples for temperature tracking are mounted at the X-ray tube including positions at the filament, coils and near the target. XCT scan parameters for both measurement series can be found in Table 1.

Table 1. XCT scan parameters

<table>
<thead>
<tr>
<th>Tube voltage in (kV)</th>
<th>Anode current in (µA)</th>
<th>Integration time in (ms)</th>
<th>Number of projections</th>
<th>Voxel size in (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>600</td>
<td>999</td>
<td>1080</td>
<td>90</td>
</tr>
</tbody>
</table>

2.3 Measurement System Analysis

The purpose of measurement system analysis is to qualify a measurement system by quantifying its accuracy, precision, and stability and to evaluate the effect of the operating environment on the measurement system’s parameters. Accuracy describes the location variation of the
measurement results, whereas precision is width variation. Repeatability and reproducibility are subsets of precision and both help to categorize the sources of variability (measurement method, user, instrument, environment, time, etc.) in a measurement system [11]. The repeatability of measurements results describes the closeness of successive measurement resulting from the same measure under the same conditions, whereas the reproducibility is the closeness between measurements results with changing conditions.

![Figure 2. Scan series for the analysis of repeatability (top) and reproducibility (bottom)](image)

The XCT system was characterized by its bias, repeatability and reproducibility of measurements. Therefore two different approaches have been tested to evaluate those parameters (see Figure 2). For the first scan series (repeatability), the specimen has been positioned once and 24 scans are acquired under repeatability conditions. The first scan has been chosen as a pre-scan, to ensure a stable state of the XCT system after a daily tube conditioning procedure. After the pre-scan, 7 XCT scans were performed within one day, whereas the scan parameters have been kept the same for all scans. Specimen handling is avoided to ensure the same measurement positions of the work piece. This procedure was repeated three times to reach a total number of 21 scans under repeatability conditions. Possible influencing factors in the case of repeatability measurements are expanding X-ray tube housing due to temperature increase at target site, positional offsets due to automatic movements of the axis for e.g. capturing reference images and inaccuracies of the turntable.

The second scan series is related to the reproducibility of the XCT system. The specimen has been aligned for each XCT-scan, including component handling, fixation, movement of the turntable to the measurement position and different initial states of the XCT system regarding tube temperature, simulating a more realistic measurement setup. An alignment and stabilization period of approximately 10 minutes in between the individual scans minimized errors induced due to potential sample movements. To comply with VDI/VDE 2630-2.1, a total number of 21 scans have been captured. The orientation of the specimen has changed for each measurement day to simulate an additional operator influence.

### 3. Measurement Uncertainty and Data Evaluation

The measurement uncertainty of the RayScan 250 E XCT system was evaluated according to VDI/VDE 2630-2.1, which describes a procedure for the determination of measurement uncertainty and test process suitability for coordinate measurement systems (CMS) with XCT-sensor. This procedure is based on DIN EN ISO 15530-3 which aims to provide a practicable technique for an uncertainty evaluation of measurements performed by a CMS. This technique applies to specific measuring tasks and to CMS results obtained from both uncorrected and corrected measurements (Equation 1). The approach for the uncertainty of measurement, according to VDI/VDE 2630-2.1, is subdivided into the following steps:

- **Step 1**: Calibration of the work piece by tactile CMM
- **Step 2**: Measurements of the specimen with a commonly used measurement strategy (more than 20 XCT scans to cover all device-specific influencing factors)
- **Step 3**: Estimation of further uncertainty contributions related to the specimen (form deviation, thermal expansion, etc.)
- **Step 4**: Calculation of expanded measurement uncertainty $U$ according to ISO 15530-3

The expanded measurement uncertainty has been determined for both scan series (corrected and uncorrected measurement results)

$$U_{\text{corrected}} = k \sqrt{u_{\text{cal}}^2 + u_p^2 + u_w^2 + u_b^2} \quad U_{\text{uncorrected}} = k \sqrt{u_{\text{cal}}^2 + u_p^2 + u_w^2 + b^2} \quad (1)$$

with $k$ as coverage factor, $u_{\text{cal}}$ as standard uncertainty for tactile calibration measurements, $u_p$ as standard uncertainty of the XCT measurements for each measure, $u_w$ as standard uncertainty related to temperature, $u_b$ as standard uncertainty of $b$ including the standard uncertainty of the mean value of these measurements and the uncertainty of the thermal expansion coefficient and $b$ as systematic error (bias). Further data processing and coordinate metrology is done with VGStudio MAX 2.2 (CMM toolbox) using a measurement template to ensure uniform evaluation. The measurement template includes the fitted reference objects and features based on those objects.

![Figure 3. The deviation of all measurement results including the pre-scans for series 1 (repeatability, top) and series 2 (reproducibility, bottom)](image-url)
4. Results

4.1 Measurement Uncertainty

The deviation of the measurement results in relation to the mean of all measurements is shown in Figure 3. Both measurement series show deviations in the sub-voxel region indicating a high precision of the measurement system. The wall thickness results measured as point-to-point distance (Features 11 to 19) show higher deviations. In contrast, feature-to-feature distances are highly suitable for dimensional measurements, since only minor deviations appear. Overall, it is recommendable to use the high information density in order to perform dimensional measurements by fitting geometrical primitives (e.g. planes, spheres, cylinders). Remarkable is the high variation of the wall thickness 22 (Feature 26) for plane-to-plane measurements in case of series 1. This is most probably introduced by beam hardening artefacts of the ball-bar, which has been placed at the same height level as the extracted feature. Therefore it is recommendable to scan reference objects for voxel size calibration above or below the specimen. The reproducibility conditions investigated in series 2 lead to an expected increase in deviation of the measurement results, indicating an influence of the specimen placement by the system operator and the initial state of the measuring system.

![Figure 4. Deviation of the XCT-results to the reference values (CMM)](image)

The deviation of the XCT measurements to the CMM results differs for every measurement features. Figure 4 shows the standard deviation of the measurement results in comparison to the reference values determined by tactile CMM. A comparison of measurement series 1 and 2 shows only slight changes of the mean values occurring in the range of 6 µm for lengths, 3 µm for diameters and 1 µm for the ribs. The measured wall thickness seems to be dependent on the placement of the specimen and higher differences of the mean values of about 20 µm arise. Length measurements can be subdivided into sphere-to-sphere distances (ball-bar), distances in between fitted cylinders (distances) and plane-to-plane distances (lengths). Sphere-to-sphere distances show low bias values and standard deviations for both series, resulting in highly accurate and precise measurements compared to CMM values. However, the absolute bias of the short ball-bar is larger than the bias of the other one. In addition, the deviation of the long ball-bar is positive and for the short ball-bar negative. This may be explained due to the positioning of the ball-bars respectively their different length scales. For the second measurement series the ball-bars have been mounted at different orientations.
In the case of non-spherical, symmetrically fit-objects, the measurement direction leads to a systematic effect. Vertical measurements exhibit a clear overestimation, whereas the deviation of horizontal measurements is in the range of 1/10 of the voxel size, even though the specimen has been tilted in horizontal and vertical direction to reduce Feldkamp artefacts. Measurements of the wall thickness of wide flat areas lead to a remarkable overestimation of the thickness. This effect arises due to an insufficient reconstruction condition using a simple circular trajectory. In contrast to wide areas, small flat areas are measured more accurately, resulting in a bias in the range of only 1/10 of the voxel size.

![Graph showing expanded uncertainty of uncorrected and corrected results](image)

Figure 5. The expanded uncertainty of uncorrected results (top) show a maximum uncertainty of three voxel. The corrected uncertainty (bottom) shows a maximum of a voxel.

The expanded uncertainty has been calculated for corrected and uncorrected measurement values, as shown in Figure 5 and Table 2. The correction method seems feasible, but it requires a calibration with CMM and repeated XCT scans of the specimen. The result of uncorrected values shows high uncertainty for wall thickness measurements by point-to-point distances (Feature 14-16) and the wall thickness measured by plane-to-plane distances (Feature 25-28). This is due to the bias, which is taken into consideration for uncorrected measurement results. The uncertainty of uncorrected results is not symmetrical to the reference value, which indicates an overestimation (distances, wall thickness, lengths) or underestimation (diameter) for specific features. High bias leads to high uncertainties and subsequently to an unsuitability of the test process. The calculated uncertainty for corrected measurements shows the expected results, regarding high uncertainty for high standard deviation of the measurement values. A slight increase of the expanded uncertainty can be seen for reproducibility measurements, except of the wall thickness measurements.
Table 2. Measurement uncertainty for repeatability and reproducibility conditions

<table>
<thead>
<tr>
<th>Description</th>
<th>No.</th>
<th>Uncertainty for repeatability in (µm)</th>
<th>Uncertainty for reproducibility in (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>uncorrected</td>
<td>corrected</td>
</tr>
<tr>
<td>Diameter of holes</td>
<td>3 - 6</td>
<td>6 ... 35</td>
<td>2 ... 3</td>
</tr>
<tr>
<td>Distance holes (vertical)</td>
<td>7 - 8</td>
<td>67 ... 86</td>
<td>22 ... 23</td>
</tr>
<tr>
<td>Distance holes (horizontal)</td>
<td>9 - 10</td>
<td>17 ... 21</td>
<td>17 ... 18</td>
</tr>
<tr>
<td>Wall thickness (floor area)</td>
<td>11 - 19</td>
<td>13 ... 22</td>
<td>8 ... 22</td>
</tr>
<tr>
<td>Wall thickness (ribs)</td>
<td>20 - 21</td>
<td>15 ... 18</td>
<td>2 ... 3</td>
</tr>
<tr>
<td>Length of specimen</td>
<td>22 - 23</td>
<td>38 ... 110</td>
<td>19 ... 24</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>25 - 28</td>
<td>183 ... 254</td>
<td>2 ... 10</td>
</tr>
</tbody>
</table>

4.2 Fast Measurement Uncertainty Estimation

The uncertainty determination according to VDI/VDE 2630-2.1 is a time-consuming process. Hence investigations regarding a faster procedure have been done. The basic idea is to use safety factors and calculate the expanded uncertainty for a small number of measurements. Thus the standard uncertainty of the measurement method can be calculated as

\[ u_p = h \frac{s}{\sqrt{n}} , \]

where \( h \) is the safety factor, \( s \) the determined standard deviation of measurements and \( n \) is the total number of measurements. The expanded uncertainty was calculated for a random selection of three measurement results of XCT scans under reproducibility conditions. To validate whether an estimation of the expanded uncertainty is permissible or not, the hypothesis (the average uncertainty for a selection of scans will not be significantly different than the uncertainty of all scan results), was tested against the alternative hypothesis (average uncertainty will be significantly higher) by the one-sample T-test. The expanded uncertainty was calculated 1330 times for a set of three measurement results out of 21 measurement results. The null hypothesis was unambiguously rejected for a significance level of \( \alpha = 0.05 \), meaning that the average uncertainty estimated with three measurement results is significantly higher than the determined uncertainty. This means an estimation of the expanded uncertainty with a small amount of measurements is in principle possible, but the uncertainty of the XCT system is rated too high.

4.3 System Stability: Temperature, Axis, Focal Spot

The aim of the study concerning system stability is to investigate the influence of the initial state of the XCT system on dimensional measurements. For these investigations, the first measurement series (repeatability conditions) has been used, in which the specimen was not realigned and the first XCT scan at the beginning of each measurement day (pre-scan) should ensure a stable state of the X-ray tube. Therefore, the systematic error of temperature induced expansion of the X-ray tube housing during scanning should be minimized allowing optimal conditions for dimensional measurements. Figure 6 shows the results of all XCT-scans (red) and the results of the pre-scan (blue) indicate an influence onto global distances. The measurement results of scan 1 (green) show the same trend. The study of the thermal behaviour of the XCT system shows an influence of the initial state onto length measurements. This can be explained by temperature induced and uncorrected source drifts due to a temperature increase at the beginning of the scan series (see
These results suggest a prolonged warmup phase, but have been deemed uneconomical, since the difference in the mean values is smaller than the expanded uncertainty.

Figure 6. Overview of the measurement results in reference to the average of the XCT scans, indicating a significant influence of a pre-scan for global distances.

Figure 7 (right) shows the focal spot drift monitored during first scan series (repeatability). The drift is below one pixel within one day of scanning. With increasing temperature the tube housing expands in horizontal direction, which causes the projected stationary ruby sphere to move to the left in the detector plane. Furthermore, the observed vertical shift of the central beam is expected to be caused by the own weight of the X-ray tube. In addition, there is also a shift by one pixel due to inaccuracies of axis movements concerning starting positions observable.

Figure 7. Temperature curves of repeatability (left) and focal spot tracking of stationary sphere, mounted at the non-rotating part of turntable (right)

5. Conclusion

The main purpose of this work has been to determine a task specific measurement uncertainty for the RayScan 250 E XCT system by an experimental method using calibrated work pieces according to VDI/VDE 2630-2.1. The feasibility of the recommended procedure could be shown. The investigations on the bias of measurement results show for both measurement series the same trends, resulting in precise but inaccurate values, indicating systematic errors. This supports the idea of a correction by calibrated features measured by CMM for a specific measurement tasks. This approach leads to remarkably better expanded uncertainties, which could increase the process suitability, since the bias is the main contributor for uncorrected measurement results.
Fast uncertainty estimation with only three XCT scans can be applicable, but will lead to a significant overestimation, meaning that the testing process suitability could be infringed for small production tolerances. However, a small sample size could be used at least for an assessment of the measurement uncertainty, especially interesting for industrial use, since the recommended number of scans in the guidelines is very time consuming.

The study of the thermal behaviour of the XCT system shows an influence of the initial state onto global features like length measurements, whereas the orientation of the specimen has impacts on local features. A prolonged warmup phase has been deemed uneconomical, since the difference in the mean values is smaller than the expanded uncertainty. Even though a focal spot drift and inaccuracies of axis movements could be detected, the tube and axis stability was found to be sufficient for dimensional measurements.

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