PRECISE 3D DIMENSIONAL METROLOGY USING HIGH RESOLUTION X-RAY COMPUTED TOMOGRAPHY (µCT)

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Abstract

Over the last years computed tomography (CT) with conventional x-ray sources has evolved from an imaging method in medicine to a well established technology for industrial applications in the field of material science, light metals and plastics processing industry, microelectronics, geology, etc. By using modern microfocus and nanofocus X-ray tubes, parts can be scanned with sub-micrometer resolutions. Currently, micro-CT is used more and more as a technology for metrology applications e.g. in the automotive industry. Especially if complex parts with hidden or difficult accessible surfaces have to be measured, CT offers big advantages comparing with conventional tactile or optical coordinate measuring machines (CMMs): high density of measurement points and a non-destructive and fast capturing of the complete sample's geometry.
When using this modern technology the question arises how precise a µCT based CMM can measure in comparison to conventional and established methods for coordinate measurements? For characterizing the metrological capabilities of a tactile or optical CMM, internationally standardized parameters like length measurement error and probing error are defined and used. To increase the acceptance of CT as a metrological method, on the one hand the definition and usage of such parameters is important. In this paper, an overview of the process chain in CT based metrology will be given and metrological characteristics will be described.
For the potential user of CT as 3D metrology tool it is very important to show the measurement accuracy and repeatability on realistic samples. A die casting Aluminium as well as an injection moulded plastic part have been measured by means of a high precision tactile CMM. A comparison of these results to the data obtained by means of CT shows that state of the art high resolution CT can provide a measurement accuracy in the order of established coordinate measurement techniques.

Keywords: 3D Metrology, Coordinate Measurement Machine, High Resolution Computed Tomography, Precision Comparison

1. Introduction

Computed tomography with x-rays is a well established technology for industrial applications. Since years, CT systems are used for qualitative and quantitative inspection of objects to perform material inspection, do analysis of voids in casting samples, and so on. Over the last years big advances were achieved regarding the increasing of the resolution in the volume as well as reconstruction speed of the 3D volume data from projections. In the meantime even 3D-Analysis of materials with sub-micrometer resolution by using of brand new technologies in laboratory systems is possible. For example with so called nanoCT®-Systems it is possible to perform applications that could be only done by using of expensive synchrotron technique so far [1], [2].

In the field of metrology it could be shown some years ago, that 2D-CT with fan beam and linear detector array is capable to perform dimensional metrology tasks [3]. In 2D-CT an object is irradiated by fan beam slice-by-slice and captured by a linear detector. Due to the very well collimated X-ray beam on the tube and detector side it is possible to reduce artifacts caused by scattering of radiation significantly and thus to increase the overall imaging quality. One drawback of this CT method is a very long scanning time.

In the last years, the cone beam CT systems with area detectors have been increasingly used for metrological tasks on complexly structured parts. Especially if hidden or difficult accessible sample parts have to be measured, 3D-CT shows a lot of advantages. In contrast to 2D fan beam tomography systems, the whole object can be captured during one rotation. Using state of the art micro- and nanofocus-tubes even very small micro-mechanical parts can be scanned with a very high resolution of much less than 1µm for purposes of very precise measurements. In this case of micro-CT (µCT) and nanoCT as well as in the case of "macro" CT with fan beam and macrofocus tubes the question arises "what measurement accuracy can be expected?"
Usually, tactile or in the last decade also optical coordinate measuring machines (CMMs) are used for metrological tasks. In order to characterize a CMM regarding possible measurement uncertainty, simple but important characteristic values like probing error and size measurement error are defined. For determination of these parameters and also for the back tracing of metrological results to the unit of meter, material standards like spheres of ceramics or steel, sphere bars, or gauge blocks are used. Appropriate international standards and guidelines regulate the usage of such test objects for determination of characteristic values as well as for acceptance and re-verification tests of CMMs [4]. Currently, the definition of a German guideline is pending, that will define such characteristic values and regulate the usage of appropriate material standards for CT based CMMs.
But not only the definition of characteristic values is important to increase acceptance of µCT for dimensional metrology, but also a good understanding and if applicable, also the compensation of effects which can negatively influence the volume quality, characteristic values and measurement uncertainty. For example the X-ray spectrum, features of the detectors, as well as the material distribution in the object can cause beam hardening and scattering artifacts in the reconstructed volume and therefore reduce its quality. Furthermore, the method used for surface determination in the volume data can also influence the metrological properties of the overall CT-system. In the chapter 2, first the process chain for dimensional metrology with µCT will be presented. After that, metrological characteristic values will be defined and examples of material standards for their determination will be shown. In the chapter 3, the influence of the beam hardening correction and in the chapter 4 the influence of different surface extraction techniques on the characteristic values will be presented.

2. Fundamentals of dimensional metrology with µCT

A schematic representation of the the **process chain** for dimensional metrology with µCT is given below.

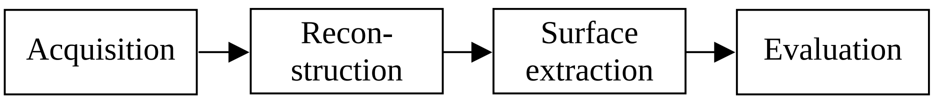

Fig. 1. Principle process chain for metrology with computed tomography.

For the operator and user of a CT metrology machine the process can be separated in two steps:

> Step (1) is the generation of surface data. It contains the acquisition of the raw 2D X-ray projection images over 360 degree of object rotation followed by a numerical reconstruction of the volume data. The volume is represented by a three dimensional array of voxels, where each voxel represents the attenuation coefficient for X-rays at the appropriate location in the volume. If a scanned object consists only of one material, the volume ideally has two-peak gray scale distribution (air and material). Depending on the material and X-ray properties, algorithms for beam hardening correction and reduction of scattered radiation can automatically be applied in order to reduce artifacts in the volume and to achieve high quality results. Another one is the extraction of the surface data from the volume. The extracted surface can be e.g. stored as a point cloud or a polygon mesh (STL). Recent

software packages like the new datos|x 2.0 platform developed by the phoenix|x-ray product line of GE Sensing & Inspection Technologies allow a very high grade of automation in order to minimize the need for operator influence.

Step (2) is the analysis of the surface data generated by the CT system. A complete 3D representation of the scanned object is loaded into 3D software packages like Polyworks Inspector™ by Innovmetrics or the coordinate measurement modules of VGStudioMAX 2.1 by Volume Graphics. These software packages allow all tasks which are well known from conventional CMM system e.g. the fitting of geometrical primitives (cylinders, planes, circles, etc) to the dataset with subsequent measurement of distances, angles, diameters and are therefore often called “virtual CMM”.

To estimate the measurement uncertainties, which could be potentially expected by using a coordinate measuring machine, characteristic values like probing error and length measurement error are used in the conventional tactile or optical dimensional metrology [4]. These values are defined as follows:

Probing error form *PF*: Accordingly to ISO 10360 [4] points on a surface of a spherical material standard have to be probed and then a regression sphere has to be fitted using Gaussian least squares method. The value *PF* is the range of radial deviations between the measurement points and the calculated regression sphere. This is identical to the difference between the maximum and the minimum distances of measured surface points from the center of the regression sphere:

$$PF = R_{max} - R_{min},$$

where R_{max} is the maximum distance and R_{min} the minimum distance of a measurement point to the sphere center.

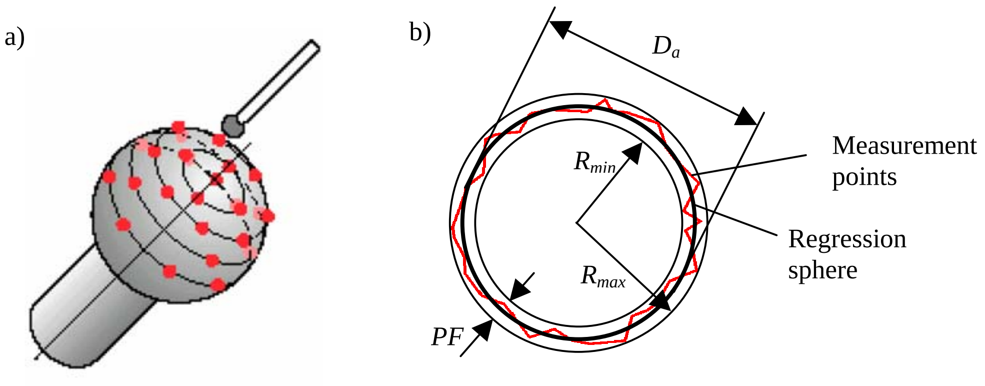

Fig. 2. Definition of metrological characteristic values: a) sphere sketched with tactile measurement points on it. In the case of CT, not only 25 points should be used but much more; b) Illustration of characteristic value probing error form *PF*. The calibrated diameter is not shown in this figure.

Probing error size *PS*: This value describes the difference between the measured diameter D_{meas} and the calibrated diameter D_{cal} of the sphere:

$$PS = D_{meas} - D_{cal},$$

Error of indication for size measurement *E*: Accordingly to ISO 10360, this error characterizes the behavior of the entire system within the total measurement volume. This error results from the superposition of various individual errors e.g. systematic scaling errors as well as random errors. For determination of *E* material standards such as ball bars having two or more spheres can be used. The distances between the central points of all spheres on the bar have to be calibrated. The value *E* is determined as deviation of the measured distance between two spheres from the calibrated distance:

$$E = L_{meas} - L_{cal},$$

with L_{meas}: measured distance and L_{cal}: calibrated distance. The sphere fitting is performed using linear least square method. Using ball bars or other similar artifacts, probing errors should also be considered, since systematic errors in the surface position are automatically compensated in the sphere fitting procedure and have a little influence on the center position.

In figure 3, some possible test objects for determination of characteristic values for high resolution X-ray tomography are shown. Objects having spheres distributed over the whole volume have the advantage that determination of deviations for distances with different lengths and different orientations is possible from a single scan only (fig. 3 c).

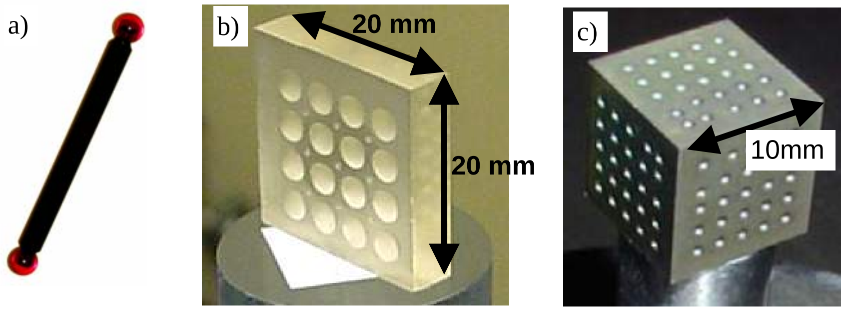

Fig. 3. Test objects for determination of characteristic values: a) sphere bar consisting of two ruby balls connected with a carbon fiber shaft; b) sphere calottes plate made of Zerodur®; c) cube with spherical calottes, material: titanium, on three sides 25 calottes are manufactured.

For subsequent evaluations presented in this paper, the sphere calottes plate made of Zerodur is used. This test specimen has the size of nearly 20x20 mm and consists of 4x4 sphere calottes array of appr. 3 mm diameter each. The calottes plate was developed, manufactured and calibrated by the German national metrology institute (PTB) [5]. The calibration uncertainty determined by a tactile CMM is ±1.5 µm for distances between sphere centers; the form and diameter uncertainties are ±2 µm.

3. Correction algorithms to improve the accuracy of dimensional metrology with µCT

3.1 Beam hardening correction

As already mentioned in the previous section, the volume artifacts caused by non linear effects like e.g. beam hardening can influence the position of the extracted surface significantly. The reason for this behavior is that due to beam hardening the distribution of voxel gray values in the material (one-material-object assumed) and in the air becomes inhomogeneous. This effect as well as some results of correction techniques that are applied during volume reconstruction will be presented in this section using the example of sphere calottes plate (see fig. 3b).

The CT acquisition of the sphere calottes plate was done with acceleration voltage of 200 kV with 0.5 mm Cu pre-filter at voxel size of 100µm. The orientation of the sample was like in the fig. 3b). The acquisition time was 13 minutes. The reconstruction was done by means of an optimized Feldkamp algorithm [6]. During the reconstruction procedure it is possible to apply an automated beam hardening correction (BHC) technique developed by GE Sensing & Inspection Technologies. In figure 4 the influence of BHC is shown.

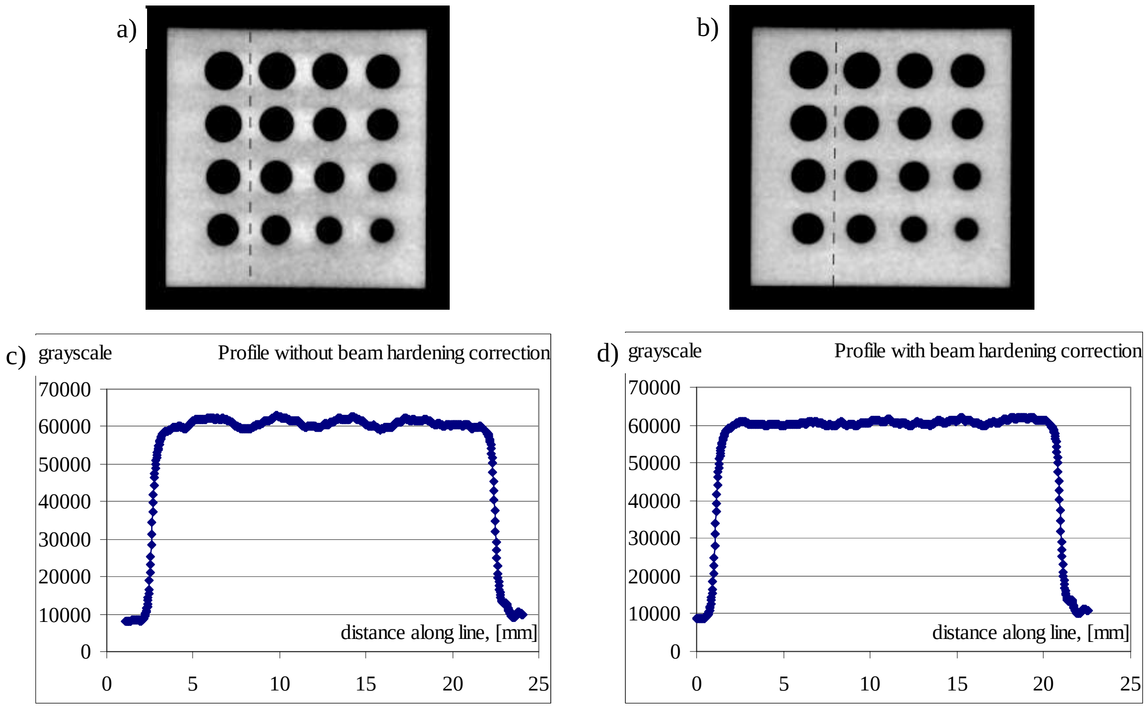

Fig. 4. Influence of the beam hardening correction in the volume: a) a slice of the volume reconstructed without application of BHC – beam hardening artifacts are visible; b) a slice of the volume reconstructed with BHC – artifacts are significantly reduced; c) gray scale profile along the dashed line in figure a); c) gray scale profile along the dashed line in figure b).

It is clearly visible that the material gray values becomes much more homogeneous when the beam hardening correction algorithm is applied.

In order to demonstrate how the beam hardening correction influences the accuracy of the measured distances between the sphere centers the surface was extracted from the volume using a marching cubes method [7]. A well known simple method for the determination of the surface position e.g. the boundary between material and the surrounding in the voxel dataset is so called ISO surface method. A global, isotropic threshold value for the gray value is either defined manually by selecting a region in the material and in the air or automatically e.g. with Otsu method [8].

The influence of the beam hardening correction on the extracted surface is evaluated as follows: Firstly, on the flat back side of the calottes plate, a plane is fitted and distances from the surface points to this plane are measured. The color coded results are shown in figure 5 a) and b). The whole range of color coding is ±25µm which is 1/4 of voxel size. It is clearly visible that the "flatness" of the surface increases significantly if beam hardening correction is used. It should be mentioned that the real flatness of this plane was not calibrated.

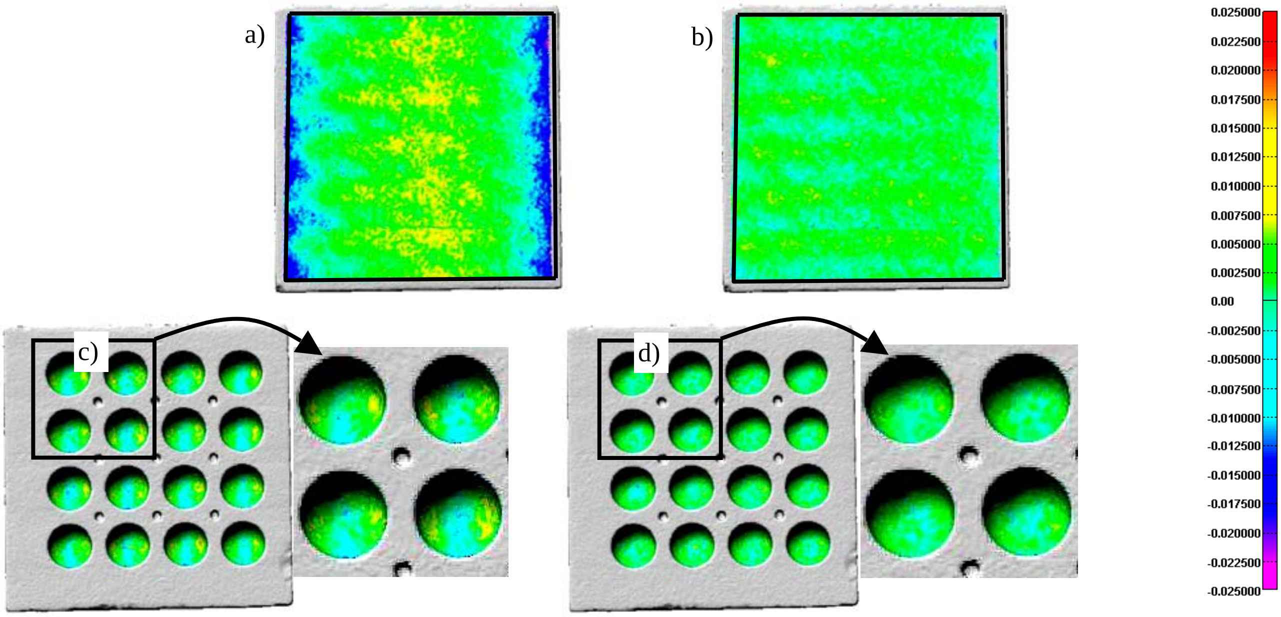

Fig. 5. Results of applying of beam hardening correction techniques – rendered views of the extracted surface. The deviation between surface points and fitted geometrical elements (plane or spheres) are coded with colors. The color coding is displayed on the right with mm-units. a) Back side of the calottes plate *without* BHC. b) Back side of the calottes plate *with* BHC. c) Deviation between surface points and fitted spheres *without* BHC. d) Deviation between surface points and fitted spheres *with* BHC.

Secondly, for every calotte a sphere was fitted using all points except calotte boundary of two voxels (0.2mm). The surface points are then compared with the fitted spheres and the comparison results are color coded. Figure 5 c) displays results for a volume reconstructed without beam hardening correction. Like in the case of plane, the influence of material on surface position is clearly visible with this method. In figure 5 d) comparison results after beam hardening correction are shown. Also in the case of calottes using of beam hardening correction shows significant reduction of material influence on the surface position.

The next test is to compare how the beam hardening correction changes the measured distances between sphere centers. As mentioned above, the positions of sphere centers were calibrated by the German national metrology institute PTB with uncertainty of ca. 1.5µm. From the positions, all 105 distances are calculated. The same distances were measured using µCT data with and without BHC. For sphere fitting Gaussian method was used. The deviation between the results obtained with µCT and the calibration values are shown in the fig. 6.

It is clearly visible that the beam hardening correction not only changes the surface position but also the central points of fitted spheres. Using BHC improves the position accuracy for the sphere centers by approximately a factor of two. Regarding the results especially in figure 6 b), one should keep in mind that the voxel size of the CT data was 100 µm and on the other hand the calibration uncertainty 1.5µm.

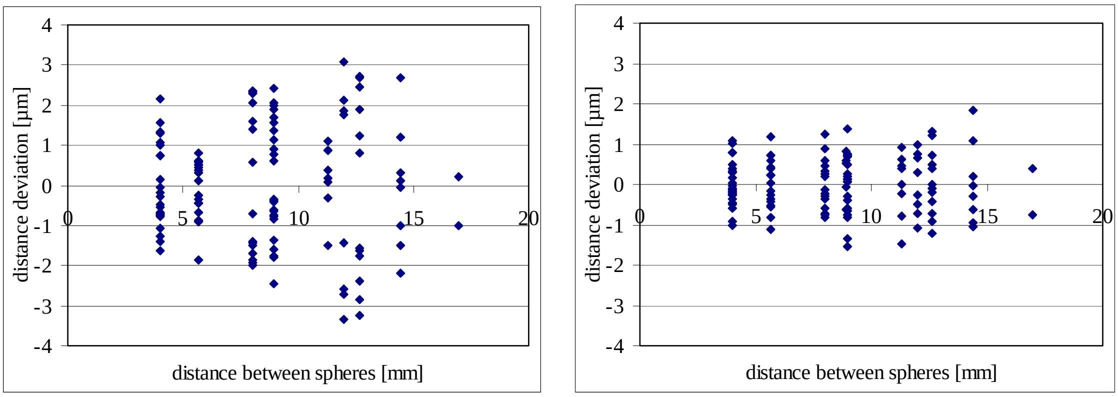

Fig. 6. Deviation of distances between sphere centers plotted vs. distance: a) without using beam hardening correction during the reconstruction; b) beam hardening correction used.

3.2 **Influence of surface extraction**

Using the ISO surface extraction method described above with only one fixed global threshold for separation between material and air causes wrong local surface positions in many practical cases due to non linear effects like beam hardening or X-ray scattering. Even if beam hardening correction is applied, noise, defect pixels and other disturbances can lead to a non-optimal ISO threshold value and would shift the surface position depending on local gray scale distribution.

In [2] a novel method for surface extraction developed by phoenix|x-ray was presented (advanced surface extraction). This method provides a significantly improved surface quality also for volumes affected by artifacts by evaluating local gray value variations in the volume. Furthermore, this method allows the extraction of boundaries between different materials in the same run without a redefinition of the threshold and saving them in the same point cloud or polygon file.

To show the influence of the advanced extraction method on the surface position and on the metrological characteristic values, the same volume data was used as presented in the chapter 3.1. The beam hardening correction was *not* used in order to allow a clear separation of the two methods.

The graphs shown in fig. 7 present the probing error size *PS* and deviations between measured and calibrated sphere centers for ISO surface extraction and advanced surface extraction methods.

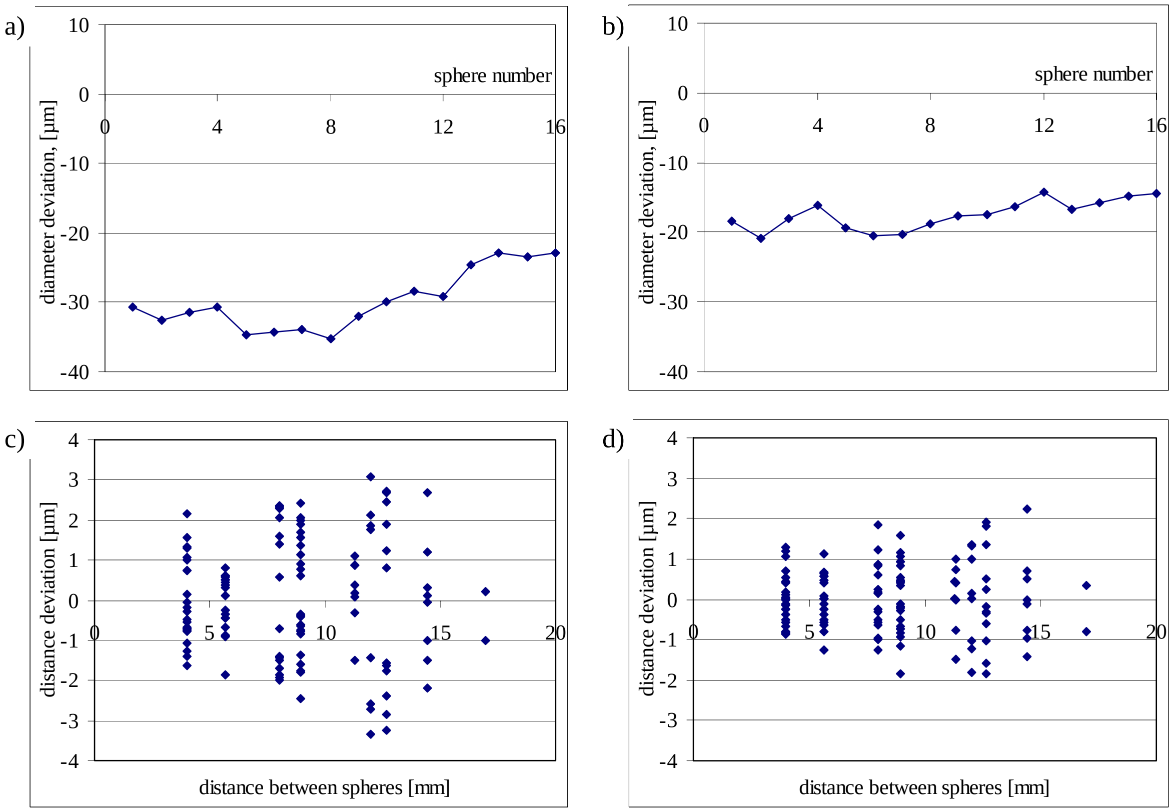

Fig. 7. Influence of different surface extraction methods on metrological characteristics: a) deviation between measured and calibrated calotte diameter for ISO surface; b) deviation between measured and calibrated calotte diameter for phoenix surface; c) distance deviation between sphere centers for ISO surface; d) distance deviation between sphere centers for phoenix|x-rays advanced surface.

To evaluate the influence on the characteristic value *PS*, the deviation between measured and calibrated diameter (1) of the calottes was plotted versus calotte number for both surface extraction methods, compare fig. 8 a) and b). Even with ISO method the diameter deviation is much less than one voxel. However, the deviation becomes significantly smaller if the phoenix|x-ray surface extraction method is used. Same applies to the distance deviation between sphere centers, see fig. 7 c) and d).

4. Performance of the X-ray tomography system phoenix v|tome|x L 300 in dimensional metrology

A new tomography system from the phoenix|x-ray product line of GE Sensing & Inspection Technologies, which has recently been launched and which features a new unipolar 300 kV/500 W microfocus X-ray tube, is enabling CT analyses of difficult-to-penetrate components at particularly high levels of magnification (fig. 8). It is the first time that a detail detectability of down to 1 µm has been achieved with a 300 kV X-ray tube. The CT system also uses a new temperature-stabilized digital detector allowing an extremely dynamic range of up to 10000:1 with 4 Mpixel and 200 µm pixel pitch. The system manipulator is granite based to ensure high mechanical accuracy and long term stability.

The general metrological properties of the phoenix v|tome|x L 300 were evaluated using the calibrated Zerodur sphere calottes plate shown in figure 3. The test specimen was scanned at a voxel size of 40 µm. Beam hardening correction was applied during the reconstruction of the volume data, and the surface data was extracted using the advanced method introduced in section

3.2. The results are shown in figure 9. One can see a significant improvement on the metrological characteristics compared with applying BHC or advanced surface extraction separately (compare with figures 6 and 7). The diameter deviation (e.g. probing error size PS) is less than 4 µm e.g. less than 1/10 of the voxel size. The distance deviation is significantly below 1 µm, e.g. less than 1/50 of the voxel size.

Fig. 8. The phoenix v|tome|x L 300: first µCT system with a 300 kV unipolar microfocus X-ray tube

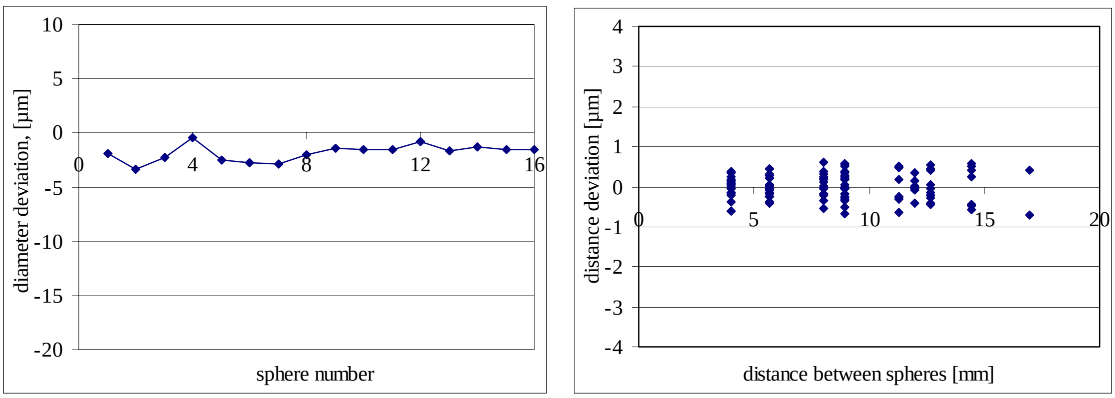

Fig. 9. Metrological characteristics of phoenix v|tome|x L 300 @ 40 µm voxel size: a) diameter deviation vs. calotte number; b) distance deviation between sphere centers vs. calibrated distance.

To further substantiate the measurement accuracy of the phoenix|x-ray computed tomography sytems of GE Sensing & Inspection Technologies, and therefore their suitability for use as 3D coordinate measuring machines, a valve block made from aircraft aluminum manufactured by Continental AG in Frankfurt with an edge length of 130 mm was subjected to a CT scan followed by a reference measurement using high-precision tactile 3D coordinate measurement technology. More than 30 distance and diameter features have been chosen for this comparison. A phoenix v|tome|x L computed tomography system was used for the CT scan. The CT scan was performed in 30 min at 100 µm voxel size. A high precision Hexagon/Leitz 3D PMM 8.6.6 tactile coordinate measuring machine (CMM) was used for the reference measurement.

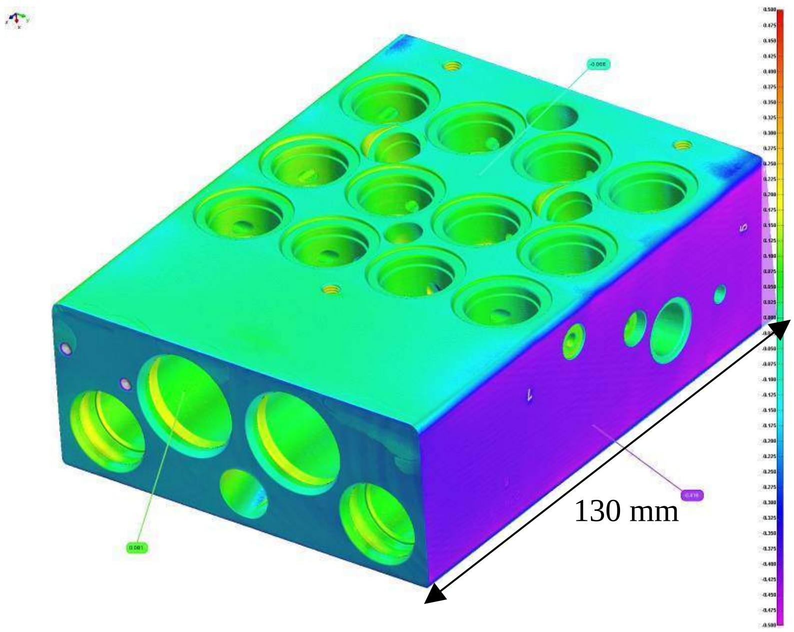

Fig. 10. Nominal (CAD) – actual (CT dataset) comparison of an aluminum valve block

A 3D comparison of the measured CT dataset to nominal CAD model is shown in figure XX. The pseudo color representation gives a quick and intuitive insight into the quality of the manufacturing process of the part.

The table given below contains extracts from the specimen inspection report and demonstrates the excellent concordance between both the CMM and CT measurement methods. The proven diameter and length variance for all 30 evaluated features is ≤10 µm.

Parameter	Ø Z 1 [mm]	Distance A 1 [mm]
Target CAD	28.000	70.500
Tolerance	0.050	0.100
Actual CT	28.035	70.442
Actual CMM	28.034	70.447
CT/CMM variance	0.001	-0.005

The comparison demonstrates that modern CT systems of the phoenix v|tome|x L series function with a precision which is comparable to that of conventional coordinate measuring systems.

Since there are different possibilities for combining hardware and software, however, this comparison does not show that, in general, every CT system offers such accuracy. The GE Sensing & Inspection Technologies phoenix|x-ray CT system product line, designed for performing dimensional measurements, is based on high-quality X-ray tubes and detectors ensuring stable acquisition conditions, precision manipulators, certified tracebility of the measurement results, and a broad range of modules for volume optimization and geometrical surface extraction.

Only the interaction of these components ensures that the advantages of dimensional measurement with computed tomography can be combined with the of conventional coordinate measurements with the accustomed precision.

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