Voxel size and calibration for CT measurements with a small field of view

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Dimensional tomographic measurement is influenced by many factors. To achieve metrological traceability of results, knowledge of influence factors and their effect on measurement is important. This includes knowledge of the true value of voxel size and edge detection. Phantoms used for characterization and correction of error sources are calibrated usually on tactile or optical coordinate measuring machines. The challenge here is the manufacturing and calibration of small phantoms, which can be used in the field of view approximately 1 mm and less, which is the case of tomographic devices aiming at high resolution. In this work, abilities of a nano-coordinate measuring machine (nano-CMM) SIOS NMM-1 (Nanopositioning and Nanomeasuring Machine) to calibration of a phantom for X-ray computed tomography (CT) with the small field of view and high resolution are tested.

Keywords: nano-CMM, SIOS NMM-1, voxel size calibration, edge detection calibration, CT

1 Introduction

To increase the impact of X-ray computed tomography (CT) in the field of non-destructive testing, it has to catch up with the demands of dimensional metrology. The CT measurement is affected by a lot of factors, which are often dependent on each other (CT system, sample, environment, data processing, operator, measurement settings, image artifacts …). Due to such a complexity of CT measurement, determination of measurement uncertainty is a challenging task. One of the necessary steps to achieve traceability of CT dimensional measurements is instrument calibration [1]. Currently, there exists a wide variety of phantom types suitable for voxel size calibration, edge detection calibration or other purposes. The smallest calibration phantoms usable for voxel size calibration by measurement of center-to-center distances of two spheres are made of ruby balls with nominal diameter 0.5 mm [1, 2]. Rigaku Nano3DX CT device can achieve linear voxel size up to 0.27 μm in the field of view (FOV) 0.9 × 0.9 × 0.7 mm³ [3]. To manage calibration of measurement with submillimeter FOV, a phantom consisting of ruby balls with a diameter less than 0.5 mm would be suitable. We will test the suitability of the coordinate measuring machine SIOS NMM-1 for reference measurement of calibration phantoms consisting of ruby balls with a nominal diameter of 0.3 mm.

2 Determination of voxel size and edge detection

The distance between two points in reconstructed CT data is calculated as

\[ L = n \cdot \upsilon x \]

where \( \upsilon x \) is the voxel size and \( n \) is the number of voxels between measured points (which does not necessarily represent integer since sub-voxel interpolation of the edge is often used to cope with partial volume effects). We will discuss factors which influence the determination of voxel size and edge detection. Analytical approach to the determination of uncertainty of length measurements in CT data from uncertainties of \( n \) and \( \upsilon x \) is described in [4].

2.1 Geometry and voxel size

Ideally, the focal spot, rotary table axis, and detector center intersect a straight line and the rotary table axis should be parallel to the detector and projected on the detector central column [5]. Misalignment of a CT system components (such as tilt or shift of the detector and rotary axis or focal spot drift) may lead to image artifacts [6] or to inhomogeneity of magnification in the measured volume [4]. Temperature instability in CT system cabin may also lead to errors in dimensional measurement due to the thermal expansion of kinematic system components and the workpiece.

Several things can be done to reduce these errors. To increase the stability of the frame supporting the kinematic system, a granite is usually used as base material [7]. To determine a position and misalignments of system components, precise measurement of components position is necessary. Bircher et. al. [8] describes the usage of fiber interferometers for measurement of SOD (source-to-object distance) and SDD (source-to-detector distance) and image sensors for measurement of straightens and displacements. To achieve a stable temperature around 20 °C during the measurement, air-conditioning of CT system cabin is necessary. To obtain actual geometry parameters of the CT system, geometrical calibration is necessary. Methods of determining CT system geometry can be divided into two categories. Methods in the first category are based on measurement of a reference object, geometrical parameters (scale errors, focal spot drift etc.) are obtained from the projection or voxel data. Other methods are based on the use of reference instruments (such as laser interferometers) [9].
Voxel size $v_x$ is determined from magnification $M = \frac{SDD}{SOD}$, where $SDD$ is source-to-detector distance and $SOD$ is source-to-object distance and pixel size $p$ as [10]

$$v_x = \frac{p}{M} = \frac{SOD}{SDD}.$$

According to this relation, the error in voxel size (and therefore in distance measurement) can be caused by inaccurate measurements of $SDD$ and $SOD$ and determination of pixel size or by other geometric distortions as was explained. To reduce these errors, calibration of CT by measurement of reference workpiece can be used. The object with calibrated dimension $l_{ref}$ is scanned and its dimension is measured ($l_{CT}$). The voxel size $v_{x, orig}$ of the subsequent scan in the same geometrical arrangement is recalculated to get the corrected value $v_{x, corr}$ as [10, 11]

$$v_{x, corr} = v_{x, orig} \frac{l_{ref}}{l_{CT}}.$$

The reference object is measured with the actual sample or with the same conditions (due to the lack of repeatability of magnification axis, the position of actual and reference measurement should not be changed [12]). Reference dimension for scale calibration must be independent on edge determination [13] (as shown in Fig. 1). An example of edge independent measurement is the distance between the centers of two spheres. It is assumed that the sphere center coordinates remain unchanged regardless of surface determination [10].

![Figure 1: Distances a) heavily (unidirectional measurement) and b) minimally (bidirectional measurement) affected distances by edge detection. According to [13].](image)

### 2.2 Edge detection

Besides voxel size determination, an important step when performing dimensional CT measurement is edge (surface) detection. Proper edge detection is important mainly for unidirectional measurements (Fig. 1). The accuracy of edge detection is influenced by many factors – e. g. source settings, spot size and magnification, beam hardening and its corrections, noise or other imaging artifacts [14].

The basic method of edge detection is global thresholding – a grey value is assigned as a transition from one material to another. Sub-voxel interpolation of the edge is important to achieve sufficient accuracy. A common method to identify the threshold is the so-called ISO-50% value, which is obtained from gray value histogram [1]. It is a mid-gray value between the peak of material and air. For different materials, the optimal threshold may be shifted in either towards the material or air peak [15, 16]. For calibration of the global threshold value, a reference sample with calibrated inner (hole) and outer diameter may be used. Measurement of internal or external diameter depends on changing threshold in the opposite way. The correct threshold value is chosen to minimize the deviations of both features dimension [17]. Another type of phantom which can be used to edge detection calibration is described in [18]. The tetrahedron phantom consists of 4 alumina spheres which are in contact with each other. The threshold is selected so that the sum of the radii of two touching spheres is equal to the distance of the centers. This method is feasible either for edge detection and voxel size calibration.

Image quality can vary throughout the volume, mainly due to the artifact from beam hardening, scattering, cone-beam effects or nose. This affects also the edge detection and may decrease the accuracy of global thresholding method [19, 20]. Edge detection can be improved by using local thresholding or other advanced methods for edge detection [20, 21].

### 3 Calibration objects for the small field of view

To access measurement characteristics and to correct measurement errors reference objects are necessary. Such objects must be dimensionally stable and be appropriately calibrated. Objects used in tactile or optical coordinate metrology are often made of high absorbing materials (such as steel) and therefore are not suitable for application in X-ray computed tomography. CT requires usage of low absorbing materials which still meets the requirements for long-term dimensional stability – materials like low-density ceramics, ruby, carbon-fiber reinforced polymers or low absorption metals like aluminum are suitable [1]. There is currently a large number of phantom designs, which can be used for characterization and correction of various error sources in
CT measurement, such as voxel size and edge detection calibration [22, 23]. Most of the phantoms are suitable for micro CT measurement with voxel size above 1 μm and object size in the order of centimeters. Manufacturing and reference measurement of calibration object for CT with the small field of view (under 1 mm) is a challenging task.

For voxel size calibration measurement of distances between two sphere centers is suitable. Measurement of sphere center position is minimally affected by edge detection and beam hardening [1]. The smallest successfully calibrated phantoms usable for voxel size calibration by measurement of center-to-center distance are made of ruby balls with nominal diameter 0.5 mm [2]. In this work, abilities of nano-CMM SIOS NMM-1 for calibration of objects made of ruby balls with diameters 1 mm and 0.3 mm are tested. Design of the two-ball phantom is shown in Fig. 3. a). Two ruby balls with nominal diameter 0.3 mm were fixed on carbon rod (diameter 1 mm) using epoxy resin. Epoxy resin and carbon fibers are low attenuating materials in the X-ray spectrum and are therefore suitable for manufacturing phantoms for X-ray computed tomography. Final phantom is shown in Fig. 3. b).

Figure 3: a) Drawing of the two-ball calibration phantom with required measurements, dimensions are in mm. b) Photo of the manufactured phantom.

4 CMM measurement

The measurements were carried out on a SIOS NMM-1 machine, which is a high accuracy positioning system based on voice coil actuators and interferometric length sensors [24]. The device is designed to minimize thermal drifts and features nanometer positioning accuracy. To perform CMM measurements this device is equipped with Gannen XP sensors from Xpress Precision Engineering Company featuring very low contact forces, small sensor radius and high accuracy [25, 26]. A special fixture that would allow firm gripping and positioning of the ball attached to a carbon stylus whose size and weight does not exceed limits of the NMM-1 machine had to be made.

Figure 4: Black-and-white photos from nano-CMM NNM-1 with a 3D-Micro probe, a) single ruby ball measurement and b) measurement of the two-ball phantom.

The number of scanned points and their position on the ball was chosen in compliance with ISO 10 360 standards. For the 1 mm sphere sample a probe with 300 μm diameter was used. For the two-ball phantom, a smallest available probe with 120 μm.
diameter was used. The measurements were 10 times repeated to obtain a sufficient set of data to evaluate the reproducibility of the measuring method. For attachment of the measured objects to the NMM-1 system, a specially designed holder was used, which enabled measurements under conditions of repeatability [27].

Data evaluation was based on a sphere fitting, performed by the NMM-1 software. Measured diameter of a ruby ball with nominal diameter 1 mm is 1000.03 µm with a standard deviation of 0.21 µm. The measured center-to-center distance of the two-ball phantom is 579.183 µm with repeatability below 0.010 µm. The uncertainty of the Gannen XP sensor, as estimated by the manufacturer, is 0.050 nm, which is the largest uncertainty component of the whole measurement. Main uncertainty component of the Gannen XP sensor is thermal drift which was minimized by using the enclosure of the NMM-1 system.

5 CT measurement

CT measurements were performed with Rigaku Nano3DX machine. The X-ray source is equipped with rotating anode (Cr, Cu or Mo, working at 35 kV, 40 kV, 50 kV respectively). The measurements were performed with Mo target. The sample is positioned on a 5-axis stage. X-rays are converted to light by the scintillator and focused on CCD camera by objective (FOV and voxel size is set by changing objectives with different magnification). Data was analyzed in VGStudio MAX 3.2.

<table>
<thead>
<tr>
<th></th>
<th>Linear voxel size</th>
<th>FOV</th>
<th>Projections</th>
<th>Exposure time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm ruby ball</td>
<td>1.08 µm</td>
<td>1.8 × 1.8 × 1.4 mm³</td>
<td>800</td>
<td>10</td>
</tr>
<tr>
<td>Two ball phantom</td>
<td>0.54 µm</td>
<td>0.9 × 0.9 × 0.7 mm³</td>
<td>800</td>
<td>16</td>
</tr>
</tbody>
</table>

First measurements were performed on one ruby ball with nominal diameter 1 mm. Ruby ball was measured 3 times, parameters of measurements are described in Table 1. Edge was detected using ISO 50% method, the sphere was fitted on the surface using the least squares method. Average value of fitted sphere diameter from 3 CT measurements compared to the result of CMM measurement are shown in table 2. There is a significant difference between the diameters acquired from CT measurement and from CMM measurement. The unidirectional characteristic of one diameter measurement does not allow to determine, how the error is associated with voxel size determination and edge detection.

<table>
<thead>
<tr>
<th></th>
<th>Diameter [µm]</th>
<th>Standard deviation [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT measurement</td>
<td>994.37</td>
<td>0.06</td>
</tr>
<tr>
<td>CMM measurement</td>
<td>1000.03</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Figure 5. Measurement of MTF function on 1 mm ruby ball, highlighted value shows value at 10% modulation.

Ruby ball measurement is also suitable for measurement of modulation transfer function (MTF) function according to ASTM 1695 standard [28]. MTF is calculated from the tomographic cross-section in the center of the ruby ball. According to ASTM 1695, the edge profile of the disk is analyzed to obtain edge response function (ERF). Point spread function (PSF) is obtained as derivative of ERF. MTF is calculated is a normalized amplitude of Fourier transform form PSF. Spatial resolution is calculated.
from the spatial frequency at 10% modulation. Fig. 5 shows the MTF obtained from ruby ball measurement. 10% value of MTF corresponds to spatial frequency 0.162 line pairs per µm.

To properly determine the error of voxel size, measurement of the two-ball phantom was performed. Parameters of CT measurement are shown in Table 1. The edge was determined by 4 detection methods to confirm that measured center-to-center distance is independent on the edge detection. Three global thresholding methods were used (ISO 50%, threshold 1 closer to background peak and threshold 2 closer to material peak). Last used method was gradient-based local thresholding with noise particle reduction available in VGStudio MAX software. For every edge detection method, measurement of center-to-center distances was performed 5 times. Average distance with the corresponding standard deviation is shown in Table 3.

Table 3: Results of CT and CMM measurements of one two-ball phantom.

<table>
<thead>
<tr>
<th>Method</th>
<th>Distance [µm]</th>
<th>Standard deviation [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 50%</td>
<td>575.47</td>
<td>0.02</td>
</tr>
<tr>
<td>Threshold 1</td>
<td>575.52</td>
<td>0.06</td>
</tr>
<tr>
<td>Threshold 2</td>
<td>575.52</td>
<td>0.07</td>
</tr>
<tr>
<td>Local thresholding</td>
<td>575.37</td>
<td>0.05</td>
</tr>
<tr>
<td>CMM measurement</td>
<td>579.18</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Figure 6: a) 3D render of ruby balls, b) tomographic cross-section.

6 Discussion

Measurement of single ruby balls showed a significant deviation of diameter measurement on CT data from reference measurement on SIOS NMM-1. Source of this deviation cannot be exactly determined, because measurement of sphere diameter is affected both by errors in scale and errors due to the edge detection. That is the reason why phantom for measurement of center-to-center distances between two spheres was manufactured.

Edge was detected by 4 methods. Deviations between obtained center-to-center distances are on order of 0.1 µm, which is sufficiently less than the deviation from CMM measurement. Measurement of center-to-center distances of two ruby ball with nominal diameter can be used for voxel size calibration. The deviation between CT and CMM measurement may be caused mostly inaccuracy of measurement of distances between source and sample and source and detector. To correct these errors, calibration by measurement of two-ball phantom before measurement of the actual sample in the same position and subsequent voxel size correction should be performed.

Future development of calibration phantoms for the small field of view should focus on shortening measurement time for calibration. In this case, the exposure time for measurement of the two-ball phantom was 16 s and total measurement time exceeded 4 hours. Phantom was suitable for calibration of CT device equipped with Mo X-ray source working at 50 kV voltage and it was not possible to measure the phantom on Cu or Cr target with fixed voltages of 35 kV and 40 kV, respectively, due to high absorption of ruby balls. Phantom should be manufactured with lower density materials than ruby to be used with lower-energy X-ray spectra. To decrease maximum material thickness for X-ray penetration, the position of the spheres should be adjusted to decrease overlapping of spheres during projections.

7 Conclusion

To get a traceable result of dimensional measurement on CT, the calibration of voxel size and edge detection is necessary. Measurement of calibration phantom with two spheres before CT measurement of the actual sample and subsequent rescaling of
voxel size was suggested as a suitable method for increasing accuracy of dimensional measurement. Also, the suitability of SIOS NMM-1 machine for calibration of a manufactured phantom was tested. A ruby ball phantom made of two ruby balls with nominal diameter 0.3 mm was manufactured and calibrated on nano-CMM SIOS NMM-1 machine. The phantom was shown to be capable of calibration of voxel size in dimensional CT measurement. The calibration of voxel size should be done before every dimensional CT measurement. Calibration must be done in the same position as the actual sample. Next development should be focused on decreasing the time of CT calibration measurement – usage of lower density material and more convenient mutual position of two spheres.

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References