An efficient procedure for traceable dimensional measurements and the characterization of industrial CT systems

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Abstract
In industry, cone-beam CT with a flat-panel detector and a micro-focus X-ray source is most used today. The targeted accuracy of its dimensional measurements might however not be reached over the full operating time. Multiple reference CT measurements at different magnifications are usually performed to allow corrections, but are extensive. As a more efficient procedure it is proposed to use 2D grid-like structures traced back to an optical imaging coordinate measuring machine. It is shown and verified by a comparison to a full CT, that with only two radiographic images and an effort of a few minutes of operation time, the magnification of a micro-CT has been determined to better than $2 \cdot 10^{-5}$ relatively. It can thus be done in most applications accompanying to each CT measurement. Additionally its function and the adjustment of the micro-CT have been checked by a newly developed cylindrical artefact made of thermoplastics. This avoids beam hardening and incorporates one unidirectional, one bidirectional and one angular measure.

Keywords: CT system qualification, dimensional CT, traceability, magnification, geometrical alignment error

1. Introduction

The accuracy of dimensional CT measurements is affected by positional and directional deviations of the X-ray source, the rotary table and the detector. The effective source position is in particular dependent on the heat load inside the X-ray source, filament changes, the target burn-off and the electron column. It is difficult to determine this position, as it is also hard to determine the effective detector position and its effective geometrical distortion, as they are not only mechanical entities. These influence factors might lead to deviations that result in the targeted accuracy not being reached over the operating time.

Multiple, time-consuming CT measurements of a dimensional well-known test object at different magnifications are usually performed to assess the deviations and to allow corrections. A work-around for precision measurements is either performing a partial tactile or optical calibration of the respective measurement object or a complete CT of a reference body before and/or after the actual CT measurement. The former solution leads to problems, e.g. with the coordinate system registration. The latter is time-consuming and, due to its long duration, might be subject to drift.

There are an exhaustive number of publications about the use of fiducial markers and the physical characterization of industrial and medical CT (e.g. [1], [2]). Even at the early stages of cone-beam CT, Sire et al. [3] briefly described a procedure to determine the geometrical X-ray cone-beam CT system calibration using a borehole grid structure in $0^\circ$ and $180^\circ$ positions. They used it in different positions to determine tilt, skew and magnification. Moreover it was
used for geometric distortion correction by modelling it with a global 2nd order and local 5th order polynomial. Weiβ et al. [4] employed a grid structure for the determination of the distortion of a flat-panel detector. Moreover they used a plastic cylinder to validate the geometrical correction for the distortion of the detector.

As there is in general no detailed and disclosing description of traceable dimensional measurements with grid structures, the Physikalisch-Technische Bundesanstalt (PTB) developed and systematically investigated this precise, cost-saving and time-efficient procedure: A 2D grid is easily traceable to SI units and can be obtained in high quality. It is proposed to use a 2D grid in reversal technique – i.e. only to capture two images in the positions 0 degrees and 180 degrees – to determine the magnification and – if necessary – the geometrical alignment errors for rectification. The images are evaluated with pattern recognition and Levenberg-Marquardt fitting to a regular grid with high accuracy. To validate this approach, a cylindrical calibration standard made of thermoplastics was developed that avoids beam-hardening effects and features one unidirectional, one bidirectional and one angular measure.

Important analysis parameters are the deduced scale factor and the trapezoidal distortion. The grid results are compared to the full CT of the grid structure and to CT results of the cylindrical standard. The bidirectional measure moreover allows a statement to be made on the probing errors of the CT system. The grid reference image approach could be used by default for every CT measurement to ensure size accuracy. Both multiple magnification determination with a 2D standard as well as using the cylindrical standard may be helpful for either CT system qualification and/or specific acceptance testing.

2. Geometrical description of the CT

2.1. Magnification

The geometrical description of the CT shows the systematic rules and dependencies in an instructive way – for more complex tasks there are CT simulation tools, e.g. [5-9]. A necessary assumption is a sufficiently defined rotary axis. Its eccentricity and regular wobble are of minor importance, as they are only equivalent to a shift and inclination of the test object. Thus only higher harmonics of the wobble error contribute (see sec. 5.2). The magnification is given by the ratio between the source-to-detector distance \( L \) to the source-to-object distance \( a \) (see fig. 1). The centre of rotation is the intercept point of the rotary axis and the area \( A \), spanned by the detector surface normal and the detector’s x-axis, projected onto the normal. An unwished shift of the rotary axis position along the magnification axis changes the apparent object size (see fig. 1, right). For the maximum diagonal in the image and for a typical detector-size to distance ratio of 1:3, the maximum length measuring error is about half of the position error.
Figure 1: The left graphic is the geometrical description of the CT. The tilt angle $\gamma$ is in the direction target to detector, the skew angle $\varphi$ for rotation around the $z$-axis is suppressed here. The right-hand sketch explains the effect of a shift of the rotary axis along the magnification axis on the apparent object size $w'$ for its largest possible width $w$. For a typical value $D / L = 1:3$ it simply holds that: $w' - w \approx 0.5 \cdot \Delta a$.

2.2. Trapezoidal distortion

 Tilting a planar object at a distance $a$ leads to a linear height dependence of the projected distance $a'$ of the single object points (fig. 2). From a simple geometrical consideration, an image of a 2D object, tilted by the angle $\gamma$ is trapezoidally distorted by an angle $\varepsilon$ given by:

$$\varepsilon = \gamma / 2 \cdot D / L.$$ (1)

For the measurements in section 5 this can be approximated: $\varepsilon \approx \gamma / 6$ with $D / L \approx 1/3$.

The slant angle (angular position offset of the rotary axis) leads to a transverse trapezoidal distortion, but is thought to be zero as it is practically achieved by adjustment (see sec. 5.1). For small angles of the tilt $\gamma$ and the skew $\varphi$ the rotational transform is commutable and separable.

Figure 2: Geometrical consideration of distortion caused by tilting the rotational axis.
For 3D objects equation 1 could slightly differ, as the object surface points traverse an interval of distances. A cylindrical object, symmetrical to the rotation axis, nearly filling the complete volume of the CT reconstruction is assumed. When tilting the rotational axis, all projection images are still the same. An example was generated using a CT simulation tool [5]. From that a reconstruction was made with the software CT Pro 3D [10], and evaluation of the surface was performed with VG Studio Max 2.2.6 [11]. These are the same conditions as for the experiments shown later. The dependence of the fitted cone angle over the tilt angle of the axis determined by this simulation is shown in figure 3. It is calculated for a magnification of 12.5 and a cylinder diameter of 20 mm. Hence only a 250 mm width of the assumed 400 mm x 400 mm detector is used and the trapezoidal angle

\[ \varepsilon \approx \frac{\gamma}{6} \cdot \frac{250 \text{ mm}}{400 \text{ mm}} \approx 0.104 \cdot \gamma \]

is expected for a flat object. There is a difference to the simulated factor of 0.121 for the cylinder of about plus 20% in comparison to the one stated for flat objects in equation 1.

![Figure 3: Simulation of a tilted cylinder. Due to the tilt it appears conical. Details see text.](image)

3. Reference standards

The main purpose of the following proposed three standard specimens is to determine the undisturbed scaling factors of a \( \mu \)-CT. Thus nearly ideal reference standards are necessary that do not lead to beam hardening or other artefacts. Their use and calibration should be easy and cost-effective. The standard should be robust and redundant, so that traces of use, e.g. scratches, do not influence the results. Figure 4 shows a sketch of the proposed chain of traceability: Thin planar grids are calibrated most easily (see sections 5.1 and 5.3) by optical coordinate measuring machines (CMMs) with video sensors. A direct comparison between radiographic and CT scaling is performed in section 5.4. In section 5.5 a cross-check between a planar grid and cylindrical artefacts is shown. The latter additionally have a bidirectional and an angular measure.
3.1. Printed circuit board (PCB)

As a planar grid structure a commercial printed circuit board with a regular matrix shape has been used. It is cut-out so that for three different magnifications, a CT filling its complete size without a spinning-out part can be undertaken (see fig. 5).

The PCB (Roth Elektronik, RE200-HT) is a high-temperature board made of a polyimide / glass fibre composite. The ring-shaped metal pads are arranged in a 38 x 61 matrix with a 2.54 mm distance. They have a thickness of 35 µm of copper chemical plated with Au/Ni. The substrate has a good X-ray transparency and satisfying homogeneity. The PCB has been tested to have sufficient image quality for X-ray voltages from 50 kV to 225 kV. Due to the spacing this specimen could be used best for magnifications from about 1.6 to 20. The substrate was assumed to be the best radiation-hard low-Z material [12] and has an optimized linear thermal expansion coefficient to copper: it was determined to be $(12.5 \pm 2 \ (p = 0.95)) \cdot 10^{-6} / \text{K}$ at $21^\circ\text{C}$ in a thermal box on a Werth VideoCheck® HA optical CMM. This CMM has also been used to measure the centre positions of the outer circular pad contours. A recalibration of the cut-out PCB after 20 months of intensive use shows a relative expansion

Figure 5: CT measurement setup. Left: X-ray source. Right: detector cover. Centre: stage with cut-out PCB in position of magnification 3.25.
of $6 \cdot 10^{-5}$. A parallel measured sporadically used second PCB showed $+2.5 \cdot 10^{-5}$, or respectively $-2.5 \cdot 10^{-5}$, relative length changes in both main directions. The difference of the length changes between the different PCBs might be caused by a few hundred hours of irradiation in the CT or by the relaxation of the glass fibres due to the cut edges.

### 3.2. Transmission electron microscopy mesh

For higher magnification in the range from 60 to 120, a commercially available TEM mesh with a 3.05 mm diameter (ATHENE AEI G215) was tested. It was held between two cover-glasses with 150 µm thickness, fixed at the sides by glue (see fig. 6). From the CT reconstruction the grid distance was determined to be 60 µm (see sec. 5.30), and the diameter of the holes to be 37 µm and the thickness of the copper to be 14 µm. There are in all 868 circular holes on a square grid.

The calibration was performed with a Werth VideoCheck® HA optical CMM: A matrix of digital images with an overlap of 50% in the X- and Y-direction has been recorded at defined coordinate positions (with ~ 0.2 µm uncertainty ($p = 0.95$)). With the pattern recognition software shown in section 4, the positions of the holes were determined. Using the pixel size in the X- and Y-direction and the camera skew angle as parameters, the overlapping hole coordinates (for each hole coordinates from four images) can be optimized to lie in an interval of 100 nm in the X- and Y-direction. It is estimated that the scale factor of the grid showing the holes’ positions is determined with a scale uncertainty of 200 nm on a diameter of 2 mm.

### 3.3. Thermoplastic “cotton reel”

For the mid-range magnification and the comparison to real 3D objects, three cylindrical standards are provided (see fig. 7): They have an outer diameter and a length of 10/20/40 mm that is defined by the distance of two double-conical rings. The mean diameter of the cylinder is a bidirectional measure, the distance is a unidirectional measure. The (non-) conicity is an angular measure. These standards are diamond-turned from solid polyether ether ketone (PEEK) with a roughness $R_z < 0.8$ µm. This material is known to be mechanically excellent and radiation hard [12].

![Figure 6: CT reconstruction image. Greyblue: cover glasses with 165 µm thickness, cuprous: TEM mesh.](image)
To enhance the long-term stability we recommend first to anneal the basis material, then to pre-machine the shape and to undertake an additional annealing process over 34 hours (up to 220°C, 20°C/hour rising/falling) before the final diamond-turning process (this was done for the later 10 mm / 40 mm version). For the earlier 20 mm version a dimensional change of up to 7 µm has been observed due to thermal treatment. The linear thermal expansion coefficient was determined to be about 60 ppm/K for the 20 mm cylinder by means of the digital image correlation technique (see e.g. [13]) on the optical CMM in a thermal box.

The calibrations of the diameter and length of the three standards are undertaken with tactile coordinate machines (Zeiss UPMC 850, Zeiss Prismo Ultra, Leitz PMM 866) at a probing force from 50 mN to 100 mN and a stylus diameter from 1 mm to 3 mm. The uncertainty of the diameter/length measurements is between 0.5 µm and 1 µm. The Hertz indentation has been calculated for each of the measurements and is about 0.5 µm. Two times of the value was added to the diameter as a correction. In figure 7 the 272 tactile measured points are overlaid onto an exemplary surface rendered CT done with VG Studiomax [11]. With this software the tactile measured points as well as the CT are fitted to the geometrical model. The diameter is simply the diameter of a Gaussian best-fit cylinder. The angle is the best-fit cone angle of this “cylindrical” surface. The length measure is defined as the distance between the two points on the cylindrical axis, given by the intersection of the planes that are spanned by the nearly circular intersection lines of each with adjoining cones.

4. Grid evaluation using pattern recognition and reversal technique

For the determination of the scaling and the rotary axis misalignment, the distortion and size of images have to be evaluated. This could be done in a continuous way by comparing a complete image with a resized and distorted version of it. For the calibration with optical CMMs it is more practicable to contour small identical substructures in a matrix arrangement. Thus naturally small identical patterns have to be recognized in that image (see fig. 8). In the (nearly perfect) position matrix a parameterized grid is fitted – these six parameters represent
the sizing and orientation information: the X/Y-position \( p_x, p_y \), the X/Y-scaling \( s_x, s_y \), skew angle \( \varphi \) and trapezoidal angle \( \varepsilon \). As mentioned in section 2.2 the transverse trapezoidal distortion due to the slant angle is suppressed. In the same way a matrix can be fitted to the CMM position data. From the quotient of the scaling values the scaling in pixel per mm can be calculated. The physical standards axis is not necessarily congruent to the rotation axis, but might be shifted and tilted. Therefore this has to be eliminated by the evaluation of two images which are 180 degree reverted around the rotation axis. The arithmetic average of the X/Y-position and the angles of skew and trapezoidal distortion describe the location and direction of the rotary axis in the coordinate system spanned by the detector surface and the source point (see fig. 1). The tilt angle \( \gamma \) is then calculated from \( \varepsilon \) by equation 1. From a simple geometrical consideration it follows that the scale factors have to be averaged harmonically but not arithmetically as the positions do:

\[
\frac{1}{s} = \frac{1}{s_{\text{deg}}} + \frac{1}{s_{180 \text{deg}}} \quad (2).
\]

Figure 8 shows screenshots of the evaluation software written in Labview™ 2011 [14] using the IMAQ package. It has this functionality: After loading the image, a bilinear background due to a gradient of the brightness is subtracted and the image is rescaled to 8 bit. Manually a master pattern is cut from the centre of the image and the borehole is masked out. Due to the thickness of the PCB the edge of the borehole varies depending on the angle of view from the source point. On the other side the metal layer is thin enough to avoid this effect. To suppress the effect of an imperfect master pattern (e.g. asymmetric cut-out, gradient) it is also used in 90°, 180° and 270° rotated orientations. The average value of the quadruple positions determines the symmetry centre position of the objects. For a typical radiography of the PCB with one minute of averaging time and power of 5 watt, the image quality is sufficient to determine the grid position \( p_x, p_y \) to typically better than 1/1000 pixel reproducibility. All data processing needs computing times of only several seconds. Thus the source stability can be investigated as it was in [2].

Figure 8: Grid evaluation: The left screenshot shows the recognition of a masked master pattern in the box of the image surrounded in green. The right screenshot shows the 50-times magnified deviations from an idealized grid disregarding \( \varphi \) and \( \varepsilon \). The quadruple shape of a single point arise from a 4-fold symmetry based evaluation (see text).
5. Measurements

All X-ray measurements have performed with a *Nikon MCT 225* CT system dedicated to dimensional measurements. It allows acceleration voltages up to 225 kV and power up to 225 W. For small-scale power up to 7 W the electron beam can be focussed down to 1 - 2 µm in diameter on the tungsten reflection target. The 40 cm x 40 cm detector is positioned about 1134 mm from the source. It is a 2000 x 2000 pixel, 200 µm pitch flat-panel detector with a CsI- needle scintillator layer of the type *Perkin Elmer XRD 1620 AN CS*. The image distortion of this detector is calibrated and corrected by default by the CT system manufacturer. The following measurements were all carried out with a 75 kV acceleration voltage, 0.1 mm copper filter and up to 7 W electron beam power. This avoids excessive heating of the focussing coils, defocussing of the beam and a high penetration depth into the scintillator material.

5.1. Determination of a 2D scale

![Figure 9: The left image shows a radiographic image of the PCB in orthogonal and parallel orientation to the beam. The right images are the detail of the central region of the parallel orientation (gamma-correction = 2.5, metal pads visible on the right side of each single image). Each sequence varies by 0.1 degrees in the rotational orientation, the middle one is optimal.](image)

For the measurement of the actual magnification at a given translational stage position and voltage, the first task is to determine both orthogonal orientations of the PCB (see fig. 9). The PCB is rotated so that the surface orientation (side with metal pads) is parallel to the cone-beam direction. This is done two times (metal pads in one orientation to the right and in the second orientation to the left) by the optimization of the coverage of the metallic pads in the line of view – independently of the operator it has been reproduced to better than 1/10 of a degree (95% probability). The orthogonal orientations are calculated as the average value of both positions, or respectively +180 degrees. Hence the cosine error of the x-scale stays smaller than \((\pi/1800)^2 / 2 = 1.5 \cdot 10^{-6}\) relatively. Due to the clamping holder of the PCB at the bottom, it could be tilted up to one degree leading to a cosine error of about 2 \cdot 10^{-4} of the vertical scale. Thus only the horizontal scale is used as it can be easily adjusted orthogonally. These two images are evaluated as described in section 4 and the x-scale is calculated referring to equation 2.
5.2. Sufficient quality of the rotational stage

As requested in section 2.1 the rotational stage has to have a minimum quality of the wobble error and of the eccentricity (starting with the three-wave error). As mentioned previously, about half of the displacement along the magnification axis corresponds to the maximal length measuring error inside the CT reconstruction volume. It is therefore recommended that the effective higher-harmonic eccentricity at the height of the object position (i.e. eccentricity plus height times wobble error) is at least smaller than the desired form error. Figure 10 shows, on the right-hand side, the manufacturer test protocol of the rotary table: at a height of 10 cm the peak-to-peak run-out of a point stays below about 1.5 µm, when the best-fit circle is subtracted. All angular positions are included weighted for every point of a CT surface reconstruction. Thus we estimate a form error due to this axis error of half of its size. For the determination of the 2D scale this means that, dependent on the relative rotary table position, the effective object position varies by ±0.75 µm. In figure 10 a repeated measurement of the scaling is shown, in which subsequently the relative angular position of the rotary table was turned. The values of 0° and 180° should be identical and are used to detrend a linear drift of the magnification, possibly caused by thermal drift due to the repeated opening of the radiation protection door – the total measurement time was about two hours. With the source-to-object distance of 175 mm and a variation of ±0.75 µm at a scaling of 82.6 pixel/g.u. (~2.54 mm), we expect a variation of ~ ±0.35 · 10^{-3} pixels which is compatible to the observation.

Figure 10: The left diagram shows the dependence of the 2D-determined magnification on the relative position of the rotary stage. The diagrams at the right are the manufacturer calibration of the stage of type RVS80CC (courtesy: Newport Corp.).
5.3. Comparison between CT and optical calibration

In the following figure 11 the results of CT reconstructions are contrasted with the results of optical calibration. This comprises three measurements of the cut-out PCB in different magnifications as well as a tentative measurement of a TEM mesh. The left column contains a combined surface and volume rendered graphic representations of the CT, whereas the surface rendered copper pads are shown in cupreous colour and the lower density PCB substrate material is volume rendered grey opaque. The magnification, or respectively the voxel size is given for information. At the outer edges of the copper pad surfaces cylinders are fitted (red contours). The fitting procedure works reliably even for these nearly flat objects, assuming the constraint that the cylinders are directed normally to the average PCB surface. The diagrams in the central column represent deviation charts of the cylinder positions similarly done to the right graph of figure 8: the deviations from an optimal rectangular (skewed and trapezoidal distorted) grid are magnified (as given below the diagram) plotted at their grid positions. The optimal x-scale and y-scale in mm / grid unit are printed below. This length measure uses the given voxel size internally. The outer right diagrams contain the evaluation of the centre positions of the optical contour measurements with their corresponding scaling. A direct comparison of the x- and y-scaling is the classical procedure to calibrate CT measurements by means of substitute measurements. The correction factor deviates a few $10^{-4}$ from 1 for the actual CT machine. Of special interest are the local deviations of the grids as they give a hint to reliability and local distortions of the detector. A closer inspection allows the identification of the fingerprint of the PCB.

Especially at the cut edges of the PCB (see arrows in fig. 11 at magnification 3.4) there are systematic position deviations of 10 µm corresponding to 1/6 of the voxel size. The reason is the missing substrate material at the outer side. This missing material breaks the symmetry of density influence in radial direction from neighboured volume elements: the locally arising density gradient in the volume-CT shifts the pads near to the edge in the radial direction. At magnification 17 there is one arrow marked point outlying for 15 µm in the optical measurement. Here visually and in the CT, a deep mark at the contour of the pad is visible. The optical contour measurement fails for this pad.

For the three PCB measurements the difference of the optical 2D deviation chart and the 3D deviation chart from X-ray CT was calculated. From 7/8 of all points with the lowest value (to avoid outliers and edges) the standard deviation $\sigma_{\text{difference}}$ has been calculated with a value of respectively 2.4 µm, 1.4 µm and 0.6 µm. This is in each case about 1/20 of the voxel size. Disregarding the optical measurement it is even a good result for a CT alone. The comparison of the optical and CT deviation chart at the last row of figure 11 for the TEM mesh standard differs slightly: the deviations from the CT seem to be statistical, but from the optical measurement a more systematic deviation pattern occurs. This is probably because of some glue from the preparation. There is a visible smear from upper left to lower right in the transmission image – for the X-ray it is completely transparent. Moreover some deficiency from the flatness and parallelism of the cover glasses might deflect the light systematically.
depending on the position. Nevertheless we believe there is a scaling accuracy of 1 µm over 2 mm length.

<table>
<thead>
<tr>
<th>Printed Circuit Board</th>
<th>Deviations: 10 µm / Grid Unit, σ_difference = 2.4 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnification: 3.4</td>
<td>Voxel Size: 58.7380 µm</td>
</tr>
<tr>
<td></td>
<td>Measurements: 2.540646 mm / 2.540655 mm</td>
</tr>
<tr>
<td></td>
<td>2.540775 mm / 2.540943 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Printed Circuit Board</th>
<th>Deviations: 10 µm / Grid Unit, σ_difference = 1.4 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnification: 7</td>
<td>Voxel Size: 28.5633 µm</td>
</tr>
<tr>
<td></td>
<td>Measurements: 2.541071 mm / 2.540787 mm</td>
</tr>
<tr>
<td></td>
<td>2.540762 mm / 2.540794 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Printed Circuit Board</th>
<th>Deviations: 20 µm / Grid Unit, σ_difference = 0.6 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnification: 17</td>
<td>Voxel Size: 11.68737 µm</td>
</tr>
<tr>
<td></td>
<td>Measurements: 2.540275 mm / 2.539730 mm</td>
</tr>
<tr>
<td></td>
<td>2.541177 mm / 2.539853 mm</td>
</tr>
</tbody>
</table>
5.4. **Comparison between CT scaling and the radiographic method**

To compare the scaling factors of the fast radiographic (2D) method and of the full CT, two images in reversed orientation were recorded before the CT scan of the PCB was carried out. Beforehand the shading correction of the detector was performed, the orthogonal positions, as described in section 5.1, were determined and finally there was a wait during some minutes of warm-up time. The integration time for both the orthogonal images was about one minute. The extra time spent on the radiographic scaling was about ten minutes, but could be reduced to three minutes if determining the orthogonal positions was not performed due to a sufficient mechanical reproducibility.

Table 1: Comparison between the radiographic and the CT scaling. For a clear view the optical calibration is added from Figure 11 and the table is supplemented in the last row with a subset evaluation (see text). The 3D x-scale in voxel is calculated as the native scale divided by voxel size.

<table>
<thead>
<tr>
<th>magnification</th>
<th>optical x-scale in µm/g.u.</th>
<th>native CT x-scale in µm/g.u.</th>
<th>nominal voxel size in µm</th>
<th>3D x-scale voxel/g.u.</th>
<th>2D X-ray x-scale pixel/g.u.</th>
</tr>
</thead>
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<tr>
<td>magnification 3.4</td>
<td>2540.775</td>
<td>2540.646</td>
<td>58.7390</td>
<td><strong>43.2539</strong></td>
<td>43.2531</td>
</tr>
<tr>
<td>magnification 7</td>
<td>2540.794</td>
<td>2541.071</td>
<td>28.5633</td>
<td><strong>88.9628</strong></td>
<td>88.9631</td>
</tr>
<tr>
<td>magnif. 17 8 x 8</td>
<td>2541.177</td>
<td>2540.275</td>
<td>11.68737</td>
<td><strong>217.3522</strong></td>
<td>217.3527</td>
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<tr>
<td>magnif. 17 6 x 8</td>
<td>2540.585</td>
<td>2539.942</td>
<td>11.68737</td>
<td><strong>217.3237</strong></td>
<td>217.3226</td>
</tr>
</tbody>
</table>

Figure 11: Comparison of CT reconstruction and optical calibration. The left column shows the CT reconstruction and the middle column the centre position deviations of its fitted holes from the best-fit parameterised grid. The optical calibration results are shown in the right column. The best-fit scale results in x- (over column number) and y- (over row number) direction are plotted below the deviation charts. For the first three rows the standard deviation of the difference of the deviation charts is calculated. The TEM mesh results in the last row are showing systematic deviations.
Table 1 shows the resulting scales in the x-direction for the optical calibration, the CT reconstruction and the radiographic method. The ratio of the optical calibration and the native CT scale is the scale correction factor and a property of the actual machine. Division of the native CT scale with the voxel size gives the scale in voxels (per grid unit). The comparison with the radiographic scale in pixels (per grid unit) coincides to better than $2 \cdot 10^{-5}$ relatively, for the medium sized magnifications this is even better than $5 \cdot 10^{-6}$. This residual could originate from the rotary table as described in section 0, distortions of the detector image or the reconstruction software. For the use of the radiographic scaling instead of the CT scaling for the correction factor it is satisfactorily good. Only the scaling in the x-direction is used because the non-adjusted tilt of the PCB in respect to the rotation axis is eliminated by the reversal technique, but a cosine scaling error remains. As remarked in the previous section, there are stronger artefacts at the cut edges of the PCB. Especially for the 8 x 8 grid evaluation for magnification 17, the distortion of the two outer columns might interfere. Thus there is also an evaluation of only a 6 x 8 grid listed in table 1. For the usual use without the need of comparison with the full CT an uncut PCB should be used.

Table 2: Trapezoidal angle for fitting the optical, the radiographic and the CT data. Smaller subsets of the PCB’s pads’ positions can have non-zero values by chance. The optical data’s value can be assumed as the true value.

<table>
<thead>
<tr>
<th></th>
<th>$\varepsilon$, optical 1/1000 °</th>
<th>$\varepsilon$, 2D 1/1000 °</th>
<th>$\varepsilon$, 3D 1/1000 °</th>
</tr>
</thead>
<tbody>
<tr>
<td>magnif. 3.4</td>
<td>-0.8</td>
<td>0.1</td>
<td>2.4</td>
</tr>
<tr>
<td>magnif. 7</td>
<td>0.2</td>
<td>-1.8</td>
<td>3.9</td>
</tr>
<tr>
<td>magnif. 17</td>
<td>-4.0</td>
<td>-3.4</td>
<td>-2.3</td>
</tr>
<tr>
<td>“, 6 x 8</td>
<td>-2.0</td>
<td>-4.3</td>
<td>-1.8</td>
</tr>
</tbody>
</table>

Table 2 lists the trapezoidal angles for the three independent measurements shown above. The actual CT machine is set-up well. Thus all values stay below 1/200 degree. After equation 1 the tilt of the rotation axis increases roughly six-fold. The optical calibration is assumed to be the true value, although the angular uncertainty can be estimated by 200 nm / base length, e.g. 1/1000 degree for 12.5 mm. From the scatter of the values an uncertainty of $\varepsilon$ of 1/200 degree for radiography and full CT is concluded. The average scale is not influenced by $\varepsilon$ because of symmetry.

5.5. Cross-check with “cotton reel”

The cotton reels represent a measure each for diameter, length and angle as discussed in section 3.3. They were measured for the three different sized specimens (called PEEK XX: PEEK is the material, XX stands for the nominal length/diameter in mm) with tactile CMMs, whereas the diameter values were corrected by Hertz’ indentation theory for 1-2 µm. Before CT measurement the magnification was determined with the PCB as described in the previous section. Care was taken to do that exactly in the same position of the stages without any motion afterwards. Table 3 shows the comparison of the results: For CT, the native and the
The corrected voxel size are given in the first column. The specimen temperatures during the measurement are listed in the second column. Under assumption of 60 ppm/°C for the linear thermal expansion coefficient, the tactile measuring results are (slightly) corrected (line “θ-corrected”) to the actual temperatures of the CT measurements.

Table 3: Comparison of dimensional measuring results obtained with tactile CMM and CT. The given angle is the cone angle of the nearly cylindrical surface.

<table>
<thead>
<tr>
<th>Material</th>
<th>Voxel size in µm</th>
<th>Temperature in °C</th>
<th>Diameter in mm</th>
<th>Length in mm</th>
<th>Angle in °</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEEK 40, tactile</td>
<td>20.54</td>
<td>39.9973</td>
<td>39.9968</td>
<td>0.0041</td>
<td></td>
</tr>
<tr>
<td>PEEK 40, CT magnification 6.0 (P714)</td>
<td>33.30747</td>
<td>40.0010</td>
<td>39.9956</td>
<td>0.0033</td>
<td></td>
</tr>
<tr>
<td>Radiographic corrected CT</td>
<td>33.30412</td>
<td></td>
<td>39.9970</td>
<td>-4.3 µm</td>
<td></td>
</tr>
<tr>
<td>PEEK 20, tactile</td>
<td>20.25</td>
<td>20.0148</td>
<td>19.9933</td>
<td>0.0081</td>
<td></td>
</tr>
<tr>
<td>PEEK 20, CT magnification 12 (P708)</td>
<td>16.68113</td>
<td>20.0258</td>
<td>20.0012</td>
<td>0.0047</td>
<td></td>
</tr>
<tr>
<td>Radiographic corrected CT</td>
<td>16.67804</td>
<td></td>
<td>20.0221</td>
<td>4.3 µm</td>
<td></td>
</tr>
<tr>
<td>PEEK 10, tactile</td>
<td>20.27</td>
<td>10.0071</td>
<td>10.0019</td>
<td>0.0127</td>
<td></td>
</tr>
<tr>
<td>PEEK 10, CT magnification 25 (P715)</td>
<td>7.99059</td>
<td>10.0131</td>
<td>10.0070</td>
<td>0.0160</td>
<td></td>
</tr>
<tr>
<td>Radiographic corrected CT</td>
<td>7.98551</td>
<td></td>
<td>10.0067</td>
<td>1.4 µm</td>
<td></td>
</tr>
</tbody>
</table>

The length measure of PEEK 10/40 obtained by CT is about $10^{-4}$ relative of its value too small. This might be explained by a material dependence of the CT scaling due to about a 100 µm different penetration depth of the absorbed X-ray spectra into the scintillator material. For the PCB the relevant absorbing material is copper that filters higher energetic X-ray photons more strongly than the PEEK polymer. That means the shadow image of PEEK is in the front of the scintillator, and the shadow image of copper is a little bit deeper inside with a larger source-to-detector distance. The diameter measure of PEEK 10/40 is additionally 0.9 µm or respectively 4.9 µm too large, if it is rescaled to the length measures. This is about 1/8 of the voxel size and could be a residual of the local “probing error” effect due to the surface finding criteria. The difference between the cone angle measured with tactile CMM and that measured with CT is nearly zero varying only a few thousandths of a degree, and corresponds to the observation of the previous section. The tactile measurements of PEEK 10/40 were done within only one week delay of the CT, whereas the tactile measurement of PEEK 20 was nine months before. This might explain why the diameter and length of PEEK 20 are noticeably too large. As mentioned in section 3.3 this prototype was manufactured first and not sufficiently annealed. Two tactile calibrations of PEEK 20 taken 19 months apart and after a short annealing process deviate by $+9$ µm in diameter and $-3.5$ µm in length. This has to be observed in the future.
6. Summary, conclusions and outlook

Dimensional measurements with industrial cone-beam CT are subject to manifold influence factors daily. Due to this, a precise and efficient method for verification, machine-drift correction and geometry parameter assessment is needed. In this paper a technique using two radiographic images in reversal orientation (Radiography in Reversal orientation Technique) is presented. An X-ray transparent substrate covered with a thin metal film grid – here a printed circuit board and a transmission electron microscope carrier grid have been used – is placed on the rotary table of the CT system. After determination of the orthogonal positions to the X-ray beam only two averaged radiographs in reversal rotational orientation are sampled. The procedure takes only a few minutes and can be fully automated. Equidistant grid positions are fitted in the radiographs using a master pattern based multiple correlation technique. By using this method an enhanced accuracy is achieved. From the fitted and averaged pattern the parameters for grid position, scaling and distortion caused by tilt are extracted. The arithmetic, or respectively harmonic, average of the two parameter sets is the wanted scaling factor, or respectively the skew and tilt angle of the rotation axis. It is shown by the experiment that the grid scaling gained with the RRT agrees with the scaling of a full CT reconstruction to better than $2 \cdot 10^{-5}$ relatively. These flat grids had been simply and accurately calibrated with an optical coordinate measuring machine and so the scaling is traced back to it.

Verification measurements were carried out at three 3D “cotton reel” specimens of different sizes made of PEEK plastics. The specimens embody a unidirectional length, a (bidirectional) diameter and an angle, respectively. The CT results obtained at the two recently calibrated specimens agree well with the tactile calibration. The above results prove the efficiency of the presented procedure as an easy tool to test CT systems without the need for time-consuming full CT scans. The procedure could become a part of the quality assurance of PTB’s CT system. Extensions of the procedure could be applied to determine specific errors, e.g. irregularities, and the sag of a magnification axis as well as squareness deviations of lateral axes could be determined without the additional use of laser interferometers, tiltmeters or autocollimators by tests at different axes positions.

The test at the moment does not include the influence of beam hardening effects and material dependencies. Furthermore it has to be examined in future if additional effort is necessary to transfer the results achieved at flat objects to thick 3D objects. A further topic of future investigations will be the realization of improved artefacts with smaller dimensions, higher accuracy, and higher long-term stability.
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References