Developments in Dimensional Metrology in X-ray Computed Tomography at NPL

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## Possible factors influencing XCT measurements

<table>
<thead>
<tr>
<th>Components</th>
<th>Influencing variables</th>
<th>Possible effects</th>
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<tbody>
<tr>
<td><strong>X-ray source</strong></td>
<td>voltage, current, focal spot, Inherent filtration, (materials thickness), Stability of focal spot</td>
<td>spectrum shape, stability of intensity, affect the resolution, affect the X-ray spectrum, affect projection image</td>
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<tr>
<td><strong>Detector</strong></td>
<td>exposure, Image lag, pixel size, resolution, linearity and efficiency, Others(dynam range etc.)</td>
<td>affect image quality</td>
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<td><strong>Mechanical parts</strong></td>
<td>alignment of the x-ray source, the detector and the sample stage, scale</td>
<td>deviations cause partially blurred reconstructions, cause error in pixel value</td>
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<td><strong>Environmental</strong></td>
<td>temperature, humility, etc.</td>
<td></td>
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<td><strong>Software</strong></td>
<td>reconstruction algorithm, surface determination algorithm, correction algorithms: beam hardening, scattering corrections.</td>
<td>affect dimensional measurements</td>
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<td><strong>Operators</strong></td>
<td>measurement and analyses approach</td>
<td>can significantly affect the results</td>
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Most frequent questions:

• What are the best settings? (voltage, current, average of images, etc.)
• Should we use physical filters or not? What are the differences of having different thickness of filters?
• What are the influences of sample orientation and position?
• What is the influence of shading correction? Linear or nonlinear correction?
• How should we evaluate the quality of measurements?
• What is the smallest feature that can be measured?
• …
Influence factors: X-ray source (focal spot)

- Stability during scan
Influence factors: X-ray source (focal spot)

- Stability during scan

Material:

*Tungsten carbide*

Sphere diameters:

- Sphere 1: 0.7954 mm
- Sphere 2: 0.7951 mm

Centre to centre distance:

0.9795 mm \( (k = 2) \)

Reference sample calibrated by traceable contact CMM at NPL.
Influence factors: X-ray source (focal spot)

Sphere centre drift along x-axis

Sphere centre drift along y-axis

Sphere separation (reflect variation of X-ray source along beam axis)

Cold start (without system warm up)

Hot start (with system warm up)

Reference:
Flay N, et al. 2015 Investigation of the focal spot drift in cone-beam industrial X-ray computed tomography, Proc. of Digital Industrial Radiology and Computed Tomography (Ghent, Belgium)
Detective quantum efficiency (DQE): describes the ability of an X-ray detector to transfer the signal-to-noise ratio (SNR) from the radiation field to the resulting digital image.

\[
DQE(u, v) = \frac{pMTF^2(f)}{\Phi \cdot K_a \cdot NNPS(f)}
\]

DQE results of the scintillation detector at 70 kV (top-left), 90 kV (top-right), 120 kV (bottom-left) and 150 kV (bottom-right). lp/mm is line pair per millimetre.

Spatial resolution

Edge response function

Slanted edge sample

Line spread function

Modulation transfer function (MTF)

Influence of magnification

Influence of current

Influence of voltage

Geometrical error modeling for coordinate measurements by XCT

Modelling radiographic binning errors due to detector angular misalignments

Modelling volumetric errors due to detector angular misalignments

Other factors considered

• Scattering
• Beam hardening
• Cone beam error
• Reconstruction algorithm
• Surface determination algorithm
• More…
Scale check – 1D distance verification

- Traceability: Calibrated Ball bar
- Scale: Distance is independent on threshold
- Downfall: measured at a fixed height, therefore alignment issues not highlighted
Ball plate – 2D distance verification

- Ball plate manufactured from 6 mm ruby spheres, 25 in total
- Allows measurements between spheres in multiple directions
- Verification of system at different scales
- Alignment issues
Holeplate– investigation

- Multi direction distances
- Bi-directional and uni-directional measurements of hole plate, immersed inside NPL cam.
- Multi-machine measurements

Bi-directional

Uni-directional
## XCT vs Other measurement techniques

<table>
<thead>
<tr>
<th></th>
<th><strong>Advantages</strong></th>
<th><strong>Disadvantages</strong></th>
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<tbody>
<tr>
<td><strong>Tactile</strong></td>
<td>Profile/surface data Can be traceable</td>
<td>Contact method, can damage surface</td>
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<tr>
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<td>External surface only</td>
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<td>Angle limitation</td>
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<td></td>
<td>Time consuming for large area</td>
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<tr>
<td><strong>Optical</strong></td>
<td>Surface data Noncontact</td>
<td>External surface only</td>
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<td>Influence of some systematic errors on measurement not</td>
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<td>fully understood</td>
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<tr>
<td><strong>XCT</strong></td>
<td>Volumetric data (both external and internal) Noncontact Non-invasive</td>
<td>Systematic errors</td>
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<tr>
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<td>Large amount of data</td>
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Dimensional summary - Verification

Standards
Tactile
• CMMs ISO 10360
Optical
• VDI/VDE 2634
XCT
• VDI/VDE 2630, (ISO 10360 Part XCT under development)

External dimensions
• Surface roughness may affects all measurement systems
• Young’s modulus affects tactile but not optical or XCT
• Optical properties may affect optical techniques but do not affect tactile or XCT

Internal dimensions
• Surface has to be accessible for tactile and optical
• XCT has the ability to measure both surfaces and material interfaces, through threshold values, however, not traceable.

Performance verification

The surface roughness of the AM parts, limit the ability to make confident dimensional measurements.
An example of NPL designed test artefact

- Corkscrew distortion during build
- Prismatic simple geometric structures
- Equivalent internal structure
- Allow traceability
- Effects of beam hardening
- AM capability

• Parallel flat side faces
• Include cube and cylinder
• Internal cube and cylinder
• Tooling balls
• External cylinders of a variety of material
• Conventional manufactured

Manufactured from XCT compliant materials: AlSi10Mg and Al for conventional
Overview of dimensional tests carried out using contact CMM

- Measurements of large flat areas on the AM surface.
  - Evaluation of best fit plane
  - Corkscrew distortion
- Measurement of cylinder at different heights, above the plane ‘A’:
  - (18.5, 21, 23.5, 26, 28.5) mm
  - Best fit circle and standard deviation of data
- External (and internal proposed work) comparison measurements.
  - AM allows easy to build but, unfortunately, sometimes difficult to measure.
Dimensional measurements - Summary

- Comparison of data from CMM, XCT and optical.
- Sphere diameter and distance
- Circle diameters and standard deviation (Std)

All units are in mm
Questions…. if time permits

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The National Measurement System is the UK’s national infrastructure of measurement Laboratories, which deliver world-class measurement science and technology through four National Measurement Institutes (NMIs): LGC, NPL the National Physical Laboratory, TUV NEL The former National Engineering Laboratory, and the National Measurement Office (NMO).