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Investigating non-uniformity of spatial resolution in X-ray computed tomography

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Abstract
An experimental study was conducted to evaluate how spatial resolution varies within the measurement volume of X-ray computed tomography (XCT). Because central position is typically associated with higher sampling, edge-positioned samples are expected to be more affected by lower sampling rates. Two Nitinol tubes from the same production batch were scanned simultaneously in both XCT simulation and physical scans, with one positioned at the centre of the manipulator and the other near the edge to study this spatial-resolution effect. Subsequently, modulation transfer function was applied to the reconstructed XCT cross-sectional images to evaluate the spatial resolution, enabling a direct comparison between the measurement results of spatial resolution at the centre and edge positions under matched scanning conditions. The results show that the edge-positioned sample consistently exhibits lower spatial resolution. The study highlights the non-uniformity of spatial resolution in XCT.

X-ray computed tomography, dimensional metrology, spatial resolution, modulation transfer function

1. Introduction

X-ray computed tomography (XCT) is being increasingly adopted in industrial applications, among which dimensional metrology is one of the most promising fields [1,2]. Compared with conventional tactile and optical coordinate measurement methods, XCT provides several distinct advantages, including non-destructive evaluation of internal features, full-volume measurements of workpieces, acquisition of dense volumetric data, support for dimensional quality assurance, and detailed visualization of internal and external object structures [3]. Nevertheless, differences in product position within the scan volume may cause non-uniformity in the reconstructed spatial resolution. As illustrated in Fig 1, products positioned near the centre of the sample stage tend to have more sampling during data acquisition than those located near the edge, resulting in higher spatial resolution in the central position. However, there is no study concerning the variance of spatial resolution in the measurement volume.

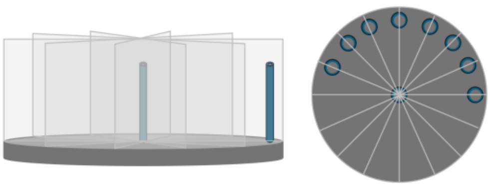

Figure 1. Scheme of the signal acquisition for samples at different location.

To systematically investigate and quantify spatial resolution inhomogeneity in X-ray computed tomography (XCT), two Nitinol tubes from the same production batch were used in this study. The tubes were scanned simultaneously, with one positioned at the centre of the sample stage and the other at the edge. Data were acquired from both simulation and physical XCT scans to enable comparison and cross-validation. The reconstructed slices were then evaluated using the modulation transfer function, allowing direct comparison of the spatial resolution differences between the centre and edge positions under matched conditions. The results show that the edge resolution of samples at the centre position is better than that of samples at the edge position. The importance of non-uniformity of spatial resolution has not been considered or evaluated in the context of XCT for dimensional metrology. By analysing the resolution of tubes at different locations, we conducted preliminary work to quantitatively evaluating the non-uniformity of spatial resolution.

2. Materials and Methods

2.1. Samples

Two high precision Nitinol (55 % nickel and 45 % titanium) tubes from the same production batch were selected as the samples for this study. The tubes have an inner diameter of 3.4 mm, an outer diameter of 4.0 mm, and a length of 50 mm, as shown in Fig 2 (left) and (middle).

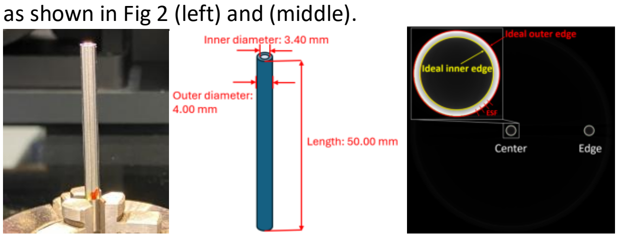

Figure 2. Sample and experimental setup. (left). A Nitinol tube. (middle). its fabrication parameters. (right). Position of tubes in simulation and physical scans. Note: ideal edges are defined by the nominal values.

2.2. Experimental Design

In both simulation and physical scans, the distance between the centres of the two tubes was approximately 30 mm. One tube was placed at the centre of the rotation, and the other was located at the edge position.

Simulation data were obtained using aRTist 2.12.6. The physical scan data were obtained from a Nikon XT H 450. Data reconstruction and analysis was performed using Feldkamp-

Davis-Kress (FDK) algorithm using Python 3.13. Slices were processed and exported using VG Studio 2025.1.

At the present stage of this research, the physical XCT scan and simulation configurations are limited to the positional arrangement of the tubes and the configurations specified in Table 1. There is also no noise and scatter considered in the simulation to evaluate the impact of space variation. The spatial resolution at the outer edge of the tubes was evaluated using the modulation transfer function (MTF).

Table 1 Configurations of XCT physical scans and simulation.

Parameters	Simulation	Physical scans
Voltage	200 kV	200 kV
Current	133 μA	133 μA
Detector size	2000 × 2000	2000 × 2000
Voxel size	40 μm	40 μm
Magnification	×5	×5
Exposure	300 ms	300 ms
Projection numbers	3142	3142

3. Results and Discussion

Fig 2(right) illustrates the slices at central height of 3D volume after reconstruction using the FDK algorithm, which shows the position of tubes in slices. The size of images was upsampled to 4000 × 4000 with linear interpolation for higher resolution. To further investigate the influence of location on resolution, the intensity profile of the tube outer edges were extracted along the normal direction, yielding the edge spread function (ESF), ESF maps were obtained for each ring along the radial direction at all angles, as shown in Fig 3(a)–(d). Taking the ideal outer-edge position as 0, the mean ESF of each ring was calculated, and its first derivative was then used to derive the mean line spread function (LSF), shown in Fig 3(e).

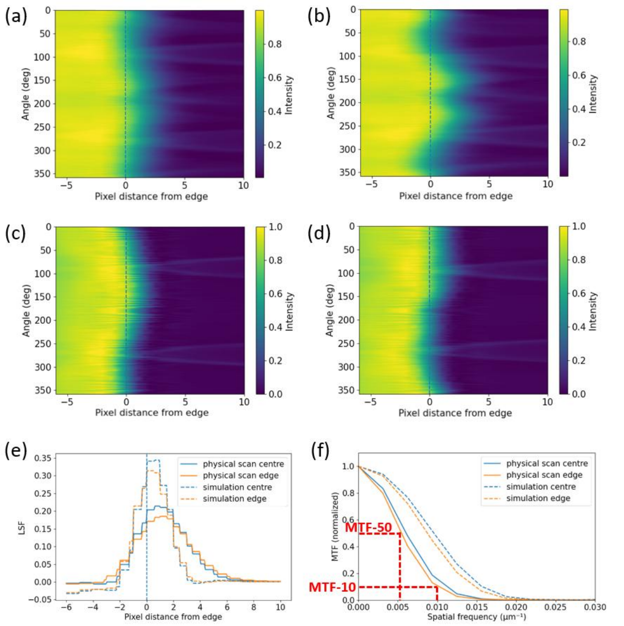

Figure 3. ESF maps of outer edge for (a) centre position in physical scan, (b) edge position in physical scan, (c) centre position in simulation, and (d) edge position in simulation. (e) Mean LSF curves. (f) Mean MTF curves.

In both the physical scanned and simulated slices, the outer edge of the tube located at the centre exhibited smaller full width at half maximum (FWHM) than that of the tube located at edge, representing a more rapid transition of intensity. This result confirms that spatial position, particularly the difference between the centre and the edge, affects sample slice quality in XCT scanning.

The mean LSF was subsequently transformed into the mean MTF through Fourier transform [4], as shown in Fig 3(f), to further evaluate differences in spatial resolution. In both the measured and simulated results, the MTF curve corresponding to the tube located near the centre shows higher spatial frequencies overall than that corresponding to the tube located near the edge. This indicates that, at the same level of contrast retention, the central tubes preserve higher spatial frequencies and are therefore capable of resolving finer structural details, indicating superior resolution. We further quantified the resolution differences between the central and edge tubes using MTF-10 and MTF-50, which represent the spatial frequencies at which the MTF falls to 10% and 50% of its zero-frequency value[5], respectively. The corresponding spatial wavelengths of MTF-10 and MTF-50 were extracted and are summarized in Table 2. Both the simulation and physical scan results showed consistently lower values at the centre than at the edges, which further confirms that image resolution is superior in the central region compared with the edges. These consistent results from both simulation and physical scans demonstrate that different position in XCT measurements leads to non-uniformity of spatial resolution, with higher spatial resolution at the centre.

Table 2 Spatial resolution characterized by MTF-10 and MTF-50.

MTF	Spatial resolution converted from MTF-10 (μm)	Spatial resolution converted from MTF-50 (μm)
simulated centre	63.7	104
simulated edge	67.3	114
physical centre	88.5	165
physical edge	97.3	183

4. Conclusion

The spatial resolution difference of tubes located at centre and edge positions within the XCT scan volume was investigated in this study. The results show that image sharpness and spatial resolution are higher at the centre position than at the edge position, indicating the non-uniformity of spatial resolution across different positions. This developed method enables the quantitative determination of spatial resolution across 3D measurement volume, providing the examination of measurement quality for XCT measurement tasks. Future work will aim to quantify the uncertainty introduced by this effect in XCT metrology and to further extend the present study.

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