Effect of the number of radiographs taken in CT for dimensional metrology

Herminso Villarraga-Gómez1, 2, 5, Darren O. Clark5, Stuart T. Smith1, 2, 3

1Center for Precision Metrology, 2Department of Physics and Optical Science, and 3Department of Mechanical Engineering and Engineering Science - University of North Carolina at Charlotte, NC, USA.
2Carl Zeiss Industrial Metrology, LLC, USA.
3Nikon Metrology, Inc, USA.

Email: hvillar1@uncc.edu, herminso.gomez@nikon.com

Abstract
This paper addresses reducing the number of radiographs taken for X-ray computed tomography (CT) to optimize the scanning time while maintaining accuracy of dimensional measurements. Reduced image numbers correspond to under-sampling of signal data in the Fourier domain. The goal is to reduce the costs of measurement processes particularly in production lines. The study was performed by experimental measurements on two objects: a (cheese-like) hole-cube made in both aluminium and nylon; and also by theoretical simulations with Matlab™ using the standard test image ‘Shepp-Logan phantom’. Image quality is assessed using three metrics: the root mean square error (RMSE), the peak signal-to-noise ratio, and the mean structural similarity Index; in all of these metrics degradation of image quality by diminishing the number of radiographs \( N_p \) collected during the CT scans was observed. Particularly, the experimental results showed the proportionality RMSE with \( 1/\sqrt{N_p} \) as predicted from the theory of imaging with X-ray photons, and the signal-to-noise ratio (SNR) of a reconstructed CT image holds the proportionality \( SNR \approx \sqrt{N_p} \). This is contrasted by observations of dimensional measurements; the accuracy of measurements of dimension with the CT technique remained about the same when collecting anything from 2000 to 400 radiographs for CT reconstruction of the aluminium and nylon hole-cubes, with deviations \(|\Delta| = |x_{ct} - x_{cumu}| \) mostly in the range 2 to 20 \( \mu \text{m} \) despite noticeable variation on image quality. This is an important result for optimizing CT measurement. Effectively, for dimensional metrology, a loss in image quality can be tolerated as a trade-off for time reduction, particularly with added uncertainties of only a few micrometers and measurement time reduction of several minutes with current technology. If less than 400 or 360 radiographs are used, \(|\Delta|\)-deviations of greater than 50 \( \mu \text{m} \) were found.

Keywords: Dimensional Metrology, Computed Tomography (CT), Optimization, and Image Quality.

1. Introduction
Reducing the number of radiographs (or projections) taken by a CT scanner for 3D image reconstruction can reduce the scanning time, which reduces the cost of measurement particularly when this information is used for manufacturing decisions. However, reducing the number of projections can also reduce image quality. Image quality can be qualified by signal-to-noise ratio metrics or by the structural similarity index (SSIM), but the ultimate objective of this paper is to directly study the effect of varying the number of projections on dimensional measurements of the part to evaluate the trade-off between image quality and accuracy of metrological characterization for purposes of optimization.

2. CT data collection
Data was collected using a cone-beam 3D CT commercial system with flat panel detector with source-to-detector distance \( SDD=1500 \text{ mm} \) and a flat panel detector of 2048x2048 pixels. Two (cheese-like) hole-cube artifacts of nominal dimensions around 92x78x63 mm were used for CT scanning, a metallic hole-cube made of aluminium (Al) and an identical plastic hole-cube made of polyamide thermoplastic — nylon (Nyl). These artifacts were placed at a source-to-object distance \( SDO=550 \text{ mm} \) for a magnification of \( M=2.74 \) and a voxel size \( Vx=73 \mu \text{m} \). CT scan data was taken with the artifacts at the same position and using the same machine settings but decreasing the number of CT projections from 2000 to 200 in steps of 200 plus an additional scan taken with only 100 projections. The local adaptive (dynamic gradient threshold) method was used for CT surface determination. The \texttt{fanbeam} and \texttt{ifanbeam} functions from Matlab™ [1] were used for theoretical simulations.

3. Effect on image quality
Figure 1 shows the RMSE of reconstructed 2D CT images as function of the number of collected CT projections \( N_p \) for a slice extracted from the 3D reconstructions made for the aluminium and nylon hole-cube artifacts. Simulated data for the reconstruction of the Shepp-Logan phantom in a 2D Fanbeam projection geometry is also included in the same chart. The RMSE is computed as

\[
\text{RMSE} = \sqrt{\frac{1}{MN} \sum_{i=1}^{M} \sum_{j=1}^{N} (x(i,j) - y(i,j))},
\]

where \( x(i,j) \) represents the reference image and \( y(i,j) \) represents the CT reconstructed (backprojected) image, and \( i \) and \( j \) are the pixel position of the \( M \times N \) image. A two-dimensional Shepp-Logan phantom of \( 800 \times 800 \) pixels generated in Matlab™ was used as reference image for the simulated data while a particular single slice image reconstructed from 2000 projections was taken as reference for the hole-cube computations.
independent of the number of projections, except for below 400 projections for which deviations larger than 50 µm were observed.

Similar conclusions apply for distance between the artifact’s holes and other length measurements reported in [4], with deviations $|\Delta| = |\bar{x}_{CT} - \bar{x}_{CMM}|$ mostly in the range 2 to 20 µm. These deviations can be tolerated as a trade-off for time optimization in CT data collection particularly if the accuracy loss is only of a few micrometers and the gain in time per CT scan can be of several minutes (see the scan time scale in Figure 3). Generally, less than 400 projections is not advisable, where $|\Delta|$-deviations larger than 50 µm could be expected. Figure 4 shows cylindricity measurements with a clear degradation in the CT data below 600 projections.

5. Conclusions
Based on these studies, under-sampling the number of projected radiographs acquired for CT degrades the quality of the reconstructed images, with particularly strong effects at less than 600 projection images. This is in contrast to what is observed for dimensional measurements: the accuracy of measurements of lengths with the CT technique were unchanged using between 400 to 2000 CT projections, with deviations $|\Delta| = |\bar{x}_{CT} - \bar{x}_{CMM}|$ mostly in the range 2 - 20 µm for the artifacts measured. However, if the main focus is the measurement of form, a larger number of projections is advised.

References