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Optimisation of the number of projections in industrial X-ray computed tomography for dimensional measurements on multimaterial workpieces

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Abstract

Industrial X-ray computed tomography (CT) has gained prominence in the field of dimensional metrology as a powerful technique for performing 3D coordinate measurements. Setup parameters with which CT scans are performed influence the uncertainty of measurements. The number of projections is an important parameter that defines the ability of the CT system to spatially resolve the features of the measured object. In this study, we propose a method for optimising the number of projections for dimensional measurements on multimaterial workpieces. The method performs a 2D-Fourier transform of a small sample of projection images and applies a low-pass filter depending on both the considered number of projections and the workpiece size. By reducing the number of projections, more and more information is filtered out from the image. The algorithm stops when a significant change in image quality can be observed. Finally, we carried out an experimental investigation to validate the method by analysing the variance of measurements on a multimaterial reference artefact. Results showed that the number of projections predicted from the algorithm minimises the standard deviations for all measured features, while ensuring the shortest measurement time.

Keywords: computed tomography, number of projections, scanning parameters, optimisation, metrology

1. Introduction

Industrial X-ray computed tomography (CT) is a multi-purpose non-destructive testing method that allows three-dimensional reconstruction of both inner and outer features of an object [1–3]. Initially developed in the 1970s for medical purposes, CT technology has spread to the industrial sector. In recent years, it has gained a key role in the field of production metrology as an alternative to conventional coordinate measuring machines. CT measurement uncertainty depends, among others, on setup parameters that are chosen by the CT user. The number of acquired projection images defines the ability of the CT system to spatially resolve the geometrical features of a workpiece and defines the duration of a CT acquisition [4]. A lower number of projections causes undersampling artifacts to occur, resulting in higher measurement uncertainty. A higher number of projections avoids that undersampling artifacts impair measurements but also increases the scanning time. A method for optimising the number of projections for dimensional measurement was proposed by the authors for dimensional measurements on monomaterial objects [5]. The aim of this study is to enhance the method presented in [5] for multimaterial measurements (Section 2) and to validate the model by analysing the variance of measurements (Section 3).

2. Method

The method for determining the optimal number of projections N^* is based on the notion of maximum spatial frequency ν_{max} of projection images. ν_{max} is given by:

$$\nu_{max} = \frac{1}{2 \cdot \Delta\gamma \cdot R_p}$$

where $\Delta\gamma$ is the angular sampling interval and R_p is the radius of the enclosing sphere that contains the reconstruction volume as projected onto the detector plane in the spatial domain [6]. $\Delta\gamma$ is defined by:

$$\Delta\gamma = \frac{2\pi}{N}$$

In general, the maximum spatial frequency tends to infinite because the bandwidth of the spectral support of the projection images is not strictly limited [7]. Correspondingly, also N and the required measurement time tend to infinite. However, high frequencies in the spectral support carry a limited amount of information. It is possible to identify a maximum useful spatial frequency ν_u in the spectral support. Deleting information from frequencies higher than ν_u does not significantly affect measurement uncertainty.

Let us consider a projection image $p(x,y)$ of a multimaterial object and its Fourier transform $P(\nu_x,\nu_y)$. In order to estimate the number of projections N^* that corresponds to ν_u, we define a radial low-pass filter based on the considered number of projections:

$$w = \frac{N}{4 \cdot \pi \cdot R_p}$$

with radial filtering frequency w. We iteratively apply the low-pass filter to $P(\nu_x,\nu_y)$ starting from a high value of N and progressively decreasing it. At every step, the contrast-to-noise ratio (CNR) of the projection image is computed. The CNR is a common indicator for the accuracy of dimensional measurements, since it is a good metric for the ability of detecting workpiece edges. Iterations stop when a significant change in the CNR is observed, meaning that relevant information was deleted. This procedure is repeated on a sample of ten projection images of the workpiece with constant angular sampling interval and the average N^* is computed over the sample, ensuring the results do not depend on the chosen projections. The projections used in this study are real X-ray images. However, the method can be applied also to simulated projections.

3. Experimental investigation

The aim of the investigation is to show that the number of projection N^* predicted with the method (Section 2) is optimal, i.e. the standard deviation of measurements u_p does not significantly decrease for numbers of projections higher than N^* and N^* is the smallest number to fulfil this condition.

The reference object used in this investigation is a multimaterial reference artefact (Figure 1) consisting of a polyoxymethylene (POM) cube with two aluminium inserts. For this artefact, the N^* predicted with the method is 1050 with 2% of tolerance on the CNR. The features of interest for measurements are listed in Table 1.

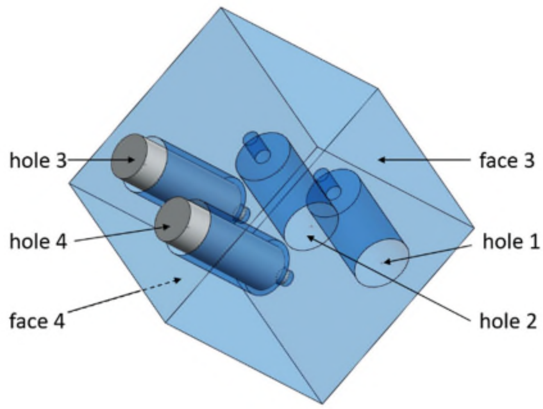

Figure 1. The multimaterial reference artefact

Table 1 Features of interest

Feature	Description
dist34	Distance between the planes of face 3 and face 4 of the cube
cl1d20	Diameter of the hollow hole 1 at 20 mm from face surface
flat3	Flatness of face 3
flat4	Flatness of face 4
cl4d30	Diameter of the aluminium insert in hole 4 at 30 mm from top surface
rnd410	Roundness of the aluminium insert in hole 4 at 10 mm from top surface
cyl3	Cylindricity of the aluminium insert in hole 3
cyl4	Cylindricity of the aluminium insert in hole 4

CT measurements were performed by varying the number of projections and keeping all other conditions (setup parameters, measurement procedure, etc.) constant. The chosen levels of the number of projections are 100, 200, 400, 600, 800, 1000, 1200, 1400, 1600. For each value of N, measurements were repeated 20 times to compute u_p. CT acquisitions were performed with a Werth Tomoscope HV Compact CT system, while reconstructed volumes were analysed with VG StudioMax by using iso-50 thresholding and local adaptive thresholding in two steps.

Figure 2 shows u_p as a function of N for feature *cyl3*. u_p decreases virtually monotonously for increasing N. At higher values of N, no significant decrease in u_p can be observed anymore. In order to estimate the optimal number of projections, an F-test on the equality of variance with $\alpha = 0.05$ was carried out to determine whether there is a significant decrease in u_p or not. Figure 3 shows the results of this analysis.

Some important conclusions may be drawn from this investigation. Some features (e.g. *cyl3* and *cyl4*) are less sensitive to the loss of information due to undersampling. The features most sensitive to undersampling required $N = 1000$, which is slightly lower than the predicted value ($N^* = 1050$). Therefore, the predicted N^* minimises both the contribution of the number of projections to measurement uncertainty and the required acquisition time.

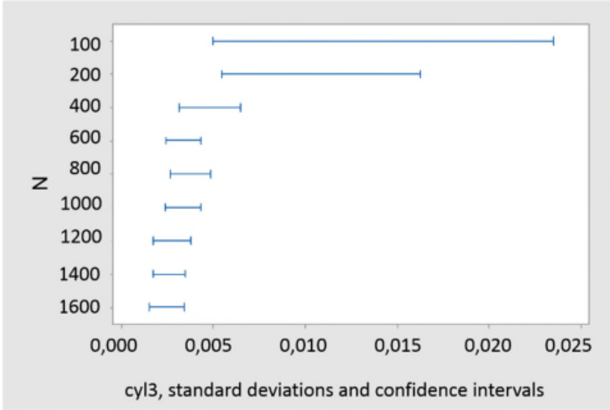

Figure 2. Standard deviations and confidence intervals vs number of projections for *cyl3*

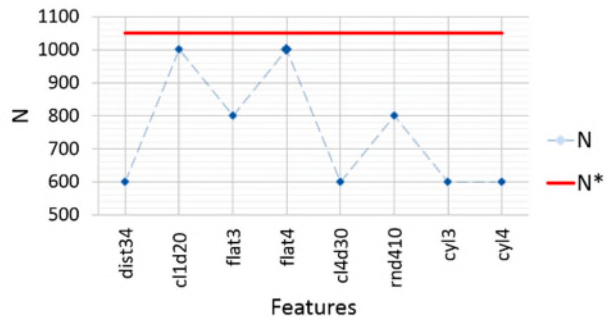

Figure 3. Optimal number of projections for each feature and predicted number of projections N^*

4. Conclusions

In this study, we proposed a method to optimise the number of projections for CT measurements on multimaterial workpieces. The method is based on the estimation of the maximum useful frequency of projection images and the associated number of projections. The estimation is carried out by iteratively applying a low-pass filter on a sample of projection images and evaluating significant changes in the CNR. In order to validate the method, we measured a multimaterial reference artefact with different number of projections and analysed the variance of measurements. Results showed a good agreement between theoretical calculations and experimental data.

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