Sinogram interpolation to decrease acquisition time in X-ray computed tomography measurement of surface topography

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Abstract

The effects of reducing the number of projections and using sinogram interpolation in X-ray computed tomography measurement were evaluated by considering the quality of volumetric reconstruction and extracted surface topographies. Using a test sample, the number of projections acquired was reduced in steps of 20\% from the theoretical reference value. The obtained data sets were upsampled by sinogram interpolation. The quality of the volumetric reconstructions was assessed by introducing dedicated measures of noise and resolution. The surface topographies extracted from the data sets were evaluated using statistical topography models. It was shown that sinogram interpolation can be used as a tool to reduce the number of projections and still obtain sufficient quality surface topographies.

Keywords: Sinogram interpolation, topography measurement, surface texture

1 Introduction

X-ray computed tomography (XCT) is a non-destructive volumetric imaging technique, which is increasingly applied as a metrological tool for dimensional and surface measurement [1]. Recent advancements have led to an increase in publications about the application of XCT as a tool for the characterisation of surface topographies of additively manufactured (AM) parts [2–4]. While XCT has been shown to be a viable option for surface measurement, long measurement times are a shortcoming, when comparing to conventional contact and optical techniques. Modern XCT systems with flat panel detectors often need thousands of projections for a full, volumetric reconstruction [1,5]. The mathematical and physical constraints of acquiring the many radiographs at long exposure times often clash with the economic and time requirements of a modern manufacturing environment. Because of the constraints on acquisition rates and the large number of projections needed, an XCT scan can last up to several hours. While rebinning the detector pixels (i.e. combining neighbouring pixels into a single recorded value) can reduce the acquisition time, the process leads to a change in effective pixel size, and hence is likely to lead to a reduction in lateral resolution. A simple reduction of the number of projections can also lead to issues, because the resulting undersampling of the sinogram leads to deterioration of the quality of the reconstructed volume data, due to the appearance of streak artefacts and noise [6]. While filtering methods on the volume data can lead to improvements, almost all filtering methods will trade off resolution and image quality [7,8]. The most prominent approach to maintain acceptable quality whilst reducing the number of projections is the use of iterative reconstruction methods [9]. Iterative reconstruction methods have a long history in XCT and have been used widely in the medical field [9,10]. However, one of the major shortcomings is the high computational cost: per iteration, for each projection in the reconstruction process, one computational forward and backward projection is normally required [9]. A simpler and less computationally expensive method, explored in the medical literature, is sinogram interpolation [6]. In sinogram interpolation, the missing projections are estimated in sinogram space by interpolation of the available projections. It has been shown that when using sinogram interpolation [2], streaks and noise are reduced. However, the resolution of the reconstructed volume is also reduced – an undesirable effect. Other computationally inexpensive methods have been applied to suppress local noise in the grey scale volume, for example filtering operations, such as a moving median filter [11].

The aim of this research is to investigate and quantify the deterioration of measured surface topography extracted from volumetric reconstructions, due to the different numbers of projections used in the reconstruction. The investigation also covers the comparative assessment of detector pixel binning, sinogram interpolation and median filtering as means to reduce the detrimental effects of reducing the number of projections. The quality of the volumetric reconstruction is assessed through dedicated measures of noise and resolution. The quality of the surface topography extracted from the volumetric reconstruction is in turn assessed via the computation of statistical topography models designed to quantify local dispersion of height values in repeated measurements, and the discrepancy between reconstructions obtained with different methods.
2 Methodology

2.1 Methods and equipment

A Nikon MCT225 with a scintillating detector of 2000 by 2000 pixels was used to collect the data. The manufacturer specifies a maximum permissible error for sphere-to-sphere distances: $MPE_{SD} = 9 + \frac{L}{56}\,\mu m$, where $L$ is in millimetres. A Ti6Al4V additively manufactured cube with nominal side length of 10 mm was chosen as the test sample, given the complexity of its surfaces [12]. The sample was manufactured on a Realizer SLM 50 laser powder bed fusion system. The raw material used is a sieved powder with a grain size below 32 µm. The XCT system was set up to a magnification of around 19, which yields a projected pixel size of approximately 11 µm. A fixture was designed to tilt the part by 5°, both to limit the effects of Feldkamp artefacts and to have an inclined edge for the edge spread analysis (section 2.3). The X-ray source of the MCT225 was set up with an acceleration voltage of 190 kV and a filament current of 53 µA. According to the manufacturer’s specification, these parameters lead to an apparent focal spot size smaller than the projected pixel size. The spectrum produced by the cooled tungsten target was filtered sequentially by 0.5 mm of copper and by 0.5 mm of aluminium. The detector exposure time was set to 2000 ms, and two exposures were taken and averaged to obtain a radiograph. The temperature of the cabinet was controlled to $20°\,C \pm 1°\,C$, and the X-ray source temperature was monitored by thermocouples at several locations. In order to further minimise measurement time the continuous motion mode of the system (i.e. taking radiographs whilst the rotation stage is moving) was used for some of the experimental test conditions. This causes motion blurring and thus loss of resolution, but it is interesting to study because of the potential time savings. In addition, for a full $360°$ rotation, 3142 projections are needed for analytical reconstruction, which limits the motion blurring to less than the size of a voxel, assuming the centre of rotation is in the centre of the 2000-pixel detector.

The Whittaker–Shannon interpolation formula was used for the sinogram interpolation, also known as sinc interpolation. Each row of projections was interpolated independently of the other rows. The sinc interpolation was implemented by inserting zeros into the DC term of the Fourier space. As part of this investigation, the number of projections was reduced from ideal reference of 3142, in steps of 0.2, to 2514, 1885, 1257 and 628 projections. One experimental condition was acquired using a 2 by 2 binning of the detector, 1571 projections, as well as a larger current and focal spot, and the exposure time was adjusted. For some experimental conditions, the reconstructed volume data was filtered using a median filter of a kernel size of 3, which was performed as a post-reconstruction filter in Nikon’s CT PRO software. A naming convention was introduced such that CONT628 describes a scan that used 628 real projections in the reconstruction, CONT628 UP3142, used 3142 projections which are interpolated from 628 real projections, which were acquired using continuous motion mode. STAT628 describes a reconstruction, which was acquired under stationary acquisition. CONT628FILT used 628 real continuously acquired projections, but the reconstructed volume was filtered using the median filter. Each experimental condition was repeated three times.

2.2. Noise in the reconstructed volume

The experimental conditions are expected to vary significantly in terms of noise. Noise can be investigated in the radiographic projections, reconstructed volume or extracted surfaces. For example, for images, there are a large range of image quality indicators, such as signal-/contrast-to-noise ratio, etc. [1]. In this work, Shannon entropy was used to quantify noise in the volumetric reconstruction [13]. This decision was made based on the work of Schienlein et al. [13], where the authors were able to show a better agreement between the occurrence of image artefacts with respect to using signal-to-noise ratio. The Shannon entropy is computed from the frequency distribution of the values in the volumetric dataset, and thus is affected by contrast, by the number of pixels and other factors affecting the distribution. In a configuration where a part of uniform material properties is imaged, a lower value of Shannon entropy is usually indicative of a bimodal distribution with better separation of the two modes (i.e. the part and the background can be better separated, which is important for surface determination), whereas higher values of Shannon entropy indicate a lower discriminability of the part and the background). Thus lower Shannon entropy is expected with better image quality, as discussed in [13]. The range is limited to 0 to 1, where 1 can be computed from a uniform histogram (no separability) and 0 would be computed of a volume which consists of a single grey level. Any change in the number of projections and application of sinogram interpolation, filtering or binning are not expected to affect the contrast of the reconstructed volume, as the contrast in XCT is mostly dictated by the X-ray settings and material properties [14,15]. Also, all reconstructions, other than the binned detector setup, were set to the same volume size, thus, the Shannon entropy is expected mainly to reflect the noise levels of the reconstructed volumes.

2.3. Resolution of the reconstructed volume

In the broadest sense, resolution relates to the detectability of small features or objects. Different definitions have been proposed, such as high- and low-contrast resolution, structural and positional resolution [16–19]. As previously discussed for noise, the concept of resolution can refer to the radiographic projections, to the reconstructed volume or to any surface extracted from it. In surface determination, the finite and variably-modulated resolution on the grey scale volume, i.e. a blurred edge, is translated into a single, finite point. Multiple solutions have been proposed to determine the resolution of XCT data in the surface domain.
However, all such solutions are based on dedicated artefacts, which render the concepts challenging to translate to the measurement of a real industrial part. Thus, in this work an oversampled slanted edge approach is used to approximate the resolution of the reconstructed grey-scale volume [20]. An oversampled edge spread function can be obtained by repeating the edge spread computation over a number of parallel lines drawn on the cross-sectional image, aligning them and by finding their arithmetic average [20]. Within this work, the method detailed in ISO 12233 [20] was implemented and ten lines were sampled to obtain one oversampled slanted edge.

2.4 Repeatability error and discrepancy in the extracted surface topographies

Statistical topography models were built from surface topographies extracted from volume data obtained by repeat XCT measurement (in repeatability conditions), according to a method described elsewhere [2]. In VG Studio Max 3.0, the reconstructed volumes from each series of repeat XCT measurements underwent surface determination, using the software default settings for advanced surface determination. The exported surfaces (mesh data) were aligned using the iterative closest point algorithm [2] before being used to build statistical topography models. Each statistical topography model consisted of a mean surface, as well as upper and lower bound surfaces defining the boundaries of the confidence interval (CI) on the local mean, at 90% confidence. Discrepancy ratios between statistical models belonging to repeats obtained in different measurement set-ups (different number of projections and amounts of sinogram interpolation) were computed as the ratio of surface areas where CIs do not overlap (i.e. the difference between mean values is statistically significant) and the total area covered by the surface. All the reported results pertain to the comparison of any experimental condition with the CONT3142 reference case (3142 projections, no sinogram interpolation). In addition, the local repeatability error of each experimental condition was evaluated as the mean width of the CIs belonging to each statistical topography model.

3 Results

Figure 1 shows the sample used in this investigation, as well as detail from slices of the reconstructed volume data for different experimental conditions. This section is split into three parts presenting the results for the Shannon entropy (noise), the edge spread function (resolution), and the statistical topography analysis (discrepancy and local repeatability error). The stationary acquisition, STAT628 took 44 minutes, CONT628 required 42 minutes of exposure, CONT1257 84 minutes, STAT1257 89 minutes, CONT1885 126 minutes, CONT2514 168 minutes, and CONT3142 209 minutes. The binned acquisitions was fastest and only required 12 minutes.

Figure 1: a) The specimen under investigation, b) a slice for the reconstruction using 1257 stationary projections (STAT1257), c) a slice of the reconstruction STAT1257 UP3142 that used 3142 projections which are interpolated from 1257 real projections, and d) which used 3142 real projections (CONT3142).

3.1 Noise in the reconstructed volume

Figure 2 shows the calculated Shannon entropy values for the different experimental conditions. The mean of three repeats is reported for all experimental conditions. The first fifteen conditions reported in Figure 2 (counting from the left) pertain to acquisitions performed with continuous motion. The following six are in the stationary mode, whilst the last two (at the right side of the horizontal axis) pertain to acquisitions performed using pixel binning at the detector, whilst using all 3142 projections.
Figure 2: Shannon entropy of the reconstructed volumes for the different experimental conditions. A low value of Shannon entropy is expected to reflect better levels of image quality [13].

3.2 Resolution in the reconstructed volume

Figure 3 shows the mean values obtained from the oversampled edge spread function evaluated over the three repeats of each experimental condition. As all data sets were acquired at the same magnification, the 10% to 90% value of the oversampled edge spread function was normalised to the nominal reconstructed voxel size, except for the case of the detector binning, where the edge spread function was normalised to half of the voxel to be comparable to the other data sets.

Figure 3: Oversampled edge spread function for the different experimental conditions

3.3 Discrepancy and repeatability error in the extracted surface topography

Figure 4 shows both the mean width of the calculated CI (repeatability error), and the discrepancy ratio of each experimental condition compared to the reference configuration CONT3142.
4 Discussion

XCT measurements of surface topographies can have large acquisition times. Reducing the number of projections reduces measurement times but may cause increased noise levels and artefacts in the volumetric reconstruction. Sinogram interpolation, pixel binning at the detector and median filtering of the reconstructed volume are methods which may be applied to reduce noise, but, together with reducing the number of projections, all such solutions have effects on resolution, and on the quality of the surfaces extracted from reconstructed volumes. This work investigated the aforementioned effects by means of the computation of quantitative indicators of measurement quality, both in the reconstructed volumes (noise, resolution), and in the extracted surface topographies (discrepancy, local repeatability error).

The noise of the datasets using fewer radiographs is expected to change as the number of recorded photons is different, but undersampling the sinogram space can introduce streaks and artefacts. Overall, the expectation is that the noise in the volumetric reconstruction is reduced both by sinogram interpolation and median filtering. Median filtering showed a larger decrease in noise than sinogram interpolation. Concerning noise in the volumetric reconstruction as measured by Shannon entropy, unexpectedly, the largest value was obtained for the binned detector case. This is probably not because the volume is actually noisier, but because of limitations intrinsic to how Shannon entropy is computed: the indicator is obtained from the frequency distribution of voxel values (histogram), and there are far fewer voxels in the binned case (one eighth of the unbinned case), which is likely to affect the final calculated value.

Assessing the resolution by means of the edge spread function does not allow to evaluate resolution along the entire measurement chain and does not directly address the problem of assessing the resolution of the extracted surface. However, only a small number of methods has been presented in the literature about assessing resolution after the surface determination stage [21–23] and resolution in the volumetric dataset already provides some indication of what resolution will be in the final surface. When assessing the resolution in the volumetric dataset using the edge spread function, the reconstruction using detector binning showed the worst resolution out of all test cases, followed by the cases based on 628 projections (the least number of projections) as expected. Reconstructions based on at least 1885 projections resulted in similar resolution levels to the CONT3142 reference setup. These resolution results were only minimally affected by sinogram interpolation or median filtering, which is not in line with expectations or with results in the literature [6].

As illustrated previously, precision in repeatability conditions, represented by the mean width of the CIs obtained from the statistical topography models, and discrepancy ratio between setups, represented by the number of regions where the mean topographies of the statistical topography models are significantly different (i.e. the CIs do not intersect) were analysed for all the investigated experimental conditions and compared to the CONT3142 reference case. When comparing median filtering as a tool for suppressing undersampling noise against sinogram interpolation, only the case using 2514 projections and median filtering showed comparable values in precision and discrepancy ratio. For all other cases, the mean width of the CI was largest (i.e. lower precision) for the cases involving median filtering. This indicates that for large undersampling, sinogram interpolation may be a better method for extracting surface topography data from highly undersampled XCT data. However, when looking at the effects of sinogram interpolation, the upsampled case of both CONT628 and STAT628 showed an increase of mean CI width (decrease of precision) when upsamplied to 3142 projections. This suggests that a larger degree of manipulation of projections deteriorates the extracted topography data through decreasing its precision.

When comparing binned acquisition setup against the other test conditions, the binned setup had both larger mean width of the CIs as well as a larger discrepancy ratio than any sinogram interpolated case using more than 1885 real projections. The binned case outperformed the CONT1257 case (i.e. better precision, smaller CI widths), but not the sinogram interpolated version of
CONT1257. However, while the binned setup showed the widest edge spread function compared to all other test conditions, it was much faster in the acquisition, as the exposure time could be reduced and the focal spot size could be increased. Overall, when comparing the acquisition time between the stationary and the continuous motion setups, the continuous motion showed a reduction of the acquisition time of around 5 min for 1257 projections, and around 3 min for 628 projections. The acquisition times of the different continuous motion acquisitions were increasing linearly with respect to the number of projections as expected. When investigating the effects of continuous motion on the quality of the obtained surface topography data, it is expected that continuous motion would reduce reconstruction quality, and consequently the quality of extracted surfaces (because of motion blurring affecting the original radiographs). However, the results showed that both the mean CI width (precision) and the discrepancy ratio with respect to the reference case (full number of projections) were better for the continuous motion setup, compared to the stationary acquisition setup. This result is against expectations and deserves further investigation. Also unexpectedly, the mean width of the CIs of STAT1257UP3142 (stationary setup) was much larger than its continuous motion counterpart. This could be due to errors in the alignment process of the statistical topography modelling method, as the STAT1257UP1257, shows similar levels of precision and discrepancy ratio with respect to its continuous motion counterparts. Overall, for further investigation, it would be interesting to develop a solution to assess resolution on the extracted surface, as opposed to in the volume data.

5 Conclusions

Sinogram interpolation can be used as a tool to suppress noise and artefacts when adopting a reduced number of projections for the purpose of saving acquisition time. Sinogram interpolation can yield improved results compared to median filtering and binning. However, further work should be pursued, to explore how sinogram interpolation compares against computationally more expensive methods, such as iterative reconstruction and other advanced reconstruction methods. Moreover, a method for assessing resolution directly on the extracted surface topography is needed.

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References

[19] Verein deutscher Ingenieure e.V., Computed tomography in dimensional measurement Basics and definitions VDI/VDE 2630-1.1 1–35.