Helical XCT measurement for correlative imaging

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Abstract
The X-ray computed tomography (XCT) is more often used to scan long objects that exceed the dimensions of the detector. Conventional scans/systems using circular trajectories touches the limits when dealing whit elongated samples. Helical scanning is a valuable solution in such a case. It enables to shorten scanning time, getting strong improvement on image quality, eliminating the cone beam artifacts and beam hardening. These benefits make from the helical trajectory strong tool for correlative approaches with other imaging techniques. In this work, images obtained by helical trajectory are investigated and compared with those acquired by conventional circular scans. Experimental results show that helical scanning with appropriate scan parameters performs better quality than traditional circular scans with an improvement in image quality.

Keywords: X-ray computed tomography, Laser-induced breakdown spectroscopy, Correlative imaging, Helical trajectory,

1 Introduction

The X-ray computed tomography (XCT) has been found to provide very good three dimensional (3D) sample characterization in the millimeters to micrometers scale [1]. This method uses the X-ray beam that penetrates the sample and its attenuation is detected. The value of attenuation is given by a density of the materials included in a sample. The basic principle of obtaining final XCT dataset is a measurement of many projections in various angles. The measured X-ray projections are then reconstructed and 3D data are visualized as cross-sections through the sample [2].

In general, there are two traditional ways of industrial XCT systems constructions. The first system has stationary X-ray source and sample rotates during the measurement. The second system has also a stable X-ray source with detector but the sample is rotating and also moving up or down. Introduced trajectories are called circular and helical respectively. The benefits of a helical trajectory were seen mainly in time reduction until now. These trajectories have different artifacts with different impact on image quality.

The circular trajectory has advantages in the scanning of the samples with similar sizes. The helical trajectory helps in the case of scanning long sample with one size bigger then detector width. The scanning time of such a sample is shortened in the case of helical trajectory. Another advantage is artifacts reduction which influences the grey value homogeneity within one material. The helical trajectory biggest advantage is the quality of the top sample surface. Top surface or top area of reconstructed images is frequently used for correlation with other imaging techniques. This area is analyzed with these imaging techniques. Different artifacts have a major influence on this part.

There are many mutual artifacts for both mentioned trajectories. The most important artifact same for both trajectories is caused by the beam hardening effect. Beam hardening appears when the mean energy of beam increases as the lower energy photons are absorbed more in comparison to higher energy photons [3]. The result of beam hardening is cupping artifact when X-rays passing through the center of a large object become harder than those passing through the edges of the object. It is due to the greater amount of material that the beam has to penetrate. The resulting profile of the linear attenuation coefficients appears as a “cup” [4], [5]. The next result of beam hardening is the appearance of dark streaks and bands in the images. These artifacts can be seen between two dense objects. This occurs because the portion of the beam that passes through both objects at certain tube positions becomes harder than the beam which passes through only one of the objects at other tube positions [5].

There are some artifacts related to cone beam XCT. These artifacts originate due to the type of scanning geometry and reconstruction method [5], [6]. One of them is partial volume averaging artifact. Partial volume averaging artifacts occur in regions where surfaces are rapidly changing in the z-direction, it means that more objects with various density are averaged. The selected voxel resolution of the scan is greater than the spatial or contrast resolution of the object to be imaged. This artifact is partly detected in fan beam geometry [6]. Next error in measurement can be undersampling. It’s a type of aliasing artifact which originates when lack of projections comes to the reconstruction process.

Last but not least, artifacts originate due to cone beam effect. It’s seen in peripheral portions of the scan, because of the divergence of X-rays in those areas. The total amount of information for peripheral structures is reduced because the outer row detector pixels record less attenuation, whereas more information is recorded for objects projected onto the more central detector pixels, which results in image distortion, streaking artifacts, and greater peripheral noise [5], [6].

Images provided by helical XCT trajectory suffer, except other types of artifacts, from windmill artifact. The artifact originates due to interpolation between two detector rows if there is a high contrast edge. Windmill artifacts are influenced by
the value of the pitch factor. A smaller value of pitch factor means less space to interpolate and more accurate value of final voxel intensity. This type of artifact creates smooth periodic dark and light streaks originating from high contrast edges [7], [8].

The presented study aims at the reconstructed image quality which can be achieved by the helical trajectory with the focus on the top surface. The image quality is the same or even better than the scan with a circular trajectory. This fact together with cone beam artifacts and metal artifact reduction makes from helical trajectory reasonable tool for correlative approaches. The study shows two new phantoms (see chapter 2.1). Phantoms were designed with the focus on the geological and oil & gas industry. The results of the second phantom scan show the influence of the noise on the different material and help to understand the difference between the helical and circular trajectories.

2 Materials and methods

2.1 Phantoms design

The project is focused on the geological field and oil & gas industry. The first phantom was designed to achieve the preliminary attempts with focus on the main goal of the 2D elemental maps with 3D XCT images correlation. The phantom consists of six structures from four different materials (see Fig. 1). The materials were chosen with respect to the future geological and industrial research. The individual parts of the phantom were united by the epoxide. The top surface was polished for the purpose of the LIBS measurement.

The second phantom represents an approximation of geological sample and it gives a real overview of the imperfections in XCT images. The phantom has seven rods with different materials. Materials have the different density going from the lowest to highest values. The results will be presented with the respect of 1st material as the one with the lowest density and 7th material with the highest density. Its purpose is to demonstrate the intensity changes along the sample. This fluctuation causes the problem with additional post-processing like segmentation and correlative approach. The rods were united by the epoxide and the surface was cut with respect to possible future analysis.

2.2 XCT measurement

The Thermo Fisher Heliscan is equipped with 160 kV X-ray source. The detector is a flat panel with 3072 x 3072 pixels. The XCT scan of the first phantom was executed with the helical trajectory. The X-ray beam 140 kV and 130 μA was chosen to acquire the sufficient image quality. The linear voxel size was 13 μm. The 2800 projections with 600 ms integration time were taken. The second phantom was scanned with 100 kV and 60 μA for helical and 100 kV and 150 μA for the circular scan. The 2880 projections were taken with an exposure time of 1.8 seconds. 13.3 and 22.6 linear voxel size was achieved for helical and circular trajectory respectively. The iterative reconstruction was done by Thermo Fisher reconstruction software. The 3D visualizations were performed with VG Studio MAX 3.1 software, image processing was done in Avizo or image processing was held in Matlab® programming environment.

2.3 LIBS measurement

The coordination of individual pixels is preserved during the elemental mapping. So each pixel of the chemical map corresponds to the intensity of the selected spectral line which is represented by a color on the selected scale. The most common case of elemental map patterns is a rectangular grid of equidistant points. The lateral resolution and the size of the elemental map are
given by the laser spot size and the number of shots in each direction. The lateral resolution is limited entirely by the ablation crater diameter. The resulting image can be presented as a classified image with the material differentiation. This is going to help with the segmentation of the XCT images and with the following classification. The of such an approach can be the 3D elemental mapping of the measured sample [9].

2.5 Image quality evaluation

The correlative approach demands good quality of XCT images mainly in the area of the correlation. The stability of grey values in cross sections along the sample plays also an important role in the following post-processing. The presented image quality parameters are used to describe the images measured phantoms. The global and also local descriptors are used to completely describe the presented problems.

2.5.1 Contrast to noise ratio

In post-processing of XCT images (NDT), the contrast-to-noise ratio (CNR) is an important parameter. It shows the detectability of features in a volume. It is calculated by the mean grey values of background and object and using the noise as a standard deviation (SD) of the pixel grey values in the selected region. CNR can be written as:

\[
CNR = \frac{|\mu_o - \mu_b|}{\sigma_b}
\]

High noise (getting low CNR) usually leads to a lower detectability. Description of the noise as an SD of grey values is a common simplification but it only takes into account uncorrelated noise. Similar CNR values are achieved for very different noise structures. The CNR thus does not completely cover the image characteristics. Therefore, other parameters are used.

2.5.2 Signal to noise ratio

The signal-to-noise ratio (SNR) is a measure for the detectability of an object in a noisy image [6]. One of the descriptions of SNR in the region of interest inside the object can be described as the ratio between the mean gray values of ROI to the noise in the same ROI, which is commonly calculated as an SD:

\[
SNR = \frac{\mu_0}{\sigma_0}
\]

where \(\mu_0\) is mean grey value and \(\sigma_0\) is the associated SD.

2.5.3 Sharpness

The standard global image quality indicators are not always able to provide enough information about the image. In addition, parameters describing the local image quality are used in the presented paper to also show the different impact of scanning approaches on resulting reconstructed images of different materials. These measures are used to describe the sharpness of an image, which in turn can influence the top surface determination on the reconstructed volume used for correlative research. With decreasing sharpness, the surface determination of the reconstructed image and the following image registration becomes less accurate [3]. The sharpness itself is influenced by the magnification of the object. It is usually required to achieve the best resolution possible. This result in the negative impact of focal spot size which has an influence on the reconstructed images. This together with cone beam artifact leads to unsharpness on top and a bottom surface, which can be used for correlation. Thus, the sharpness parameter is calculated in this paper. One possible sharpness measure is the local contrast, which can be calculated as:

\[
C = \frac{g_{\text{max}} - g_{\text{min}}}{g_{\text{max}} + g_{\text{min}}}
\]

where \(g_{\text{max}}\) and \(g_{\text{min}}\) denote the maximal respectively minimal grey value in the region of interest [9].

2.5.4 Line profile measurement

Line profiles are used as a simple tool to describe the grey values fluctuations along the sample. The AVIZO Line probe module was used to get the presented graphs. The beam hardening was studied on the cross sections in the top, middle and bottom part of the sample. Line profiles of grey values fluctuations along the sample are calculated for every of the eight material in the second phantom. The graphs always consist of 3 measurements and the mean value is taken. This was done to decrease the influence of randomness in the graphs.

3 Results and discussion

Correlative approaches are more and more used for research in many scientific areas. The most important example is material science in general (geology and oil & gas industry). They need to analyze different materials and examine the real structure of the samples. The XCT produce images of the sample completely in 3D with non-destructive benefit. Unfortunately, the XCT images are only in grey values and the material differentiation is not very good in the case of the materials with similar density.
In that case, the correlative approaches give a high benefit. It is possible to resolve the material distribution. The correlation is based on the finding the same position (same images) in chosen imaging techniques. In the case of the presented study, the correlation is supposed to be done between the reconstructed XCT images and LIBS maps. The first reasonable cross section is found in XCT and it is related to the LIBS map. The top surface is commonly used for the analysis and it is usually affected by artifacts. The study was performed to show the relatively new helical scanning trajectory which reduces cone beam as the most significant artifacts and provide enough image quality for a correlative approach. As the helical trajectory is new in the laboratory-based XCT systems, the big involvement can be made in the future.

The first analysis is made for the study of differentiation of materials within one scan. The second phantom materials were chosen to represent the best approximation of industrial samples. The average and standard deviation of grey values in the selected areas are calculated for all of the seven materials. Helical trajectory has the materials in the range going from 11 287 to 45 816 this gives enough space for differentiation of all seven materials. The circular scan has the materials averages from 11 362 to 53 712. The SD shows very similar values for both scans with a better outcome for helical trajectory. The SD is changing with the material density and it is higher with the increasing material density. This is an interesting fact and it should be investigated more. It can be helpful in the case of denoising and segmentation of such images. The individual averages and areas of grey values contained with SD have sufficient spacing and enables very simple segmentation.

Table 1: Calculated averages and standard deviation of gray values for the seven materials with different density.

<table>
<thead>
<tr>
<th>Material</th>
<th>Circular</th>
<th>Helical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Standard Dev.</td>
</tr>
<tr>
<td>1</td>
<td>11362.48</td>
<td>36.13</td>
</tr>
<tr>
<td>2</td>
<td>11977.73</td>
<td>37.10</td>
</tr>
<tr>
<td>3</td>
<td>13161.13</td>
<td>72.33</td>
</tr>
<tr>
<td>4</td>
<td>22680.96</td>
<td>152.26</td>
</tr>
<tr>
<td>5</td>
<td>41058.19</td>
<td>176.15</td>
</tr>
<tr>
<td>6</td>
<td>51875.14</td>
<td>226.97</td>
</tr>
<tr>
<td>7</td>
<td>53712.06</td>
<td>245.51</td>
</tr>
</tbody>
</table>

Other parameters calculated for the image quality estimation in different trajectory are SNR, CNR, and Sharpness. All presented parameters are expressed for all of the seven materials and results are in table 2. It shows a very similar outcome as the previous table. SNR analysis presents expected results from the average and SD. Very high SNR in the low dense material is achieved which is the result of low noise for that materials. The material four has lower SNR than expected. The similar results are found for both scans. The CNR shows very well discernible for dense materials in both trajectories. Sharpness is the only parameter where the circular trajectory scan is better than helical. To better understand the results the line profiles are expressed.

Table 2: Calculated image quality parameters for seven materials with the resin as an eight material.

<table>
<thead>
<tr>
<th>Material</th>
<th>SNR</th>
<th>CNR</th>
<th>Sharpness</th>
<th>SNR</th>
<th>CNR</th>
<th>Sharpness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>314.469</td>
<td>45.309</td>
<td>0.011</td>
<td>309.138</td>
<td>52.958</td>
<td>0.009</td>
</tr>
<tr>
<td>2</td>
<td>322.839</td>
<td>65.818</td>
<td>0.010</td>
<td>333.957</td>
<td>76.542</td>
<td>0.008</td>
</tr>
<tr>
<td>3</td>
<td>175.646</td>
<td>105.264</td>
<td>0.057</td>
<td>243.743</td>
<td>110.784</td>
<td>0.010</td>
</tr>
<tr>
<td>4</td>
<td>148.964</td>
<td>422.592</td>
<td>0.054</td>
<td>136.852</td>
<td>423.964</td>
<td>0.017</td>
</tr>
<tr>
<td>5</td>
<td>165.736</td>
<td>1035.166</td>
<td>0.048</td>
<td>215.114</td>
<td>1062.512</td>
<td>0.013</td>
</tr>
<tr>
<td>6</td>
<td>184.362</td>
<td>1395.731</td>
<td>0.038</td>
<td>204.027</td>
<td>1417.295</td>
<td>0.011</td>
</tr>
<tr>
<td>7</td>
<td>187.158</td>
<td>1456.962</td>
<td>0.025</td>
<td>206.819</td>
<td>1476.263</td>
<td>0.013</td>
</tr>
<tr>
<td>8</td>
<td>317.457</td>
<td>37.585</td>
<td>0.011</td>
<td>304.421</td>
<td>44.057</td>
<td>0.010</td>
</tr>
</tbody>
</table>

The sharpness can be also evaluated by the line profiles going in this case from the air into the different material. Fig. 2 presents line profiles of 1st, 2nd, 4th, and 5th material. The results are very similar in the case of the low dense material. In the case of high dense material, the helical scan gives better results which are in harmony with the previous results. The edge of the material consists of 5 to 6 voxels in the low dense materials. The material edge for higher dense material is represented by 4 voxels.
Influence of different artifacts is studied in the last comparison. It is made with the same cross section from both scans (see Fig. 3). The cross sections were chosen with respect to the image quality and the purpose of the correlative approach. The first cross-sections were taken which will be used in that case. Beam hardening correction was applied to the data for both scans. The cross section for helical trajectory has a small impact of the windmill artifact as discussed in the introduction. The cross-section shows reduced metal artifacts together with low changes in grey values. The circular scan has still ring artifacts even in the case that the reconstruction was made with ring artifact reduction. The cross-section also shows small changes in grey values on the left part of the sample. The high dense material causes the metal artifacts. The comparison for both scans gives better results for helical trajectory as these images will be used for the correlative approach it is the main advantage of the helical trajectory. Also, the small influence of cone beam artifact can be found in the images which also gives the benefit to the helical trajectory. The line profiles of these cross sections are shown in figure 4. The beam hardening correction help in both cases to reduce the impact of the artifact.

Figure 2: The line profiles are shown for 1<sup>st</sup> A), 2<sup>nd</sup> B), 3<sup>rd</sup> C) and 5<sup>th</sup> D) material to present the sharpness of different trajectories.

Figure 3.: The cross section for A) helical and B) circular trajectory with the line profiles shown in Fig 4.
Figure 4: Line profile through the cross-section in Fig. 3 shows the results for the beam hardening corrected images.

4 Conclusions

New phantom was applied for the study of the difference between helical and circular trajectory. Several parameters were calculated to find the difference. The results show better image quality for the helical trajectory except for the sharpness parameter. Sharpness was again estimated by the line profile going from air to the sample with different materials. The results of line profiles show very similar results for both trajectories. Another evaluation was made on cross-sections. The first cross sections are usually used for correlation with other imaging techniques. These images are investigated and the helical trajectory has the lower impact of the metal artifact. These facts together with no cone beam artifacts make the helical trajectory useful tool for correlative approaches when the sample should be examined by the non-destructive processes. Also, the results show that the correlation can be done with the top cross section. Following segmentation and classification can be done with the corresponding image from other imaging modality.

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