Improved analysis techniques for new applications in neutron imaging

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Abstract
Neutron imaging provides a method for high contrast imaging of many low density materials in combination with high density materials. For samples with suitable material composition this makes neutron imaging techniques very valuable in comparison to the more common X-ray techniques. The two neutron imaging beamlines at the Swiss Spallation Neutron Source (SINQ) serve a wide user community with applications for material inspection and materials research, geo-science, cultural heritage studies, and energy production and storage. For this purpose, the beamlines have evolved into versatile instruments that can be modified to meet the user requests in short time. We show some recent results to demonstrate the performance of the imaging facilities. Topics covered by the examples are combined spatially and time resolved imaging, low contrast imaging, high resolution imaging of large samples. Neutron tomography on different size scales is used in routine mode. Often, these investigations operate close to the limit of the instrumentation or even the limits of analysis methods. The examples represent applications from construction engineering, combustion engine engineering, and electro-chemistry.

Keywords: neutron imaging, computed tomography, resolution, spatio-temporal imaging, filter methods

1 Introduction

Advanced neutron imaging (including high resolution tomography, energy selective imaging, and grating interferometry) has a long tradition at Paul Scherrer Institut (PSI), Switzerland. There are two fully dedicated and versatile beamlines for neutron imaging installed at the Swiss spallation neutron source [1] (SINQ). The two beamlines NEUTRA [2] (thermal neutrons) and ICON [3] (cold neutrons) serves a wide user community with academic as well as industrial research projects. Figure 1 shows the wide variety of research applications that uses neutron imaging as a method to gain new knowledge about processes and samples. In the year 2011 a total of 121 projects were started. The chart shows the distribution of projects topics for all users (proposal, industry, and internal) at the two beam lines ICON and NEUTRA. A continuous development of acquisition and data processing methods is required to meet the requests of a wide user community. The acquisition methods used in the different projects include single image radiography, time series radiography, stroboscopic imaging, tomography, energy selective radiography and tomography, X-ray/neutron experiements, and grating interferometry. In some experiments, we have encountered experimental conditions that puts our equipment near the edge of the possible performance. In these cases new developments or changes in the measurement strategy were required to meet the experimental requirements.

There are five main challenges to solve to provide the expected results. The challenges lies in the neutron statistics, spatial and temporal resolution, beam divergence, and the inherent sample dynamics. All are directly or indirectly related to the strength of the neutron source and also coupled with each other. The neutron statistics are directly connected to the source strength that
sets the maximum available neutrons. This amount can only be increased within small variations during normal operation. The amount of neutrons reaching the detector has a direct impact on the image contrast and exposure time. Currently, the state of the art detection system in neutron imaging consists of a scintillator and a camera for visible light. The scintillator that converts the neutrons into visible light also plays an important role for the contrast since its design and composition determines the neutron to photon conversion ratio. The scintillator is also important for the spatial resolution of the imaging system. The thinner the scintillating layer is, the higher the resolution gets. With higher detector resolution smaller pixels are acquired which means that the detecting area is decreasing. This again has an impact on the contrast since less neutrons are collected over this smaller area. This in turn requires either to increase the exposure times or the amount of neutrons. Increasing the amount of neutrons mostly means that the neutron aperture size is increased. The consequence of changing the aperture is that the collimation ratio changes. A larger aperture gives a lower collimation ratio and hence a larger beam divergence. This introduces geometric unsharpness when the sample is too large or too remotely positioned from the detector, i.e. the resolution suffers from this action. In the end a trade-off must be made where an acceptable compromise between contrast and resolution has to be met.

Until now, all challenges are related to the instrument conditions. The last challenge is related to the sample itself. If there is an inherent dynamic component in the sample or experiment process this will cause motion blurring in the acquired images. In photography this blurring is used artistically, but for scientific imaging the blurring introduces an additional uncertainty to the measurement. The impact of the motion blurring is visible when the motion exceeds a pixel size while the image is acquired. The temporal resolution must be increased to reduce the motion blur. For tomography this requirement is even stricter, the sample must remain static during the complete scan otherwise motion artifacts will appear in the reconstructed images.

In recent applications we have had measurement conditions that tangent the limitations of the current methods in terms of resolution and contrast. In this paper, we will present some actions that have brought the performance of neutron imaging at PSI one step further.
2 Methods

2.1 Anisotropic high resolution of thin layers

The spatial resolution is an important factor for the feasibility and quality of many measurements. A method to increase the resolution in one direction is to use a tilted scintillator in combination with a mirror that provides a stretched image of the scintillator, figure 2. This arrangement allows thin segments of a sample to be visualized with higher resolution. Factors that must be considered when the resolution is increased are the beam divergence which together with the scintillator sets an upper bound on the resolution. High resolution without sufficient contrast will not provide the information asked for, hence the neutron statistics must be considered. In [4, 5] the neutron beam has an additional one-dimensional collimation using the source beam limiters. The higher collimation in one direction is used to meet the conditions required but the tilted scintillator devices while the beam intensity is to large extent preserved. By this arrangement, a pixel size of 2.35 \( \mu m \) can be achieved with the micro setup at ICON and a camera with 2048x2048 pixels, this corresponds to a spatial resolution of 8.7 \( \mu m \).

![Figure 2: Schematic drawing of the tilted detector used at ICON. The device increases the spatial resolution in one direction.](image)

It is also possible to make tomographies using the tilted device. The fact that the scintillator is tilted makes that the geometric unsharpness becomes a function of the slice position. This makes the slab that can be reconstructed thinner than first expected, the further away from the detector-mirror intersection point the slice is located the stronger the cone-beam artifacts become. Ideally, a reconstructor that includes the tilted geometry should be used reconstruct this kind of acquisitions. Furthermore, the contrast of the projections is often very low. Therefore, tomographies with the tilted detector are mostly only useful for high contrast samples, otherwise the scan times become very long.

2.2 Tomography of large samples

In neutron imaging it is often assumed that the collimation ratio is sufficiently large to make parallel beam geometry a valid approximation for the reconstruction of the projection data. This assumption only holds when the sample can be placed close to the detector. By the use of a high resolution setup, we observed that this assumption is incorrect for large samples. The collimation ratio \( L/D \) is composed of the distance between source and detector \( L \) and the source aperture \( D \). This is related to the geometric unsharpness, \( d_g \), by the distance, \( l \), of the contributing part of the sample as

\[
d_g = l \frac{L}{D}
\]

For a tomography reconstructed with parallel beam geometry the most remote part of the sample in each projection causes the greatest geometric blurring, location (a) to the left in figure 3. The
blurring of each pixel is however more complex than that, since the total blurring is determined by contributions along the line integral through the sample. This becomes more prominent for fine detailed porous samples than for homegeneous samples. For example, a sample composed of a rectilineral grid like the diesel particle filter presented in the applications section. Such structures show less blurring when the beam is parallel aligned with the grid than when then sample is oriented 45° to the beam.

The solution is to this problem is to change reconstruction method from the mostly used parallel beam reconstruction to cone-beam reconstruction by the Feldkamp method [6]. Using cone beam computed tomography (CBCT) for the reconstruction eliminates most of the unsharpness effects and an artifact free image can be provided for the following evaluation. Figure 4 shows a reconstructed cross-section of a diesel particle filter with a diameter of 140 mm. The figure illustrates the improvement of using CBCT reconstruction for normal imaging conditions at the ICON beamline (L/D=342, FOV=150mm, and a 1024x1024 pixels camera). This means that the most remote parts of the sample would cause a spot width of 1.0 mm which corresponds to about seven pixels. In figure 4, it can be seen that the central region (c) does not show any direct improvement in the sharpness using CBCT. For the regions further away from the center (a and b) the blurring is clearly visible. Region a which corresponds to case where the beam hits the structures at a 45° angle has the most pronounced blurring and the grid structure is barely visible. The cone angles at the ICON beam line are 1-2 orders of magnitude less than those found at commercial micro-CT devices. Nevertheless, the use of a CBCT reconstructor shows a clearly visible improvement of the image quality. This data was reconstructed using the Octopus software [7]

2.3 Handling dynamic samples

The sample dynamics can be categorized into two types: cyclic and continuous. The cyclic process repeats itself with a given frequency. This makes it possible to use a signal that triggers the image acquisition when a process condition is fullfilled. With a continuous process on the other hand all information must be acquired at any moment in time since this condition is unlikely to return. Here, the sampling rate must be tuned to match the time constants of the
observed process. For a successful imaging experiment with a dynamic sample, it is essential to provide sufficient neutron statistics for each time-frame. For the cyclic experiment this is solved by using the accumulated images from several acquisitions triggered in a stroboscopic manner. This makes it is possible to work with very short exposure times. The number of exposures required to accumulate for a single image of the process depends on the needed image contrast.

For computed tomography the sample dynamics will introduce motion artifacts when the process changes faster than the scan rate. A direct approach to reducing the motion artifacts would be to increase the scan rate. This is unfortunately not always feasible since the neutron statistics will be too poor to provide the required image contrast to distinguish the investigated features from their background. A different way to reduce the artifacts is by changing the order in which the projections are acquired from the commonly used incremental with constant steps to an irregular sequence. In [8] two such methods are described. Both methods are demonstrated to be capable of handling change rates in the order of 0.1 pixels/projection. In addition to the reduction of motion artifacts these methods also makes it possible to divide the scan into complete sub-scans that can be reconstructed into a time sequence and thereby provide a spatio-temporal sequence of volumes. The Golden ratio reconstruction is supported by the MuhRec software [9]. Figure 5 shows how water evaporates from a sample arrangement of light weight aggregates and super absorbing polymers. The size of each item is about 3 mm. The complete scan consisted of 900 projections but was divided into six sub-scans that all contain the complete information for a reconstruction. The number of sub-scans can be arbitrarily chosen after the scan. The sampling theorem must be fulfilled even for the sub-sets otherwise sampling artifacts are to be expected. Therefore, the projections must be down-sampled to meet the number of projections in the sub set. The consequence is that the higher temporal resolution results in a lower spatial resolution.

2.4 Image processing

Image processing has an essential part of the data evaluation. In some cases, it is sufficient to provide basic volume- or surface-renderings of the sample. If the structures of sample has to be quantified, it is mostly required to segment the gray levels in the image into classes representing different components of the sample. The segmentation requires relatively noise free data to per-
Figure 5: A time sequence of volume images showing the evaporation process of water from porous spheres (∼3 mm) brighter regions have higher water content. The projections were acquired with the Golden ratio protocol. The images were reconstructed with projections from a single scan.

form with acceptable accuracy otherwise a tedious manual segmentation is required. The image noise can be suppressed by applying a filter with low-pass properties. For many applications it is sufficient to use convolution with a low-pass filter like a box- or Gauss-filter. The median filter is often also a good choice. Unfortunately, these filters are not discriminating between edges and flat regions which has the consequence that edges are smoothed along with the noise reduction, i.e. a blurred image will be the output.

More advanced filters are required for samples with thin structures since it is important to preserve the edges while the noise is suppressed. Filters that have these properties are for example diffusion [10] and non-linear inverse scale space (ISS) filters [11]. In our experience, the ISS-filter is the one that best meets our requirements regarding edge preservation and noise suppression. This filter is also capable of removing some ring- and line-artifacts since these structures mostly only appear on single slices. We have implemented the ISS-filter for three-dimensional data. The third dimension adds more structure information from the image data while the statistics are improved. It has the ability to preserve thin film-like structures with thicknesses down to a few pixels with nearly no information loss. When the ISS filter is tuned it is important to observe that not relevant structures are eliminated or severely modified. A good help for this check is the difference image between the filtered and the original images. Ideally, the difference image should only show the noise component of the image. Figure 6 shows the impact of applying the ISS-filter on a three dimensional image of a diesel particle filter. The histogram of the original image is mono-modal, figure (7). Such images are very hard to segment into multiple classes, especially since the relevant features are the films that coats the walls of the filter. The other three panels (b–d) in figure 6 show the significance of decreasing the time increments between two iteration steps. In both images and histogram it is clear the smaller increments improve the signal to noise ratio while the edges are well preserved. The cost of small increments is longer processing times. In our opinion, the cost of more computational
time is worth taking for the improved segmentation accuracy. After filtering it is possible to measure the thickness of the ash and soot coatings on the ceramic filter walls. The thickness measurements were verified with SEM measurements of the soot and ash layer thickness.

![Image](image_url)

Figure 6: A fraction of a diesel particle filter unit of the type shown in figure (4). The effect of using an inverse scale space filter on the original image (a) with the same solution time but different number of iterations. The other images show the result using 10 iterations (b), 50 iterations (c), and 500 iterations (d).

![Histogram](image_url)

Figure 7: Histograms of the images shown in figure 6.

### 3 Applications

The use of the previously described improvements has made many experiments feasible using the neutron imaging beam-lines at Paul Scherrer Institut. Recent applications that have made the most benefit of these methods are fuel cell performance monitoring using the tilted detector to study the water distribution inplane on both sides of the cell membrane [12]. In the reported experiments the use of different H isotopes made it possible in-situ track the migration of H in the fuel fuel cell. The start-up behaviour of polymer electrolyte fuel cells at cold temperatures has been observed and water in the super-cooled state was identified in all subfreezing temperatures [13].

In the experiments reported in [14] diesel particle filters were investigated at different resolutions. After the application of CBCT reconstruction it was possible to measure the spatial distribution of the average density change of each filter channel in a filter unit sealed in a steel
container. The filter is shown in figure 8a. The images shown in figure 6 were made after cutting a part from a filter brick, the segmented volume rendering of the sample is shown in figure 8b. This destructive step was needed to fit the sample into the field of view of the high resolution setup at ICON. In the resulting images it was possible to discriminate between all relevant components in the sample (air, soot, ash, and ceramics).

Figure 8: A neutron tomography of a diesel particle filter (diameter 140mm). The whole filter is shown in (a) and a fraction of a single filter unit is shown at higher resolution in (b).

The use of irregular scan strategies for tomography has improved the performance of investigations of the drying process of concrete similar to the experiments reported in [15]. These scan methods have also been used for pragmatic purposes like making the most out of the remaining beam time of an experiment. Since it is always possible to reconstruct a Golden ratio scan, the scan can be terminated at the end of the shift. A traditional sequential scan would then mostly be incomplete at the end of the beam time slot with reconstruction artifacts to be expected.

4 Conclusions

We have presented instrumentation improvements and processing methods that take the results beyond the limitations given by the conventional practice in neutron imaging. Some of the limitations only apply to systems with high spatial resolution while others like the filter methods apply to any imaging system with limited beam intensity and low signal to noise ratio. The change from parallel beam geometry made it possible to reconstruct grid structures that were blurred and distorted with parallel beam reconstruction. By changing the acquisition scheme from incremental steps to an irregular scheme it is possible to capture time sequences in three dimensions, even when the dynamic process changes faster than the scan times of the data set. Filtering may be a delicate task since it may alter the original information if done carelessly. We have shown some examples of how the application of the non-linear inverse scale space filter can improve the image quality to a degree that makes it worthwhile to start working with visualization software to render different regions of a sample.
References


