Abstract

For experiments with low contrast between the relevant features it can be beneficial to add a second modality to reduce ambiguity. At Paul Scherrer Institut the two neutron imaging facilities NEUTRA (thermal neutrons) and ICON (cold neutrons) we have installed X-ray beamlines for on-site bimodal imaging with neutrons and X-rays. This allows us to leave the sample untouched in the sample environment throughout an experiment and to reduce the waiting times between acquisitions using each modality. The applications and energy ranges of the X-ray installations are different at the two facilities. At NEUTRA larger samples are intended (60-320kV) and at ICON small samples and simultaneous acquisition are intended (40-150kV). Here, we report the more recent installation at ICON. The X-ray beamline uses a cone beam source and is arranged across the neutron beamline. The beamline is designed to allow up to ten times magnification. This matches the voxel-size that can be achieved with the micro-setup for neutrons. The oblique arrangement of the X-ray beamline further makes real-time acquisition possible since both modalities have a free view of the sample at any time. Reconstruction of cone beam data requires more knowledge about the beam geometry and sample position. Therefore, the beamline is equipped with laser based distance sensors and a calibration procedure has been developed to increase the accuracy of the reconstruction. The purpose of using multimodal acquisition is to fuse the data in a way that enhances the output of the experiment. We demonstrate the current system performance and provide a basic analysis with experiment data.

Keywords: Neutron imaging; X-ray imaging; computed tomography; bimodal imaging; beamline; calibration

1. Introduction

Applications for bimodal imaging using neutrons and X-rays can be found in many research topics like material testing, fluid flow in porous media, and cultural heritage. This imaging approach is mainly useful when the samples contain material combinations that reveal some complementary information. These differences can be exploited when images from the two modalities are combined. Ambiguities in the image information like low contrast for one modality can be reduced by fusing data from a bimodal image experiment and help the user to better describe the observed sample or process. A further reason to use bimodal imaging is to minimize the impact of artifacts, e.g.
beam hardening, starvation, scattering etc, that are more or less pronounced depending on material composition and modality.

Neutrons and X-rays can both be used to acquire radiographs. The two modalities have different sets of attenuation coefficients that are correlated for some elements while they are uncorrelated for other elements. This makes them an attractive combination for bimodal imaging. Initial bimodal experiments were made using separate imaging facilities which required that the sample was moved to acquire with the second modality Carminati et al. (2006). This approach may be attractive as it makes it possible to obtain images with the best performance for each modality. Unfortunately, this also introduces waiting times and requires transport that may alter the sample. These aspects are of particular importance for porous media experiments were it is important to see the sample with both modalities more or less simultaneously. Encouraged by the results using complementary information provided by the combination during the first combined experiments, we have now installed X-ray imaging capability at our neutron imaging instruments NEUTRA and ICON. The combined installation addresses the issue that the sample has to moved between two facilities and that the installation always is available for the experiment users as an additional method to investigate the sample.

In this paper we will describe the X-ray imaging beamline that is installed at ICON and report some experiences from the first experiments.

2. Instrumentation

2.1. Design

There are basically two different approaches to integrate a second imaging modality to a neutron imaging instrument; in-line and across the neutron beam. These alternatives are schematically shown in figure 1. The inline approach was chosen at the NEUTRA beamline (Vontobel et al., In review 2016). This installation has the advantage that essentially the same beam geometry applies to both modalities, making pixel-wise comparison possible without the need to register the images on a common coordinate system. On the other hand, simultaneous acquisition is hard to achieve with the in-line approach as the X-ray source hides the neutron source and would also be exposed to the direct neutron beam. At ICON (Kaestner et al., 2011), we chose to mount the X-ray beamline across the neutron beamline with the advantage that simultaneous acquisition is possible. Figure (2) shows the hanging arrangement of the X-ray beamline at ICON. The hanging arrangement was chosen due to space constraints under the neutron beamline. It is possible to mount or dismount of the X-ray beamline within an hour to provide more space for experiments not requiring the X-ray option.

The used X-ray source (Hamamatsu model L212161-07) has a wide cone beam with 43° divergence. The strong divergence of the source defines tomography as the main acquisition mode using X-rays at ICON. Radiography is only relevant for thin samples that are less sensitive to perspective projections. Mounting the X-ray beamline perpendicular
to the neutron beamline is not ideal for the neutron acquisition as this would have the consequence that the X-ray beam would be shadowed by the neutron camera setup. Shadowing the X-rays has two effects 1) the X-rays will not reach the X-ray detector and blind out relevant information and 2) the X-rays will hit the neutron detector unless it is shielded. Therefore, we chose a mounting that allows the X-ray beamline to be slanted at arbitrary angles in the interval $80^\circ \leq \theta \leq 135^\circ$ relative to the neutron beam as shown in fig. (1c). With this concept it is possible to arrange the X-rays in a manner that minimizes the shadowing effect and at the same time it reduces the sample detector distance for neutrons to minimize unsharpness caused by the penumbra blurring. The X-ray images are acquired using an amorphous silicon flat panel detector (Varian 2530HE). The beamline is designed to allow up to 10× magnification with the chosen components. The highest magnification provides a voxel size of $13.9 \mu m$. This matches the voxel size of the so-called neutron micro-setup (Lehmann et al., 2007). The pair of source object distance (SOD, actually to center of rotation in the beam direction) and source to detector distance (SDD) gives the magnification of the acquired projections as $M = SDD / SOD$. The same magnification can be achieved with different distance combination and longer distances should be preferred over shorter to avoid too strong cone beam artifacts. The specifications for the chosen components are listed in table (1) below.

<table>
<thead>
<tr>
<th>X-ray source</th>
<th>X-ray detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Hamamatsu L212161-07</td>
<td>Model Varian 2530HE</td>
</tr>
<tr>
<td>Tube voltage 40–150 kV</td>
<td>Active area 250×300 mm$^2$</td>
</tr>
<tr>
<td>Tube current 500 $\mu$A</td>
<td>Pixels 1792×2176</td>
</tr>
<tr>
<td>Max power 75 W</td>
<td>Pixel pitch 139 $\mu$m</td>
</tr>
<tr>
<td>Spot size 7-50 $\mu$m</td>
<td>Max frame rate 9 full frames/s</td>
</tr>
<tr>
<td>Cone angle 43°</td>
<td>Scintillator 200 $\mu$m GadOx</td>
</tr>
</tbody>
</table>

Table 1. Specifications of the X-ray components used for the bimodal imaging setup at ICON.

The detectors are mutually sensitive to the radiation of the other modality. The neutron detector in particular requires protection from incident X-rays as the sample is placed close to this detector and the X-ray source should not be switched off between two projections. Two options are provided 1) a shutter (2 mm tungsten) mounted on the X-ray source and 2) a sheet of 2 mm lead on the incident side of the neutron detector. The X-ray detector is usually placed outside the neutron beam using beam limiters, which mostly makes shielding unnecessary. A sheet of 5 mm boron plastic is sufficient if shielding should be needed. The shutter is intended for alternating acquisition and the shielding for simultaneous acquisition, fig. (3). Both modes of cross talk protection are implemented and successfully tested. The sequential mode is the preferred approach for static experiments and in particular if crystalline samples are investigated as diffracted spots may hit the opposite detector, e.g. Peetermans and Lehmann (2016). For dynamic
experiments the simultaneous acquisition mode is preferred as it shortens the waiting times between images. This makes is possible to increase the frame rate up to the limit of the detector with the lowest frame rate.

2.2. Calibration

In most cases the neutron beam is considered being parallel. This limits the calibration efforts to identifying the center of rotation and possibly to determine the acquisition axis tilt while tuning the tomographic reconstruction. On the contrary, this is not the case for the strongly divergent cone beam of the X-ray source. The instrument geometry must be well-defined to be able to reconstruct a cone beam tomography. For this type of reconstruction, it is of fundamental importance to describe the beam geometry in terms of beam piercing point on the detector (the point where the beam hits the detector perpendicular to the detector plane) and the distances between source, sample, and detector (SOD and SDD). The piercing point is needed to avoid skewing effects of the reconstructed data. It can be found as the location of the intensity maximum in the open beam image. The piercing point is located by fitting a quadratic 2D curve using the least squared fit of the image intensities to find its maximum analytically using the curve function. The distances (SOD and SDD) are measured using two laser distance sensors mounted on the source and detector respectively. They measure the distance to the sample position from each side and provide SOD and the object detector distance (ODD, $SDD = ODD + SOD$). The sample position is decoupled from the X-ray beamline in our system and can move independently. A guiding system with a downward pointing laser mounted on the beamline rail is used to identify the center of rotation on the turn table. The distance sensors are not mounted perfectly aligned with the positions of the X-ray target spot and the detector plane. Therefore, the readings from the distance sensors will be biased. We designed a calibration sample made of a Teflon cylinder and with three thin Cu threads mounted as rings on the sample (figure 4). The Cu rings will cast different ellipse shapes when the sample is placed at different positions relative to source and detector. These shapes change for different measured distance combinations that are used in the calibration procedure to estimate the distance biases $a$ and $b$. The estimation procedure to find $a$ and $b$ is outlined in Appendix A. The calibration procedure requires that the central ring is aligned with the central beam. The projection of this ring will thus appear as a line instead of an ellipse as shown to the left in figure (4).

3. Data processing

The goal of an imaging experiment is to describe and quantify the features present in the sample. This can only be done by means of computational methods and in this case methods are needed to allow reliable data fusion that benefits from the added information provided by a second modality. The processing and analysis of bi-modal imaging data requires a modified processing pipeline compared to single modal imaging. The important differences are that registration is needed to align the two data sets on a common coordinate system and that the analysis shall combine information from the data sets at some level of abstraction (Mitchell, 2010).
3.1. Reconstruction

The normal mode of operation of the bimodal setup at ICON is computed tomography. Therefore, the reconstruction of the projection data is one of the first processing steps. The neutron data is mostly reconstructed using parallel beam geometry, it can however be beneficial to use cone beam reconstruction when the sample is large or remotely placed from the detector (Kaestner et al., 2012). The X-ray data which is acquired with a large beam divergence has to be reconstructed using a method for cone beam geometry. In these initial experiments we have used the Feldkamp algorithm (Feldkamp et al., 1984) to reconstruct the data since the acquisition trajectory is the same as for parallel beam reconstruction. The results from this algorithm are on exact for the central slice and slices remotely from the center are prone to suffer from geometric distortions caused by an incomplete coverage of the Radon space. The impact of the incomplete Radon space can be reduced when the cone angle is decreased, i.e. by increasing SOD and SDD at maintained magnification. In the future we intend to implement helical acquisition, this provides data for exact reconstruction. Currently, the two data sets are reconstructed independently. Combined reconstruction techniques using structural priors from a second modality have been developed Kazantsev et al. (2014), but have not yet tested on data from the installation at ICON.

3.2. Registration

The two data sets acquired during a bi-modal experiment at ICON are not aligned. This is due to the fact that two detectors are used. They have different resolutions and the position relative to the sample also differs. A registration operation is needed to identify the required transform matrix and to transform the data sets. In our case the relevant degrees of freedom are: linear translation, rotation (mainly about the acquisition axis), scaling, and skew. This results in five or seven degrees of freedom depending on how many rotation axes are used. The registration algorithms perform better when initial guesses are provided, this helps to avoid being trapped in a local minimum of the parameter search.

Our experience has shown that local features in neutron and X-ray data are very different and that it is hard to find a good registration solution based on such features. Successful results have mostly been achieved with global optimization strategies supported by initial guesses provided by the calibration data.

3.3. Analysis

The analysis strategy of the bi-modal data very much depends on the purpose of the experiment and the information expected to be gained from the data. The analysis types can be divided in the three categories. **Bivariate estimation** – uses the mutual information to improve the quality when the intensity variations are quantified. **Bivariate classification** – aim at separating different intensity combinations into classes with higher precision than when single modalities are used. Estimation often needs support from segmentation to identify relevant regions in the images. This is the third category, **classification guided estimation**.
Segmentation is often more relevant for samples with distinct boundaries e.g. mechanical devices, while estimation is more suited for porous media samples with intensity gradients. An example of classification guided estimation is the study of root water uptake where the first step would be to identify regions representing container, soil, and roots. The root example is well suited for bivariate segmentation as can be seen in the bivariate histogram in figure (5). The neutron data would alone provide an acceptable preliminary segmentation by there would be a great amount of miss classified voxels, in particular near boundaries between different. This will be illustrated in the next section.

Further quantitative analyses can be done within the segmented regions. The task in the soil case would be to estimate the water content, either globally or relative to a structure like a root.

4. Experiment

We have chosen a soil sample with roots as an example for bimodal imaging. The sample is a polycarbonate cylinder (inner diameter 25 mm) filled with soil and the roots of a single lupine plant. In this case the soil moisture content was relatively low, therefore there is a good contrast between roots and soil in the neutron data, figure (6). The data was reconstructed using the cone beam reconstruction mode of Octopus (Inside Matters, 2016). Observing the histograms for each modality we see that there is a clear separation between void and sample. The separation between soil and roots is however less clear. With neutrons it would be possible to find a threshold that identifies most roots, but there is still a degree of uncertainty. This can be reduced when bivariate information is used as soil and container appear as two separate peaks. These peaks are identified by the X-rays thanks to the density difference between roots and container.

A simple method to segment bivariate data is to use the Euclidean distance from an intensity pair in the image to each of the classes present in the image. The class is selected as the one closest to the pixel intensity pair. This approach gives a decision space with linear separation between the classes as shown in the middle panel of fig. (6). Applying this approach to the image data results in the segmented image to the right in fig. (6). This image was produced using the information of single pixels only.

The resulting image shows several miss-classified pixels. There are several reasons for this 1) physical; beam hardening, scattering, too small difference in attenuation coefficients, 2) signal processing; Multi class segmentation of unsharp features, noise, too small sampling region, choice of classifier. A practical detail to consider for this particular sample is that the sample container has more or less the same attenuation coefficient as the roots. A change of container material from polycarbonate to aluminum would possibly make sense as it would provide a complementary contrast to roots and soil.

5. Conclusions

We have presented the bimodal instrumentation that is now installed at ICON, the cold neutron imaging beamline at Paul Scherrer Institut. The installation combines the cold neutrons with a cone beam X-ray beamline across the
neutron beam. The instrument hardware allows simultaneous bimodal acquisition without cross-talk. The calibration of the X-ray geometry is handled using a laser guided system that provides distances describing the positions between source, sample, and detector.

A remaining challenge is to develop methods to efficiently process and analyze multivariate image data. This is a complex task depending on the sample composition and how it interacts with the two beam types. Each beam type has its characteristic interaction related artifacts that have to be corrected to provide reliable data for bivariate analysis. Next steps will focus on preparing data to make unambiguous analysis possible. The routines for analyzing bimodal data will be refined and developed with the availability of relevant experimental data with related investigation objectives. Until now, we have used test samples from our stash of items to demonstrate what can be visualized using the beam combination.

The applications and the user community of the new is very versatile. An example from soil science has been presented in this paper. Other applications are on man made samples engineering objects (Kaestner et al., 2016) with different material combinations that provide incomplete information when only a single modality is used. The man made samples can also originate from the cultural heritage (Mannes et al., 2015) where combinations of organic and non-organic material can be found.

The added modality introduces new experiment conditions that will have an impact on experiment setup, sample containers, sample dimensions but also on the methods to evaluate the data. Therefore, we need to perform experiments on different sample types to explore the limitations and benefits of bimodal imaging. In this process we welcome the creativity of our users to find challenging experiments that benefit of the additional information offered by this new instrument feature.

Appendix A. Deriving the distance calibration

The distance sensors need to be calibrated to provide reliable distance readings. This calibration is done by using a calibration sample having three thin rings that are projected on the detector. Several projections are acquired during calibration. The distances for SOD \((A + a)\) in the figure) and ODD \((B + b)\) in the figure) are noted for each projection.

The basic geometry estimation relies on the assumption that the central ring is that is aligned with the central beam, i.e. it will appear as a thin line on the projection since the is no perspective view when the beam is perpendicular to the detector. The other two rings will be projected as ellipses. This information will be used to determine the magnification of the current distance combination. The front- and back-sides of the ring are magnified according to

\[
R_0 = \frac{p_0}{h} = \frac{A + a - r + B + b + r}{A + a - r} \tag{A.1}
\]
\[
R_1 = \frac{p_1}{h} = \frac{A + a + r + B + b - r}{A + a + r} \tag{A.2}
\]
where $p_0$ and $p_1$ are metric distances (not pixel distances), $h$ is the distance between the two rings and $r$ is the radius of the ring. Rearranging these equations in we can write the relation in matrix form as

$$
\begin{bmatrix}
(R_0 - 1) - 1 \\
(R_1 - 1) - 1
\end{bmatrix}
\begin{bmatrix}
a \\
b
\end{bmatrix}
= \begin{bmatrix}
A - R_0 (A - r) - B \\
A - R_1 (A + r) - B
\end{bmatrix}
$$

(A.3)

More projections would add more lines to the matrices and help to provide a more reliable estimate for $a$ and $b$.

$$
\begin{bmatrix}
(R_{1,0} - 1) - 1 \\
(R_{1,1} - 1) - 1 \\
\vdots \\
(R_{N,0} - 1) - 1 \\
(R_{N,1} - 1) - 1
\end{bmatrix}
\begin{bmatrix}
a \\
b
\end{bmatrix}
= \begin{bmatrix}
A_1 - R_{1,0} (A_1 - r) - B_1 \\
A_1 - R_{1,1} (A_1 + r) - B_1 \\
\vdots \\
A_N - R_{N,0} (A_N - r) - B_N \\
A_N - R_{N,1} (A_N + r) - B_N
\end{bmatrix}
$$

(A.4)

Solving this equation system will yield the least square estimates of $a$ and $b$ that can be used to adjust the readings from the laser distance sensors.

References


