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# Techniques in helical scanning, dynamic imaging and image segmentation for improved quantitative analysis with X-ray micro-CT

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ABSTRACT

This paper reports on recent advances at the micro-computed tomography facility at the Australian National University. Since 2000 this facility has been a significant centre for developments in imaging hardware and associated software for image reconstruction, image analysis and image-based modelling. In 2010 a new instrument was constructed that utilises theoretically-exact image reconstruction based on helical scanning trajectories, allowing higher cone angles and thus better utilisation of the available X-ray flux. We discuss the technical hurdles that needed to be overcome to allow imaging with cone angles in excess of 60°. We also present dynamic tomography algorithms that enable the changes between one moment and the next to be reconstructed from a sparse set of projections, allowing higher speed imaging of time-varying samples. Researchers at the facility have also created a sizeable distributed-memory image analysis toolkit with capabilities ranging from tomographic image reconstruction to 3D shape characterisation. We show results from image registration and present some of the new imaging and experimental techniques that it enables. Finally, we discuss the crucial question of image segmentation and evaluate some recently proposed techniques for automated segmentation.

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## 1. Introduction

The last decade has seen an explosion in the number and quality of micro-computed tomography (MCT) instruments installed at numerous location worldwide, capitalising on the availability of high-quality components for the generation and detection of X-rays, as well as the rise of GPU computing that allows full-scale image reconstruction on personal computers. MCT beamlines now exist at all major synchrotrons, including TOMCAT at the Swiss Light Source (SLS), ID19, ID22 and ID15 at the European Synchrotron Radiation Facility (ESRF) and 2-BM (XOR) and 13-BM (GSECARS) at The Advanced Photon Source (APS) in the US, to name but a few. These facilities offer 3D imaging resolution at a range of scales, from 100 nm to about 20 μm, with some form of X-ray optics required for resolution better than 500 nm. The most efficient beamlines can acquire datasets of $2000^3$ voxels at 2–5 micron resolution in less than one minute.

Laboratory facilities have seen similar advances, with commercial instruments from several vendors also offering resolutions approaching 100 nm and datasets of $2000^3$ voxels obtainable in several hours at resolutions from 2–50 μm. The MCT facility at the Australian National University (ANU) has been under constant development since first becoming operational in 2000 and has been used for research into many areas, most notably geology [1], petrophysics [2], tissue engineering [10], granular materials [3] and paleontology [17]. Three instruments are currently in operation: the first instrument using a 200 kV reflection-style X-ray source still functions although the original CCD detector has been replaced by a large area amorphous-silicon (a-Si) flat panel detector offering higher quality images, better radiation tolerance and a faster readout rate, while two new instruments have been constructed with transmission-type sources and a-Si detectors. The older system has a resolution of about 3 μm while the newer systems are about 1.5 μm. Since its inception the facility has aimed to derive quantitative results from the imaging program, an emphasis that has driven continual development in both hardware and software. In this paper we describe some recent advancements at the facility.

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## 2. Helical-scanning cone-beam tomography

One major constraint in laboratory MCT is beam flux. Laboratory sources generate X-rays from a micron-sized region in a target material, usually tungsten, onto which an electron beam is focussed. If the electron beam intensity is too high ($>\sim 2\ \mathrm{W}/\mu\mathrm{m}^2$) then the target material is vaporised. The maximum allowed X-ray flux is therefore proportional to the area of this region. Since the instrument resolution is proportional to this region's diameter, improving resolution by a factor of 2 causes a factor of 4 reduction in the maximum tolerated beam power. Other types of X-ray source have been proposed to overcome this limitation, but as of 2013 no alternative is sufficiently stable or suitably housed for use in our facility.

Because the X-rays are produced uniformly in all directions from the target, one can maximise the flux passing through the sample and captured at the detector by placing the sample closer to the source. This results in the detector capturing a larger solid angle of X-rays. Unfortunately, circular-scanning cone-beam tomography depends on approximations that are only valid at low cone angles, with the artifacts resulting from this approximation becoming unacceptable above a cone angle of $\sim 5°$. We have implemented theoretically-exact helical-scanning MCT [24], based on the Katsevich inversion formula [12] and believe that the ANU facility is the only high cone-angle MCT instrument. A number of technical obstacles have needed to be overcome while developing high cone-angle helical scanning, we describe these in the following text.

The first issue is that of thermal drift causing relative movement between source and sample. While all effort is made to avoid such movement, our experience has shown that some thermal drift is sufficiently common to be worth correcting. At lower cone-angles one only need be concerned with transverse movements, whereas at high cone-angles slight changes in the source-sample distance cause an appreciable change in magnification. Thermal drift effects are removed by extending the reference-scan drift correction method introduced by [22] to accommodate magnification changes [21].

The second issue is overall system alignment. This is more onerous for helical scanning for which there are two additional geometric alignment parameters as compared to circular scanning, making a total of 7. In particular, the source-sample distance must be known to several microns, in contrast with circular scanning where source-sample distance only affects voxel size. This parameter is very difficult to determine to sufficient accuracy experimentally since the source spot is several hundred microns behind the front face of the X-ray tube. To correct for any potential geometric misalignments, we use an iterative passive autofocus method [13,25] that finds the 7 helical geometry parameters as those which generate the sharpest tomogram. This technique is particularly effective since it finds the optimum value for the geometric parameters for the overall data acquisition, which may be slightly but significantly different to those measured prior to the imaging.

Another major issue is that of inhomogeneous magnification. At high cone angles, the side of the sample close to the X-ray source sees a much higher geometric magnification than the far side; a factor of 3 variation in magnification is typical. In 1-PI helical scanning, rays encompassing 180° are collected for each voxel, so that each part of the sample is in the radiographic field of view for about one half-turn of the helix (it is not exactly one half-turn due to the fan-angle). Some parts of the sample will be predominantly on the far side during this half turn and consequently see a relatively low magnification, while other parts see a relatively high magnification, resulting in a tomogram where some regions are sharper than others. This is a fundamental problem that has no straightforward solution; we have chosen to use a "double helix" scanning trajectory [25], which largely removes the inhomogeneity in resolution, at a cost of a doubling in the volume of acquired data and consequently a doubling of the reconstruction times.

A final problem that is more serious in high cone-angle imaging is that of secondary radiation, emanating from surfaces inside transmission-type X-ray sources. This problem was discussed extensively in [6]; for high cone-angle imaging the secondary radiation can only be reduced to acceptable levels through the placement of a pinhole collimator on the front of the X-ray tube.

Having resolved these issues the facility produces images of significantly higher quality that are captured in significantly shorter times. Nevertheless, for the bulk of the images acquired at the facility the highest practical image quality is desired, so that scan times of 10–20 h are typical. Fig. 1 shows an example of the data acquired using a helical scanning trajectory.

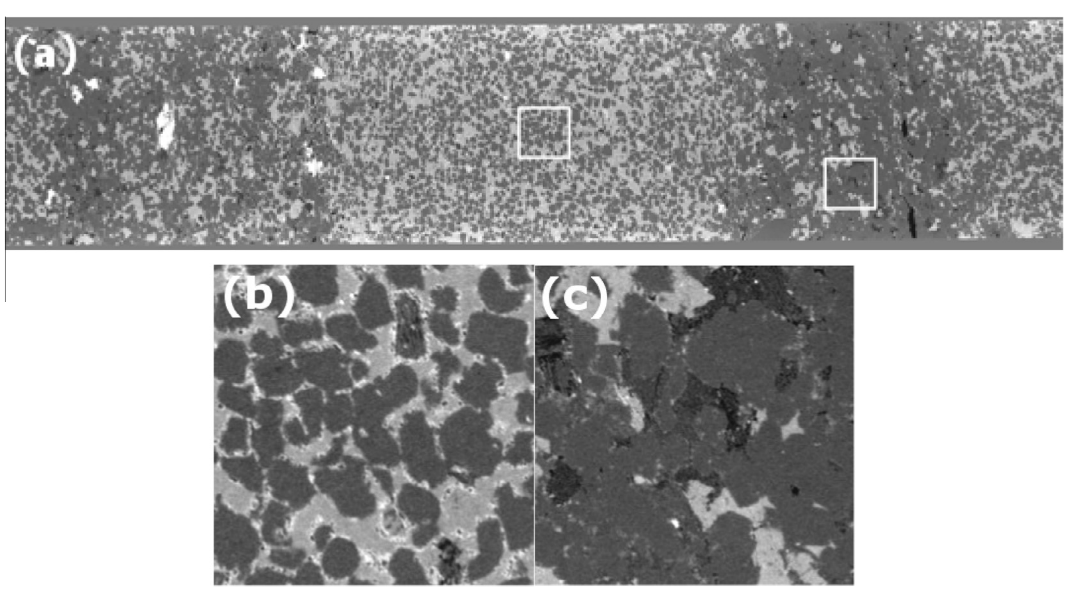


**Fig. 1.** (a) Slice through an image of a rock core 36 mm long and 8 mm in diameter, with 5.8 μm voxel size. The two white squares on the image show the regions zoomed in (b) and (c), which show a field of view of 1.75 × 1.75 mm. Acquisition of a dataset of the same field of view and quality by stacking circular tomograms would have taken nearly 10 times longer. From [24], used with permission.

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