High resolution computed tomography at the Ghent University: measuring, visualizing and analyzing the internal structure of objects with sub-micron precision

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Tomography is a non-destructive research technique which allows investigating the internal structure of objects in 3D . The "centre for X-ray tomography (UGCT)" of the Ghent University has developed a modular X-ray micro/nanoCT scanner which is used for multi-disciplinary research. In this paper we give an overview of the different components of the UGCT scanner with special attention to the X-ray imaging detectors. Also the software tools for data reconstruction and analysis and some obtained results are discussed.

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[1] Speaker

1. Introduction

Tomography is a non-destructive research technique which allows investigating the internal structure of objects in 3D using penetrating probes like ultrasonic sound, neutrons or X-rays. A well known example is the CAT scanner (Computed Axial Tomography) used in hospitals for medical diagnostics. X-ray CT is also used for other applications and the possibilities of microtomography, and recently also nanotomography, are opening a whole new world for researchers of many different disciplines. X-ray CT can be realized in different configurations depending on the X-ray source (e.g. an X-ray tube or a synchrotron beam line), the beam geometry (parallel, fan or cone) and the detector geometry and type (1 "pixel", 1D pixel row or a 2D pixel matrix). At UGCT (Centre for X-ray tomography of the Ghent University) we have developed a cone beam absorption tomography system with a micro and nano focus X-ray tube and a 2D flat panel detector.

2. About computer tomography (CT)

Figure 1 shows a picture of the absorption tomography scanner built at our university based on a micro- and nano-focus X-ray tube. The behaviour of the linear attenuation coefficient as a function of the position inside an object can be reconstructed in 3D by using a large number of 2D radiographic projection images of the object taken from different angles. The X-ray tube produces a conical X-ray beam emitted from a small focal spot. The object is positioned in the beam between the source and the detector with translation stages where the distances between the components determine the magnification of the image. It is rotated stepwise around a vertical axis by means of an accurate rotation stage, taking digital projection images at every step between 0° and 360°. These images are stored on the computer for later processing.

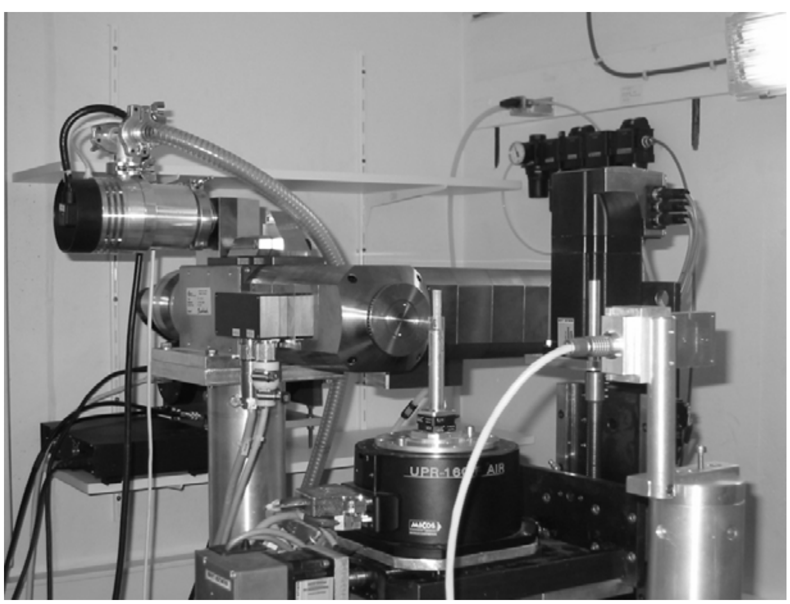

Figure 1: Picture of the nanoCT scanner at the Ghent University

3. Technical information about the scanner

The CT facility houses three different systems. The newest device is the high-resolution CT scanner. The other two systems are a medical CT scanner and microCT scanner. More detailed information about the systems can be found on the website of the facility (http://www.ugct.ugent.be). The main components of the new CT scanner are the X-ray tube, the sample manipulator and the X-ray detectors. On top of the rotation motor there is a micro-positioning system to facilitate the sample centering.

3.1 The X-ray tube

The X-ray tube is a state-of-the-art FXE-160.50 dual head open type source from Feinfocus. Open type means that one can open the tube to clean it or to replace filaments or targets. The dual head means that there are two tube heads, a high power directional head and a "nano-focus" transmission head. The system has one high voltage unit and one vacuum system to evacuate the air. The X-ray source is mounted on a rotating platform. The reason is that the X-rays are emitted in the forward direction for the transmission head and under 60° with respect to the tube axis for the directional head. When we change from one head to the other, we need to rotate the X-ray source by 60°. The specifications of both heads are listed in the table below.

Table 1: Properties of the X-ray tube heads

Property	**Directional Head**	**Transmission Head**
Voltage (kV)	20–160	20–160
Power (W)	Micro-focus: max. 10	Nano-focus: max. 1
	High power: max. 160	Micro-focus: max. 3
		High-power: max. 10
Feature recognition (µm)	2 (defined by manufacturer)	0.3 (defined by manufacturer)
Min. sample distance (mm)	4	0.2
Cone angle (°)	40	170

3.2 The X-ray imaging detectors

The modular design of the CT-scanner allows the use of different detectors which can be selected depending according to the samples to be scanned. There are many commercial detectors available which are optimized for a certain X-ray spectrum. In the case of the high resolution CT scanner we can choose between three energy ranges (low energy, medium energy and high energy). Furthermore we can choose between a large field of view (FOV) or high speed imaging.

- Low energy (<20 keV)

Biological samples and polymers are typically scanned at low kV settings to obtain high contrast projections. For these type of samples, we use a Photonic Science cooled CCD detector with a thin scintillator coupled to the sensor using an optical plate (taper ratio 1:1). The scintillator consists of 5 mg/cm^2 Gadolinium Oxysulphide. The size of the sensor is 36 mm×24 mm and it consists of 4008×2672 pixels of 9 µm×9 µm. The fiber optic connection between the scintillator and the CCD is not free from distortion. All images from the camera have to be remapped to correct the distortion. Due to limited computing power at the facility and the limited X-ray flux the camera is never used in full resolution for CT scanning but in binning mode. High resolution radiographic imaging can be performed in full resolution mode. As an alternative to the Photonic Science camera, we can also use a RadEyeHR CMOS flat panel with 1600×1200, 22 µm pixels and beryllium X-ray window for low energy distortion free imaging.

- Medium energy (20-100 keV)

Denser samples, like geological objects, are scanned with a remote Rad-eye EV detector from Rad-icon Imaging Corp. It is a CMOS sensor with 1024×512 pixels of 48 µm×48 µm. The scintillator is a Lanex Fine with a thickness of 34 mg/cm^2 which is replacable and is pressed onto a FOP (Fiber Optic Plate). The resolution is 48 µm (10 lp/mm). EV stands for extended voltage, which makes it possible to use the detector up to a tube voltage of 160 kV. The entrance window of the detector is 1 mm graphite. The dynamic range of the sensor is 4000:1, approximately 12 bit. The linearity is rather poor but correction methods do exist. Although the RadEye detector should allow us to work at 160 kV, it is not recommended. The dark current in the CMOS sensor increases quickly due to radiation damage. It is relatively easy to replace the sensor in case of damage.

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For most of the medium energy scans we are using the Varian PAXSCAN 2520, a a-Si TFT flat panel detector with columnar CsI:TI scintillator. This 14 bit detector has a fast read out and a very good linearity through its dynamic range. It has 2000 by 1600, 127 µm by 127 µm pixels. We notice a non-linear response of the detector to spectral variations which makes the normalization of the raw images often difficult. We believe this is due to the spectral hardening of the X-ray beam after traversing the objects. The average energy of the X-rays shifts from a value below the K-edge of CsI (around 35 keV) for open beam images to a value above the K-edge of CsI for absorption images. This effect is less strong in the case of Gadox (Gd2O2S:Tb) scintillators which have a K-edge at 50 keV.

- High energy (>100 keV)

For the high-energy applications, we are using an image intensifier coupled to Sensicam PCO camera. The dual field image intensifier was bought from Precise Optics and has a circular field of view of 6″ in low-resolution mode. The gain of the intensifier is fixed and it is important to optimize the ratio of the X-rays at the input to the electrons in the CCD camera. We use an optical filter in front of the CCD lens to reduce the visible light intensity. The distortion inside the intensifier is considerable. For CT scanning, the distortion has to be corrected by a grid image and a calibration algorithm. The radiation damage is negligible at 160 kV. Cupper beam hardening filters are placed in front of the detector to remove the low-energy X-rays. The pixel size is 136 µm in 6″ mode or low-resolution mode.

A second detector is a camera box. Inside the box, the Sensicam CCD camera is observing the light from a scintillator. Since not all X-rays are stopped inside the scintillator we are using a surface coated mirror to deflect the light over 90°. The optical lens is a NIKKOR 50 mm f/1.4 MF lens. If well shielded this type of detector can be used up to MeV energies or even for neutron imaging.

In the case of higher energies (>160 keV) it is recommended to use line detectors with a high efficiency for high energy X-rays. The second advantage of the line scanner is the possibility to use a collimator to transform the cone beam into a fan beam which in turn will filter out the scattered radiation from the sample and sample surroundings. The collimator is placed in front of the line detector. This type of detector is not available at the facility.

3.3 The sample manipulator

The sample manipulator is an XYZ-theta CT system. The linear spindle modules are using Berger-Lahr Intelligent Compact Drives (IcIA IFA). The controllers and amplifiers are integrated inside the stepper motor housing.

The rotation motor is an ultra precision rotation stage from MICOS (UPR-160F AIR). To reach sub-micron resolution CT scans, the rotation stage requires a low wobble (<2.5 µrad) and eccentricity (<0.1 µm) which can be guaranteed by high precision toroid air bearings. The load capacity is 5 kg. The air pressure is 4.5 bar and the air is filtered for oil, particles and humidity.

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For nanotomography, it is almost impossible to place the samples exactly on the rotation axis. To facilitate this process, we use a PI miniature XY piezo stage M-662.470. The step-resolution is 50 nm, the travel range 20 mm, the acceleration 20 g and the load capacity is 5 N or 500 g.

4. Software tools for CT reconstruction and analysis

During scanning of a sample usually over 800 projection images are taken which have to be converted from raw data to 3D volumes. After this reconstruction process one has a digital model of the sample. Analysis tools make it possible to perform 2D or 3D calculations to determine object parameters, e.g. porosity.

4.1 Reconstruction

For the reconstruction part we use the in-house developed software package, called Octopus (http://www.xraylab.com). Octopus is a scanner independent package for cone beam, fan beam, parallel beam and cone beam spiral CT. The reconstruction software is capable of reconstructing large data sets on a single PC or via distributed reconstruction on a computer cluster. After reconstruction we usually have hundreds of CT cross sections through the objects which yield information about the local X-ray attenuation coefficient and therefore about the morphology of the sample. More information about Octopus can be found in a paper by J. Vlassenbroeck [1].

4.2 3D Visualization software

For the volume visualization we use the two packages VGStudio MAX and 3D Volume Viewer. VGStudio MAX is a powerful voxel renderer from Volume Graphics® with a lot of functionality (http://www.volumegraphics.de). 3D Volume Viewer is an in-house development which allows one to create 3D images and animations of the reconstructed CT data. The multithreaded algorithms for volume rendering, iso-surface rendering, X-ray projection and maximum projection are written for 64bit and 32bit operating systems (more information can be found on the website http://www.xraylab.com). Figure 2 is an example of a 3D rendering of a seahorse with the in-house developed 3D Volume Viewer.

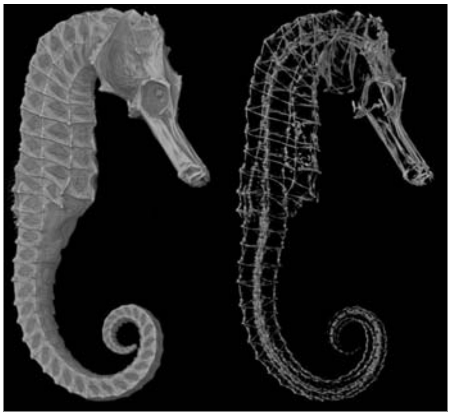

Figure 2: 3D rendering of a seahorse with 3D Volume Viewer.

4.3 3D Volume Analysis

3D analysis poses a lot of challenges. Some tools can be implemented as an extension of 2D counterparts, but others have to be approached differently. Adding an extra dimension also results in extra memory requirements and a clear need for high performance routines. Different packages for 3D analysis are already available. However, they often use external libraries, with limited control over the routines. Memory constraints are often present, and the approach is often aimed at a specific type of analysis. Since 3D analysis is a very complex discipline and the variety in the samples scanned at our facility is large, we decided to develop our toolkit Morpho+. We describe some of the integrated functions:

- **Determination of porosity and volume fraction:** The total porosity or volume fraction of a certain component has to be derived. Also, this parameter can be determined for sub-volumes and provide information about local variations. This can be done easily after an initial single or dual (or hysteresis) threshold and some possible cleaning operations to simplify the binary volume (opening, closing, hit-or-miss opening and closing, filling holes). More advanced threshold techniques can be introduced in the future.
- **Object identification:** Each object (a pore network, air bubble, grain, ...) inside a volume has to be identified as being a separate unit. This way, the problem of the analysis of a large volume is reduced to the analysis of a list of smaller objects. A connected-component labeling is used to obtain this. The combination of the threshold operation and the object identification is often called segmentation.
- **Object parameterization:** Each object can be characterized by deriving a set of size parameters, shape parameters, information about orientation, ... Some size parameters can already be derived using Morpho+ (maximum opening using an euclidian distance transform and equivalent diameter), the other parameters are in development.
- **Object separation:** Some objects (pore network, ...) have to be separated into a set of sub-objects. Their individual parameters combined with the information about their interconnectivity can be used to characterize the object better. Sometimes, this separation is also necessary for disconnected objects which appear connected due to the limited resolution/contrast of a CT scan. This separation can be done by computing the watershed transform of the inverse distance transform, after some filtering to avoid erroneous separations. We are working on a method to use the medial axis as an additional tool, which can also help in structure and shape analysis.

5. Examples of high resolution CT scanning at the UGCT facility

Below one can see two results of nanoCT scans. Figure 3 shows a single reconstructed slice through a wood sample. The measurement was done with the Photonic Science detector in binning 8 mode (Full Frame = no binning, binning 8 is grouping 8 by 8 pixels into super pixels). Figure 4 shows a 3D rendering of a Foraminifer. The object was scanned with the Varian PAXSCAN 2520 detector. Both samples were scanned with the nanofocus tube head at 50 kV. More examples can be found on the UGCT website (http://www.ugct.ugent.be).

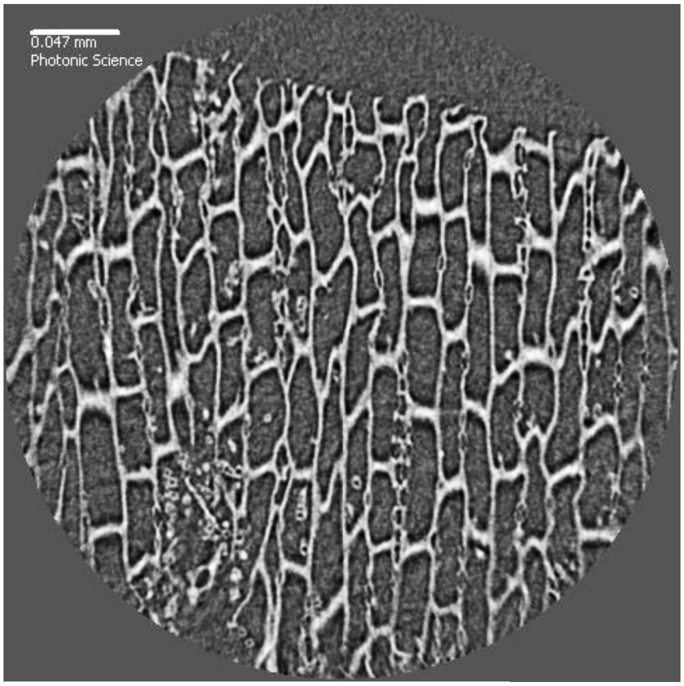

Figure 3: Single nanoCT slice through a wood sample.

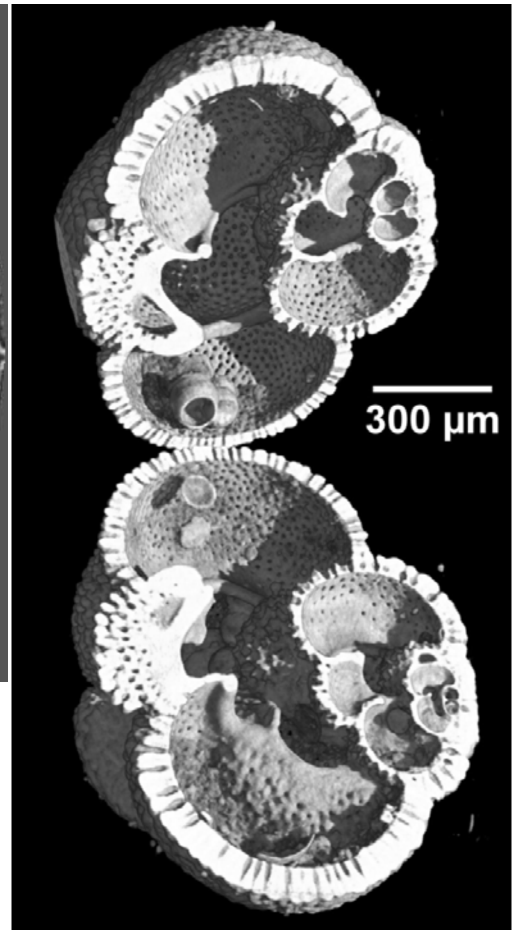

Figure 4: 3D rendering of a nanoCT scan of a foraminifer.

Acknowledgements

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References

[1] J. Vlassenbroeck, M. Dierick, B. Masschaele, V. Cnudde, L. Van Hoorebeke, P. Jacobs, *Software tools for quantification of X-ray microtomography at the UGCT*, Nuclear Instruments and Methods in Physics Research A 580 (2007) 442–445F.