A Flexible and Modular X-ray Micro and Sub-micron CT Scanner for Multi-resolution and Interdisciplinary Research

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ABSTRACT

Several types of CT systems are commercially available, but they are typically focusing on one specific range of samples and are therefore limited in terms of resolution or sample size. They come in closed cabinets and have pre-defined acquisition routines. These restrictions are often limiting the experimental freedom necessary to apply X-ray tomography to its full extent as required when the technique is used in a very wide range of applications and imaging resolutions. UGCT has designed and built a modular micro/sub-micron CT scanner with maximal flexibility destined for multi-resolution imaging of samples from many research disciplines. Its dual source / dual detector design with eight motorized axes and in-house developed acquisition software offers the possibility to optimize acquisition depending on the type and size of sample under investigation.

1. INTRODUCTION

In laboratory based high resolution CT systems, achievable resolution and field of view depend on the installed X-ray source and X-ray detector. The resolution is determined by the pixel size of the detector, the size of the spot where the X-rays are generated and the magnification of the sample. A general formula for the resolution (R) as a function of detector pixel size(d), magnification (M) and spot size(s) is:

$$R = d/M + s\,(1-(1/M)) \quad (1)$$

The magnification (M) is given by the ratio of the distance between the detector and the spot (Source Detector Distance, SDD) and the distance from to sample to the X-ray spot (Source Object Distance, SOD).

A first possible approach to achieve high resolutions is to use an X-ray detector with small pixels (d). Most of the current X-ray detectors rely on a scintillator to convert X-ray photons into visible light photons. During this interaction, light is emitted in all directions and therefore an increasing thickness of the scintillator layer will cause less sharp images on the sensor. Matching scintillator thickness and pixel size is very important. The disadvantage of a thin scintillator is its low conversion efficiency, especially for higher energy X-ray photons. This method is often used at synchrotron facilities to achieve high resolution with a parallel beam.
The second option to achieve high resolutions is to use an X-ray source with a small spot (s) and geometrical magnification. This allows using a detector with much larger pixels and thus scintillator. While, in this configuration, the efficiency of the detector is much better, the efficiency of the X-ray source is the limiting factor. The maximal beam power deposition in the X-ray source target is

approximately linearly dependant on the radius of the spot. Also, a high magnification (M) has to be achieved to get the desired resolution.

For large samples, a large detector is required to be able to scan the object at once. For small samples, either a detector with small pixels can be used or a larger detector in combination with an X-ray source with a small spot. If the small sample is highly attenuating, the large detector will be recommended as it is more sensitive for higher energy X-ray photons, while if the small sample is very low in attenuation, a thin scintillator is recommended. For very small samples that need to be scanned with a resolution close to or better than 1 µm additional problems occur both on the level of small pixel detectors and X-ray sources with a very small spot.

The presented setup has been designed with a combination of detectors and X-ray sources to be able to scan a wide range of samples in optimal conditions and to offer sufficient flexibility on hard- and software level for specific experiments and addition of peripheral equipment.

2. MATERIAL AND METHODS

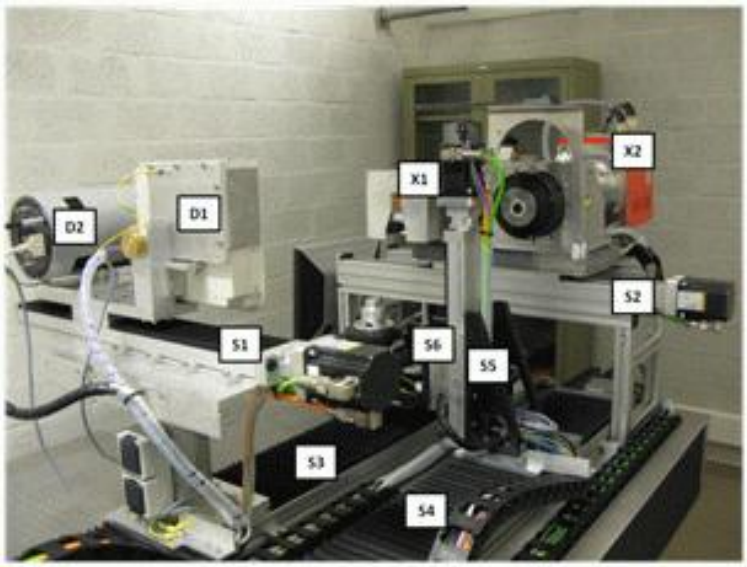

Figure 1: *Picture of the setup and its components (letter+number)*

2.1. Sources and detectors

The first X-ray source(X1) consists of a closed tube with a directional target that allows a spot down to 5µm, a high voltage generator up to 130kV and a maximal power of 35W. This source can be used in combination with two detectors that are placed on a translation stage(S1) for easy change and also for tiling, to increase the maximal field of view. For large objects, the detector(D1) with a size of 25X20 cm and a pixel pitch of 127µm can be used. for objects larger than 20 cm, the detector can be tiled to achieve a field of view of 50x20cm² or 40x25cm². This combination is suited for most of the samples with a resolution down to 5µm. At a resolution around 5-20 µm, some samples have very low attenuation (mostly organic material such as plants) and a detector with a thin scintillator is recommended. For these samples, the second detector(D2) can be used which has a size of approximately 3x2.5cm² and a pixel size of 7.4µm.

The second X-ray source (X2), which can be interchanged with the first using a second motorized stage (S2), consists of a transmission target, a high voltage generator up to 100kV and a maximal power of 3W. This source has two advantages over the first, the first advantage is the very small spot of 400nm resolution that can be achieved, secondly a transmission target has a very small focal object distance (FOD) that allows samples to be placed very close to the focal spot and thus achieve a high magnification. This source can be used with the second detector(D2) as small samples typically have a low attenuation or with the large detector(D1) if the sample has a high attenuation.

2.2. Motorized stages

Apart from the two stages for positioning the detectors and the sources, the system has 6 more axes to optimize the efficiency and flexibility for different samples. The third stage (S3) is a magnification stage to change the position of a sample with respect to the source and detector. The fourth stage (S4) can be used to change the distance of the detector to the source. This change can be used to increase the number of X-ray photons that are collected in one pixel of the detector. Being able to change the SDD is not only of importance for the beam intensity but it also affects the cone beam artifacts in the reconstruction and the level of phase signal when phase contrast is occurring. The system is also equipped with a vertical stage (S5) with a travel of 20 cm. The primary function of this stage is to offer an easy way to adjust the sample position but the stage has also been optimized and installed in such a way that high resolution helical scans are possible. The accuracy of the rotation stage (S6) is crucial for sub-micron-CT. Ball-bearings have the disadvantage to cause unwanted and often unpredictable movements of the sample during rotation. For this reason, a high precision air-bearing stage is used to perform correct acquisitions. On top of the rotation stage, two micro-positioning stages (S7, S8) are mounted in an X-Y configuration. This combined stage is used to perfectly align even the smallest samples in the centre of the rotation axis to be able to achieve the highest magnification.

Finally, the overall stability of the system in terms of thermal and mechanical effects is optimized by a combination of acclimatization, thermal buffers and a vibration damping table. This entire setup is placed in a bunker to shield the radiation. The large room where the system is accommodated is suited for the addition of peripheral equipment, often necessary for experiments where climate control or environmental conditions such as pressure and stress are applied to the sample during the scan.

2.3. Software

The entire setup is controlled by an in-house developed acquisition software package (Dierick 2010). It consists of a GUI (Graphical user Interface) and a library of components where other components can be plugged in.

3. RESULTS AND DISCUSSION

3.1. Large objects

Objects that are larger than 20 cm do not fit in the field of view of D1. In order to be able to scan such objects, for example a corrosion cast of a human liver with a diameter of 35 cm (fig.2A), the field of view of the detector is virtually doubled in the width by tiling using the translation stage (S1). A script based routine is generated by the software that automatically acquires the necessary projection images of the detector in both positions.

3.2. Multi-resolution

Many samples that are analyzed with micro-CT have different features on various levels of resolution. It is often more sensible to take subsets of the large structure and scan it at a better resolution than to try to resolve all features in one scan of the entire sample. This does not only limit scan times and dataset size but it also offers the possibility to perform each scan with its optimal settings. This is illustrated with a multi-resolution approach on a corrosion cast of a mouse kidney (fig.2B) which has blood vessels with a diameter between 1 mm and 10 µm. The entire kidney cast was first scanned at a resolution of 7.5 µm in approx. 1 hour using D1 and X1. The tube power (10W) was adjusted to the resolution of the scan and using D1 is better than D2 as the cast is doped with lead, causing relatively high attenuation, especially for the larger blood vessels. In this scan it is possible to visualise the morphology of the larger vessels, smaller vessels are visible but it is not possible to discern the smallest vessel nor to perform measurements on the medium sized vessels. A second scan was performed on a 1mm section of the cast using lower power and thus better resolution of the X-ray source (X1) and slightly longer exposure times. In order to obtain the same resolution and quality of scan for the entire cast, a scan of at least 20h would have been necessary. In this scan the medium sized vessels can be measured and the smallest renal structures are visible. A second sectioning was performed on the 1mm sample of the cast to retrieve one single glomerulus, the smallest capillary structure in a kidney. This sample was scanned at a resolution of 0.5µm in approx. 1 hour using D2 and X2. The D2 detector is more sensitive than D1 to the lower energy photons which is important as this very small sample has low attenuation. D2 also offers a better signal to noise ratio when very low power is used as the sensor of the detector is deep cooled. In this

scan even the very small capillaries can be measured. By applying this multi-resolution approach, good quality scans of each type of vessels are obtained which is necessary for detailed study of the total renal morphology.

3.3. Helical-CT

The typical acquisition routine for cone beam-CT consists of rotating the sample over approximately 360° while acquiring projection images. This method has a major drawback as the acquired data is mathematically only sufficiently sampled in the central region, resulting in cone artifacts in the upper and lower regions of the sample (fig.2C1). By using helical acquisition, consisting of an additional vertical movement during the rotation, adequate sampling is obtained for the entire sample. This method eliminates cone artifacts and also has the advantage that long objects can scanned at once without the need of incorrect and cumbersome stitching of the reconstructed volumes.

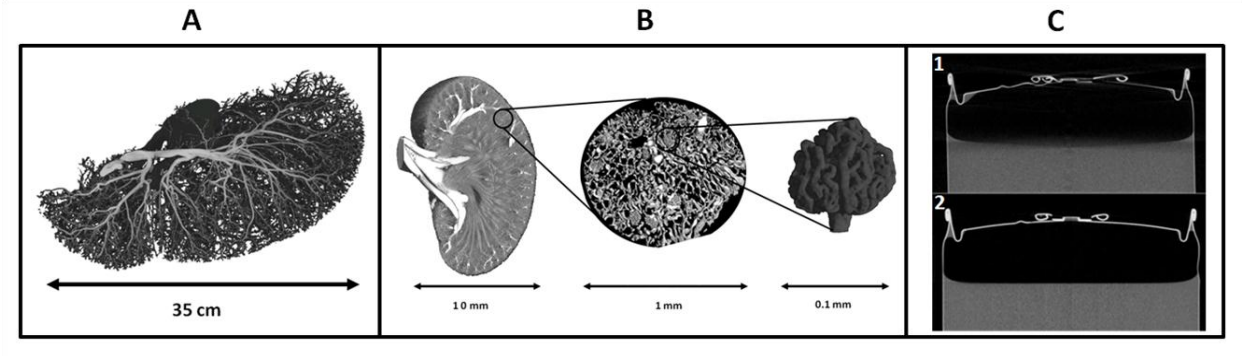

Figure 2: *3D rendering of the corrosion cast of the human liver (panel A), several renderings of the corrosion cast of the mouse kidney (panel B) and a comparison of cone-artefacts on a soda can (panel C)*

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5. REFERENCES

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