APPLICATION SPECIFIC COMPUTED TOMOGRAPHY SYSTEMS FOR CORE ANALYSIS

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ABSTRACT

Fraunhofer Development Center X-ray Technology EZRT develops procedures and systems for non-destructive testing, covering the whole range of industrial X-ray imaging from beam generation across material interaction, simulation, X-ray detection, image processing and automatic evaluation. Special focus is put on quantitative evaluation, differentiation and visualization of material and density distributions, surface extraction of complex parts for dimensional measurement and material characterization.

In this contribution we present two application specific X-ray computed tomography (CT) systems we designed according to customer needs: a micro-CT system for the automated analysis of ice cores and a gantry-CT system for time-resolved monitoring in process engineering.

The ice core CT-scanner developed for the Alfred-Wegener-Institute for Polar Research is able to scan cores with a length of 1 m and with a diameter of 10 cm with a high spatial resolution (12,5 µm voxel size) using helical CT, enabled by a specially developed X-ray detector with a large active area and high resolution (8000 x 4000, 32Mpixels). Using a multi-resolution region-of-interest method it is possible to scan the center of the core with a resolution of down to 3.5 µm voxel size. Analyses include porosity, pore sizes and their distribution.

The gantry-CT system developed for the Department of Chemical and Biological Engineering of the University of Erlangen (Germany) is designed for the observation of viscous liquid solutions transiting each other or flowing through upright standing cylindrical pillars with internal structures. This allows surveying the process of liquid propagation within each other or within the internal structure. The size of these columns can range from 50 to 300 mm in diameter and up to 1000 mm in length. One single slice can be scanned and reconstructed in 1 second at a spatial resolution below 100 µm. This

online reconstruction allows the observation of the dynamic process by the user in near real time and also enables one to react to different states of the experiment in time. After the acquisition, deep analysis of any region of interest is possible by reconstruction of the automatically stored high-resolution projections.

The setup of these CT-systems, implemented methods for data acquisition and analysis and results will be presented.

COMPUTED TOMOGRAPHY

X-ray computed tomography (CT) is a well-known and mature technique to obtain cross sectional images and has been used in medical imaging since the 1970s. Over the last years, it has become common in technical and industrial applications like non-destructive testing and material characterisation as well, both for high speed as well as high resolution [1]. It has been used in petroleum engineering research for several years [2], but advances in both spatial and temporal resolution allow new kinds of applications.

Figure 1 shows the typical setup of an industrial CT system. X-ray projection images are acquired from different angles as the object rotates. From these projection images, cross sectional images of the object can be reconstructed. For elongated objects, the scanning process can be combined with a vertical travel to generate a helical scanning path [3].

The resolution that can be reached generally increases with smaller object diameters and can be better than 1 µm for small objects of approx. 2 mm diameter [4].

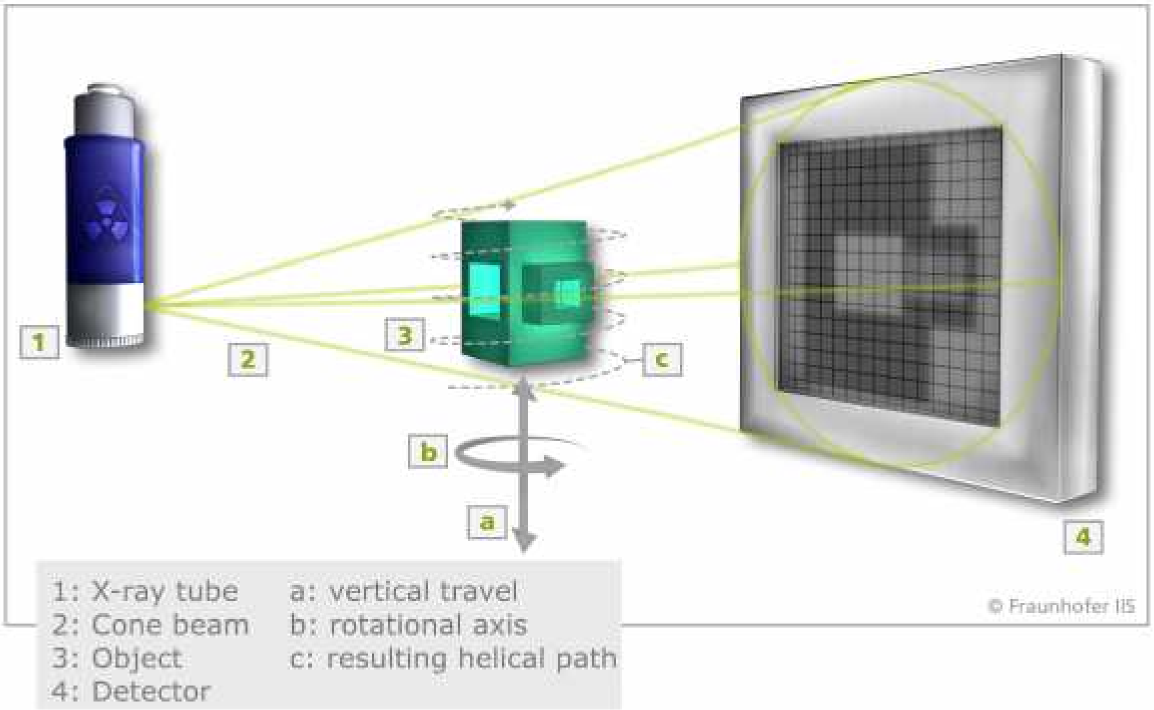

Figure 1: Setup of a typical industrial X-ray computed tomography system

ICE CORE SCANNER

The computed tomography (CT) system allows analysing ice cores, to determine the porosity of the ice and to correlate those results to the climate of the respective range of time [5]. For this purpose, drill cores of 3000 m length are drilled from the Antarctic or Greenland. The ice cores to be scanned have a length of 1 m and a diameter of 10 cm. Since high image quality is required to get precise results, a vast amount of measurement data will arise. Geometric challenges raise the requirements on X-Ray components and furthermore measurements will be made in an environment of -15 °C.

The Fraunhofer IIS XEye radiation imaging detector with 8000 x 4000 pixels and 50 µm effective pixel size was used. Due to the large active area (400 mm x 200 mm, no horizontal displacement is necessary to cover the ice core in its full diameter) in low magnification. The detector's image lag is extremely small (< 0.1%) and an external trigger mode is available. Both circumstances cause a noticeable reduction of scan time. Additionally an accurate manipulation system with a vertical wobble of only 0.8 µm on 1 m traverse path allows a high-precision alignment of the system.

In order to cover the object in its full length, the core will be inspected with a Helical-CT. In contrast to conventional computed tomography, the Helical-CT uses a vertical feed of the object axis with a simultaneous rotation. Thereby, Feldkamp artefacts that are caused by transversal penetration of the object near the outer borders of the X-ray cone beam are reduced. The focal spot and the vertical center row of the X-ray detector span the central plane of the CT system. Only those parts of the object that are penetrated by the X-ray beam parallel to the central plane can be reconstructed without Feldkamp-artefacts. Since standard 3D-CT systems work with cone beam geometry, this part only consists of the intersection of the object with the central plane itself. A vertical feed of the object with a simultaneous rotation ensures artefact reduced information about more than only one slice of the object. Depending on the mechanical limits of the used manipulator, objects of arbitrary height can be scanned. In this case the vertical feed is used to measure the ice core over its full length.

For an analysis of the porous ice in an adequate precision, a reconstruction of the complete volume in a high spatial resolution (12.5 µm voxel size) is essential. Conventional acquisition techniques result in scan times up to several days for a full resolution scan of a 1 m core. Optimized so-called "Fly-By" procedures reduce the scan times dramatically. Instead of acquiring one projection after the other at discrete axes positions, the linear and rotational stages are moved simultaneously at a defined speed while images are being acquired continuously. Due to a high sensitivity of the detector a short exposure time per frame can be used such that hardly any movement artifacts occur. With this technique data for the reconstruction of a full-size core with a voxel size down to 50 µm can be acquired within less than two hours without any loss of information.

For higher resolved image information, the inner parts of the core are scanned and reconstructed with a voxel size down to 3.5 µm. Smaller regions of special interest can hence be analysed with an increased spatial resolution without having to destroy the core by preparing smaller samples.

As mentioned before, the drill cores have a total length of 3000 m. The cores from the upper 100 m consist of firn which is characterized by a high porosity (~30%) and completely connected pores (see Figure 2). In the other, deeper lying regions, enough pressure has been applied during the last millennia, such that the pores are not connected anymore, but clearly separable. A 3-D visualization of a typical porous ice can be seen in
Figure 3. The mean porosity decreases with increasing drill depth.

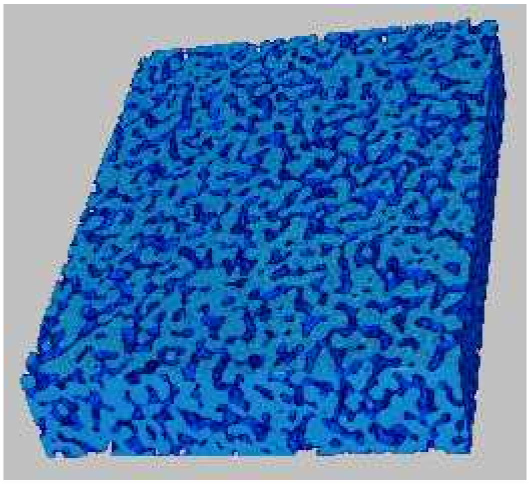

Figure 2: 3D visualisation of firn with open pores from 35 m depth, 56 µm voxel size

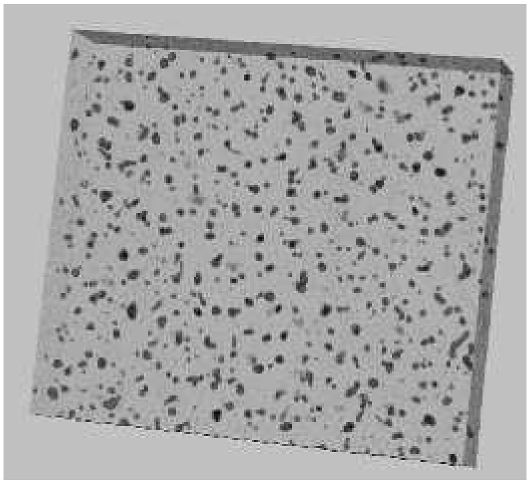

Figure 3: 3D visualisation of porous ice from 159 m depth, 16 µm voxel size

GANTRY-CT SCANNER

The developed gantry-CT system is designed for observation of viscous liquid solutions flowing through upright standing cylindrical pillars filled with pellets consisting of different materials or other liquids [6]. The task is to analyse the spread and behaviour of the liquid film while it makes its way through the material with a temporal resolution of 1 second. Depending on the attenuation properties of the involved materials, a low contrast in the reconstructed images may complicate the interpretation. The size of the columns can range from 50 to 300 mm in diameter and up to 1000 mm in length. To be able to observe and record this dynamic process near real time, high requirements are set especially to the speed of data acquisition and the transfer of image data. It was achieved doing the full scan of one single slice within 1 second at a spatial resolution well below 100 µm.

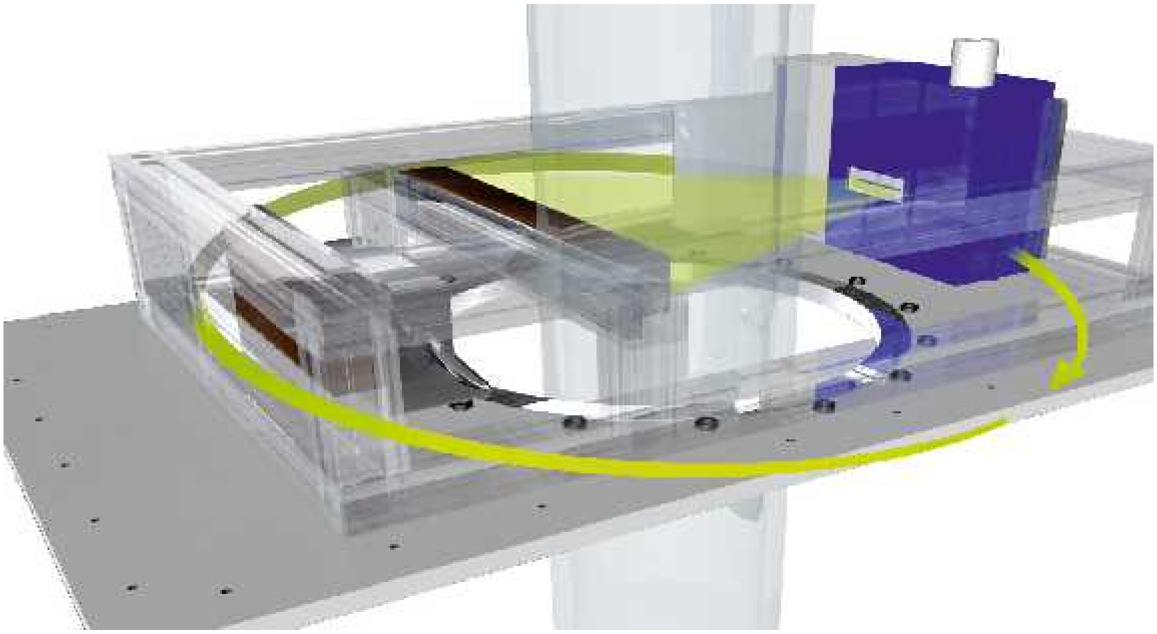

Figure 4: Drawing of the gantry CT system

For tasks like the inspection of diffusion in liquid solutions, a high time-resolution CT system was designed. Unlike the ice core system this system is not designed to acquire volumetric data, but a fast sequence of reconstructed slices, still containing depth information. To do so, a line detector is used rather than a flatpanel detector. The advantage of using a line detector is a higher frame rate due to fast image readout and a usually scalable length which allows for larger scannable cross sections. Additionally the image quality is expected to be generally better due to a smaller influence of scattered radiation or Feldkamp artifacts.

As the scanned structures are partially or fully liquid and the columns are stationarily mounted, the specimen itself cannot be moved as usual in the industrial application of CT systems. Therefore the X-ray line detector and X-ray source have to be installed on a rotational gantry as known from medical systems. A 3-D drawing of the gantry CT system can be seen in Figure 4.

For the specific analysis of the faster dynamic processes a user interaction is required. To enable a wide range of different experiments and allow the screening of varying aspects of the specimen, a live view of the reconstructed slices was implemented, such that the user can react on the process, e.g. manipulate the system with respect to the scan height. On the other hand a high spatial resolution with a voxel size below 100 µm is required to gain maximum information out of the scans. A binned data set is hence reconstructed for a fast live view. The data are stored in full resolution, however, such that the full-resolution reconstruction is performed after the scan has finished. A specific analysis of the reconstructed slices with high temporal resolution can be performed on the full-resolution data set.

CONCLUSION

Two highly application specific CT systems were presented. The ice core scanner can comply with different requirements of the application. It allows a relatively fast scan of a complete core of 100 mm diameter and 1 m length or a very high resolution to analyze even small pores. On the other hand, the gantry CT scanner was optimized for very fast data acquisition to obtain a full cross sectional slice in less than 1 second which allows the monitoring of dynamic processes and therefor the examination of time resolved experiments.
It was possible to solve very specific problems that would not have been feasible with commercially available, standard systems.

REFERENCES

[1] Zabler, S., C. Fella, A. Dietrich, F. Nachtrab, M. Salamon, V. Voland, N. Uhlmann, “High-resolution and high-speed CT in industry and research”, *SPIE Optical Engineering+ Applications*, International Society for Optics and Photonics, (2012) 850617-850617-11.

[2] Akin, S., and A. R. Kovscek. "Computed tomography in petroleum engineering research." *Geological Society, London, Special Publications* 215.1 (2003): 23-38.

[3] Scholz, O., S. Oeckl,, T. Schön, S. Kasperl. “Helical 3D Computed Tomography as an Advanced Inline NDT Method”, *SAE International Journal of Materials & Manufacturing*, (2010) *3*(1), 592-596.

[4] Salamon, M., R. Hanke, P. Krüger, N. Uhlmann, V. Voland, “Realization of a computed tomography setup to achieve resolutions below 1µm”, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, (2008) *591*(1), 50-53.

[5] V. Voland, J. Freitag, N. Uhlmann, R. Hanke, “A CT System for the Analysis of Prehistoric Ice cores”, *Microelectronic Systems*, Springer Berlin Heidelberg, (2011), 265-276.

[6] Reisinger, S., T. Wörlein, A. Ennen, M. Schmitt, S. Hebele, T. Schlechter, V. Voland, “Monitoring of Time-resolved Processes in Industrial Computed Tomography”, *Proceedings of the 1st International Conference on Tomography of Materials and Structures*, (2013), 55-58.