Abstract

This paper describes the design and development of a high-precision microfocus X-ray inspection system for ultra-high resolution 3-D computed tomography (CT) and 2-D real-time radiography for a wide range of industries.

3-D CT involves not only acquiring a set of high-resolution 2-D X-ray images, but also demands a comparably high accuracy in the positional alignment of these images when reconstructing the 3-D volume. Although many systems allow the capture of very high resolution 2-D images, the accuracy of any 3-D CT data falls short due to inaccuracies in the relative known positions of source and manipulator.

The use of high-brightness, high-resolution X-ray sources (up to 385kV, some using LaB₆ cathodes) is covered in detail, together with a description of a range of high-resolution detectors optimised for various X-ray energy ranges.

Particular attention is paid to the dimensional stability of the system and the accuracy of the sample manipulator, so that the high resolution information present in the radiographic images is not compromised in the reconstruction of the CT volume. For small samples, volumes with resolution down to 5 microns can be obtained with this system, whereas the volume resolution for larger samples is down to 0.1% or 0.03% of the object size, depending on the detector option chosen.

The paper will also outline the trade-offs between resolution, sample size, penetration and the speed of both acquisition and reconstruction. A number of real examples will be discussed to illustrate the wide range of applications.
Introduction

Multi-purpose microfocus X-ray inspection systems are capable of two dimensional (2D) X-ray imaging with a spatial resolution of down to 5µm. With the addition of computed tomography (CT) software these multi-purpose systems can be used to collect and reconstruct three dimensional (3D) models of samples with resolutions (volume element sizes) down to around 25 x 25 x 25µm.

To achieve a resolution of 5µm in 3D CT data, several aspects of these systems need to be improved. The methods by which this is done are is described in this paper.

First the resolution in individual radiographs needs to be increased. This is the 2D resolution of the system. Then the manipulation of the sample needs to be improved so that better registration of these images can be performed. Lastly, system parameters need to be calibrated, so that the software can use them to further improve image registration, and hence improve the 3D resolution of the system.

Higher resolution detectors with more, smaller, pixels digitised to a higher bit depth, require a higher X-ray flux, if image capture times are to be kept reasonable. A smaller higher-brilliance X-ray source allows shorter exposure times whilst maintaining X-ray throughput.

Obtaining brighter, higher resolution radiographs.

The 2D spatial resolution is limited by the X-ray source size when the unsharpness due to the finite source size is greater than the detector pixel size. This is true at high magnification, when the sample is close to the source. Therefore, at high magnification, smaller, more intense X-ray sources are required to improve the spatial resolution of a system.

There are two main problems to overcome. The production of a small, high-brilliance electron beam and the thermal management of the target under electron beam bombardment.

Smaller, high-brilliance electron beams

Assuming good electron optics, the size of the electron beam waist at the target is governed by its initial divergence at the cathode. Initial electron beam divergence is determined by the work function of the cathode material\(^{[1]}\). Decreasing the cathode work function reduces the average energy of the emitted electrons and reduces the spread in the initial energies. This produces a more uniform and laminar electron beam entering the electron lens and a more brilliant electron beam at the target.

This reduction in work function can be achieved by moving from the usual tungsten filament (work function 4.7eV, operating temperature 2300-2500K) to a Lanthanum Hexaboride (LaB\(_6\)) cathode (work function 2.66eV, operating temperature 1600 -
1900K). These cathodes are mechanically and chemically stable, have more ideal shapes and relatively long lives. However, they are more expensive, need lower partial pressures of oxidising gases (below $10^{-7}$ mbar) and require precise alignment within the electron optical system.

**Thermal management of target**

The maximum power density that can be applied to a target material increases as the focal spot size decreases [2] [3]. For a focal spot of the order of 2-10µm the electron beam brilliance from a tungsten filament is sufficient to produce localised melting of most common target materials [4]. For focal spot sizes below 1.5µm this is not the case and the emitter limits the emission. With a lower work function emitter, focal spots below 1.5µm can melt the target material.

To increase the maximum power density that can be applied to the target, a high speed rotating target can be used. This spreads the power over a greater surface area of target material whilst keeping the spot stationary in space. With a 40 x 40µm source, a target rotation speed of 7000 rpm (surface speed 36ms$^{-1}$), and continuous cooling applied, loadability increases approximately 10 times (e.g., 1500W continuously rated at 35kV).

**Fundamental Limitations**

The X-ray source size is limited by the brilliance of the electron beam, the maximum power density that can be applied to a target (stationary or rotating) and the finite size of the interaction zone within the target for high-energy electrons.

Statistical modelling illustrates the spherical nature of this zone for a tungsten (W) target with an electron beam incident at an oblique angle [5]. Therefore, the energy of the electron beam and the thickness of the target will also influence the achievable spot size.

![Figure 1](image.png)

*Figure 1. A diagram showing the interaction of an electron beam of a single stage X-Tek microfocus X-ray source with a tungsten (W) target.*
For very high voltages (from 230 - 285keV) the interaction zone is larger, however, a 20 x 40µm source at 385keV can still be achieved.

**Optimisation of microfocus X-ray systems for CT**

*Sample manipulation*

In 2D radiography the repeatability in the positioning of the sample is generally not a priority. However, when positional registration between high-resolution X-ray images is required, as in CT reconstruction of small samples (<500µm), the sample manipulation becomes as important as the source size.

For ultra-high resolution CT (voxel sizes below 5x5x5µm) the rotation must be about a single precisely known fixed axis (within 5µm). If this is not the case the precession, eccentricity of rotation and linear slide backlash prevent accurate registration when the data is backprojected through the reconstructed volume. This gives rise to artefacts within the reconstructed volume, as illustrated in Figure 2.

![Figure 2. Left & centre: CT slices from two different quality sample manipulators taken during the X-Tek CT development project. Sample: 198 µm diameter drilled suture needle. Right: Precession “petals” visible around 5µm voxel reconstruction of 2mm diameter rod.](image)

Therefore a turntable with low precession and eccentricity of rotation must be used. In addition, the accuracy of the linear stages that translate this turntable, both perpendicular and, to a lesser degree, parallel to the X-ray beam, must match the resolution provided by the X-ray spot size.

Similar effects will be generated if thermal expansion becomes significant. If, for example, the manipulator arm expands at a different rate to the source or detector supports, then any temperature fluctuations in the cabinet over the period of the inspection will cause the image of the object to move sideways on the detector, and therefore degrade the 3D resolution of the system. Because the commonly used materials steel and aluminium have coefficients of expansion of around 16µm and 27µm per metre per degree Celsius respectively[^6][^7], a change of only a few degrees Celsius can alter the relative position of the source and sample by several microns. Careful choice of materials and a temperature-compensating design can reduce these effects.
by making sure that all parts of the system expand at the same rate. Thermal expansion along the source to detector axis can be shown to be of an order of magnitude less of an effect than expansion across the X-ray beam, and is therefore not so important. Careful control of temperature within the cabinet can reduce such effects, but since the X-ray source is acting as a heat source itself, such changes in temperature can be difficult to eliminate entirely.

For larger samples (>10mm) the geometric magnification of the image is necessarily reduced and so the resolution of the CT data is often limited by the detector pixel size. In these cases, the manipulator accuracy may be reduced and a larger X-ray source size tolerated.

Figure 3. View of cabinet from imager showing three steel mounting brackets of equal length for source, sample manipulator and imaging system.

Detectors

High specification detectors have very small pixel sizes, but for microfocus CT inspection all of the object must be in view at all rotation angles and the signal to noise ratio in the image must be maintained. Therefore, it is the number of pixels across the sample determines the resolution of the CT data. The minimum pixel size that can be tolerated is limited by the efficiency of each detector element.

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\text{Smallest voxel size} = \frac{\text{Sample diameter}}{\text{Number of pixels across detector}}
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In some special cases, where smaller pixels can be tolerated and / or the detector area is not sufficient to image the whole sample in a single exposure, scanned detectors or algorithms that stitch images together can be used. These are generally high-resolution applications for research where the data acquisition time and detector price are not key issues.

The following detectors are suitable for use in CT systems, depending on the sample size and densities: image intensifiers with analogue or digital video cameras, amorphous silicon flat panel detectors, CMOS flat panel detectors, flat scintillating screens with cooled CCD cameras.

Image intensifiers can be used with Aluminium or Beryllium entrance windows for the energy ranges 35keV – 320keV and <35keV respectively. The limiting factor for resolution in these detectors is usually the phosphor grain size on the output window of
the intensifier. In practice 1024x1024x12 bit data is the highest cost-effective resolution with this type of detector. The field of view is determined by the size of the intensifier entrance window, typically 100, 150, 230 and 300mm for Aluminium windowed tubes and 100mm for Beryllium windowed tubes.

Flat panel detectors are available using two detector technologies. High-resolution large area detectors based on amorphous silicon (up to 3200 x 2300 pixels) and high resolution, small area detectors based on CMOS sensors.

- Amorphous silicon detectors have slow read-out times (up to several seconds for the largest areas) and high dynamic ranges (up to 16 bits). Variations in sensitivity between pixels (including completely insensitive pixels) can be a problem in these types of detectors and must be removed in software. However the images are much sharper than those obtained with image intensifiers due to lack of cross-talk (blooming) between pixels. Lower resolution flat panels with faster read-out times (up to 30 frames per second) make an excellent substitute for image intensifiers when X-ray flux is not limited.

- CMOS sensors are smaller, faster devices, that can operate closer to real time than their larger amorphous silicon counterparts. However, for generalised CT systems, the detector areas are small in comparison with image intensifiers and amorphous silicon panels. This limits the maximum sample size.

Flat scintillators and cooled low-light-level CCD cameras can be used when small defects in much larger samples are of interest. They are therefore not so useful for microfocal CT.

The use of higher resolution detectors with more or smaller pixels (or both), digitised to a higher number of bits, leads to a demand for a higher X-ray flux. This is one reason for the need for brighter X-ray sources. High resolution CT using such detectors demands a higher number of projection images and hence a longer data collection time. Brighter X-ray sources can help reduce the acquisition time of each image.

**CT Reconstruction**

The CT reconstruction algorithm implemented by X-Tek is a modified version of Feldkamp's generalised fan-beam algorithm, originally coded by LETI (the Electronics and Information Technology Laboratory of the Atomic Energy Commission (CEA), Grenoble, France). The algorithm has been modified to run on multi-processor systems, and has been further optimised for speed. The reconstruction can process acquired frames individually and can therefore start reconstruction on acquisition of the first frame. The volume is therefore usually available for analysis immediately after completion of acquisition, though 2D slices through the volume can be viewed as it is being reconstructed.
Results

The inspection of small electronic packages tests the resolution of a microfocus CT system very well. The detection of small (a few micron sized) defects and sub-components in a sample only a few mm across requires very accurate sample manipulation and image registration. The fact that this can be done in a system which can also CT castings up to 150mm across, and inspect larger components radiographically is very attractive to the user.

Figure 4. CT volume of a hybrid chip stack approximately 15mm x 10mm x 10mm (left) and one chip extracted (right) showing bond wires.

Figure 5. Suture needle 198µm in diameter.

Figure 6. Tip of endodontic file (120µm across)
Future Developments

The recent development of a microfocus rotating anode source has enabled higher resolution medical imaging than conventional medical sources [8]. Further work will shortly give rise to a 225kV source with a 2µm focal spot and a maximum continuous output of over 300µA (at 225kV).

Use of a recently developed 385kV microfocus source (with a focal spot size of 40µm) for industrial CT will enable customers to examine larger components in much greater detail than previously possible.

Figure 7. A diagram showing the new 385kV double-ended X-Tek microfocus X-ray tube.
Conclusions

To take high resolution 3D CT from its first concept to a wide range of industrial applications has required significant X-ray source development, careful choice of manipulator design and detector specification that in some cases has demanded bespoke detector technology.

This paper has tried to give an overview of the key design criteria and an explanation of some of the practical problems that have had to be overcome. In particular, the crucial rôle that accurate, stable manipulators play in determining the ultimate resolution of 3D computed tomography data has been described.

Results from X-Tek’s CT systems have illustrated the quality of data which can be obtained from a properly constructed microfocal CT system.

For further information, please contact the X-Tek group at www.xtekxray.com.

References


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