

# Enhanced Affordable Computed Tomography Solutions

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**Abstract.** High cost and complexity of commercial X-ray computed tomography systems act as a barrier to the adoption of such technology by small and medium sized companies. The work presented here attempts to address these issues through the development of affordable solutions for both CT reconstruction and X-ray projection data set acquisition.

## Introduction

The Precision Measurements Group at SIMTech has been providing X-ray inspection services to local industry for over 10 years mainly for hidden defect and internal structure visualisation of components and materials from the electronics, semiconductor and precision engineering sectors.

One recurring comment from our interaction with local industry has been the relatively high entry cost for X-ray and computed tomography based inspection. We approached this concern from both a hardware and software perspective.

In the first part of this paper we discuss the initial development, and subsequent further refinement of a software package to provide simplified access to 3D tomographic reconstruction of 2D X-ray projection images.

The package incorporates projection image pre-processing, user-defined area-of-interest selection, fan-beam and cone-beam reconstruction with variable reconstruction filtering and SIMTech's patented central ray determination techniques.

Performance enhancement using customised implementations of the back-projection process on both host and GPU devices is evaluated. Input data can come from any suitable X-ray inspection machine by providing a definition of that system through various configuration options. Output data is made available in a range of standard formats or can be examined directly by an accompanying visualisation software tool.

In the second part of this paper we discuss the upgrading of a low cost manually controlled 2D X-ray inspection machine by adding a rotation stage suitable for the acquisition of projection image data sets.

A computer-controlled rotation stage was mounted on a removable platform within the inspection machine. Scanning and alignment software was developed to operate the system whilst following a series of defined procedures. Methods for correction of distortion introduced by the image intensifier have been developed which do not require prior knowledge of the intensifier geometry.

The upgraded system can provide input data to the reconstruction and visualisation package described in the first part of the paper.

## 1. CT Reconstruction Software Package Development

The objective in our development of a CT reconstruction software package was the creation of a hardware independent solution for reconstruction and visualisation that was useable on general purpose PC hardware.

The software was required to process projection images and associated calibration and control information to yield a series of reconstructed slice images perpendicular to the axis of rotation during projection image acquisition that represent the 3D model of the object under examination.

Simple visualisation of the reconstructed slice images was required to be integrated with, or closely coupled to, the processing required to generate them. The visualisation allows the user to view sections through the reconstructed volume along the axial, frontal or sagittal axes.

The user was also to be provided with sufficient control over the process to allow the software to operate with projection images generated by any suitable X-ray inspection machine.

### 1.1 Theoretical Background

As illustrated in Figure 1, computed tomography is an X-ray imaging technique that makes an image out of thin cross-sections of a part. Only a thin X-ray plane moving through a part is detected. X-ray data are collected through all points of the X-ray plane, and from many angles. This process produces many thin images ‘slices’ which are combined by mathematical operations.

In performing computed tomography, the system must scan around an entire part to collect all the data needed to create a CT image. In most X-ray inspection systems for industry applications, the scan is performed by simply rotating the part on a part manipulator turntable.

The most straightforward form of tomographic reconstruction is based on the fan-beam algorithm [1]. Suppose a parallel beam projection on the  $j^{\text{th}}$  detector cell at an angle  $\theta$  is denoted as  $p(j, \theta)$  and its Fourier Transform is  $P(w, \theta)$ , the reconstructed image is then obtained as

$$f(x, y) = \int_0^\pi d\theta \int_{-\infty}^{+\infty} P(w, \theta) |w| e^{j2\pi w(x \cos \theta + y \sin \theta)} dw$$

A detailed description of the computer implementation of this equation can be found in [2]. When used in conjunction with an area detector the fan-beam algorithm operates on single lines of pixels extracted from the image acquired at each projection angle. Each slice is individually reconstructed and the effect of the axial position (relative to the X-ray source) is not generally considered.

In order to achieve an improved and more consistent quality of reconstruction over the field-of-view of an area detector it is necessary to make use of the cone-beam or FDK algorithm [3]. The simplest way to obtain the cone-beam reconstruction algorithm is to start from the fan-beam reconstruction algorithm and calculate the contribution of each ray to an object point based on the geometry as shown in figure 2.

The reconstructed image is obtained from

$$f(x, y) = \frac{1}{2} \int_{-\gamma}^{2\pi-\gamma} \left( \frac{D}{D+y'} \right)^2 d\beta \int_{-\gamma_m}^{\gamma_m} q(s, v, \beta) h(s' - s) \frac{D}{\sqrt{(D^2 + s^2 + v^2)}} ds$$

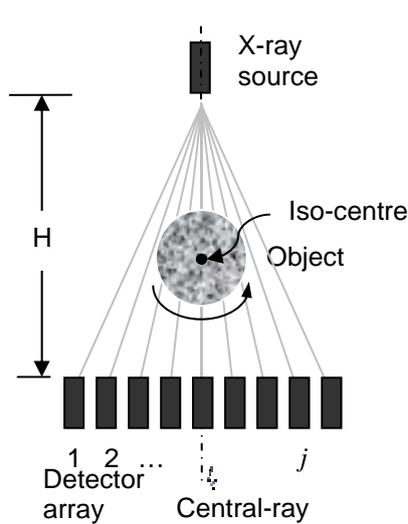


Figure 1 – Fan-beam Micro-CT Geometry

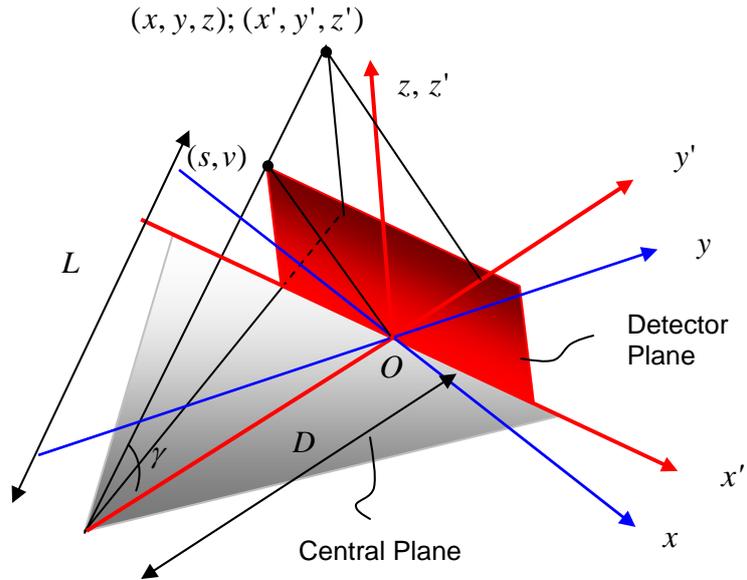


Figure 2 – Cone-beam Geometry.

### 1.2 Software Implementation

The implementation of the reconstruction algorithms was programmed using Microsoft Visual Studio in C++ with various open source support libraries including FreeImage and OpenCV. The package comprises approximately 5500 lines of code split across five modules as shown in figure 3.



Figure 3 – Major Modules in Software Implementation

Screenshots of the graphical user interface are shown in figure 4.

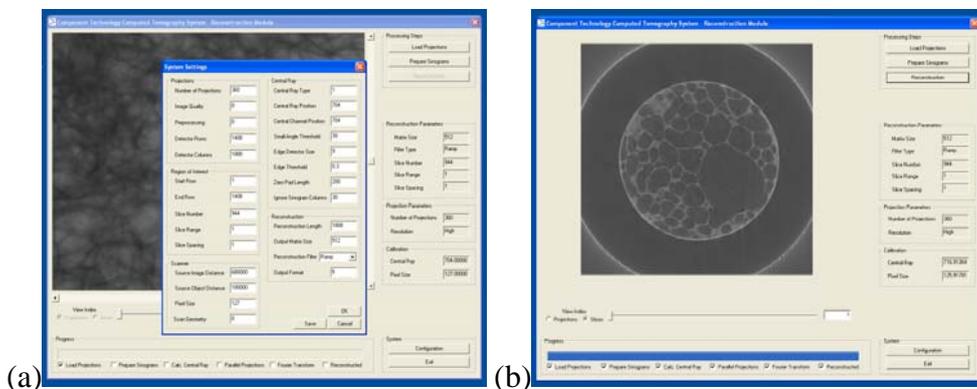


Figure 4 – Screenshots of Reconstruction Module showing (a) Configuration (b) Output.

### 1.3 Performance Evaluation

In order to characterise the performance of the reconstruction module a set of 180 projections (1888x1408 pixels, 8-bit tiff format) were reconstructed into 512 slices with a reconstruction matrix size of 512 by 512 pixels. No pre-processing was used. A ramp filter was applied in the Fourier domain. Output files in raw and tiff format were generated. In all host-based examples no multi-threading was used i.e. execution runs on a single core.

Table 1 shows the performance of the first generation implementation using fan-beam reconstruction.

Table 1 – Reconstruction Performance (Fan-beam)

System	Benchmark
Laptop : 2.0 GHz Centrino / 2Gb 533MHz DDR2	28 minutes
Desktop 1 : 3.4GHz Pentium 4HT / 2Gb 466MHz DDR	22 minutes
Desktop 2 : 2.4GHz Core 2 Quad / 4Gb 800MHz DDR2	15 minutes

Table 2 shows the performance of the second generation using cone-beam reconstruction with and without the use of GPU processing.

Table 2 – Reconstruction Performance (Cone-beam)

System	Benchmark
Desktop without SSE4 : 2.4GHz Core 2 Quad	17 minutes
Desktop with SSE4 processor : 3.4GHz Core 2 Duo	7 minutes
Base with GPU : NVIDIA GTX295 with 2Gb Memory	4 minutes

### 1.4 Visualisation

Although comprehensive visualisation solutions are readily available commercially to support medical and industrial 3D imaging, these tools offer an extensive set of functions and navigation features that are not required by many users particularly in the electronics and semiconductor industries. Further these packages generally have a long learning curve and require a well-trained, experienced operator to fully utilize the benefit of the tools.

In order to address these issues we have designed and developed a simplified visualisation tool, CTVisual, which is user-friendly and interactive. The user interface is shown in figure 5. Further details can be found in [4]. The tool allows examination of three orthogonal planes extracted from the reconstructed data set supported by a range of image processing functions to highlight regions and features of interest.

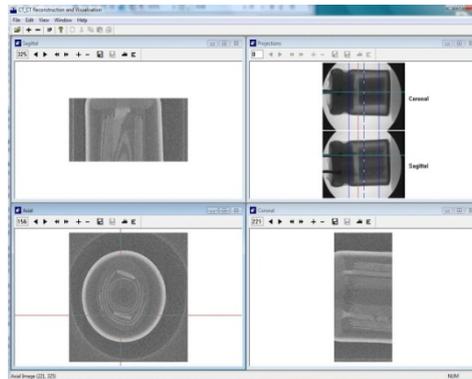


Figure 5 – Screenshot of CTVisual Visualisation Tool.

## 2. Upgrading of 2D X-ray Inspection System

The second stage of providing increased accessibility to CT technology required the development of an affordable hardware platform for the acquisition of projection image data sets. The starting point for this work was the 2D X-ray inspection system shown in figure 6 from FocalSpot Inc. [5].

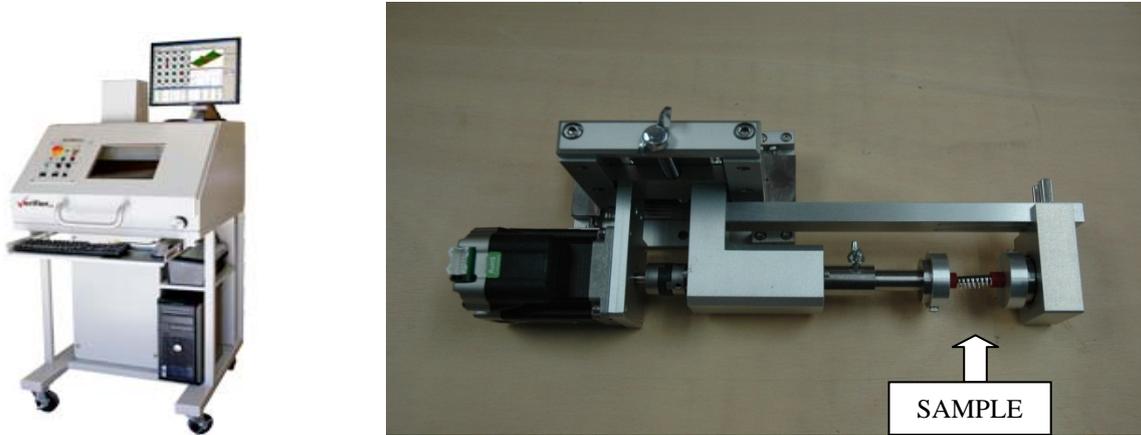


Figure 6 – 2D X-ray Inspection System (Courtesy of FocalSpot Inc.) and our rotation unit with spring-loaded sample mount indicated.

Also shown in figure 6 is the add-on rotation unit designed by SIMTech. In use this unit is fixed into position inside the X-ray chamber of the 2D inspection system. The stepper motor which provides sample rotation is linked to the host computer via a USB interface.

A software application, CTScan, which runs on the host computer (GUI shown in figure 7), provides the user with functions to

- Align the rotation unit to ensure that the axis of rotation is correctly aligned relative to the image intensifier/CCD detector array
- Rotate and image the sample from various projection angles to assess appropriate X-ray parameters
- Collect bright and dark field calibration images
- Fix the parameters of the acquisition scan in terms of rotation angle, number of projections, image pre-processing and integration
- Perform the predefined scan

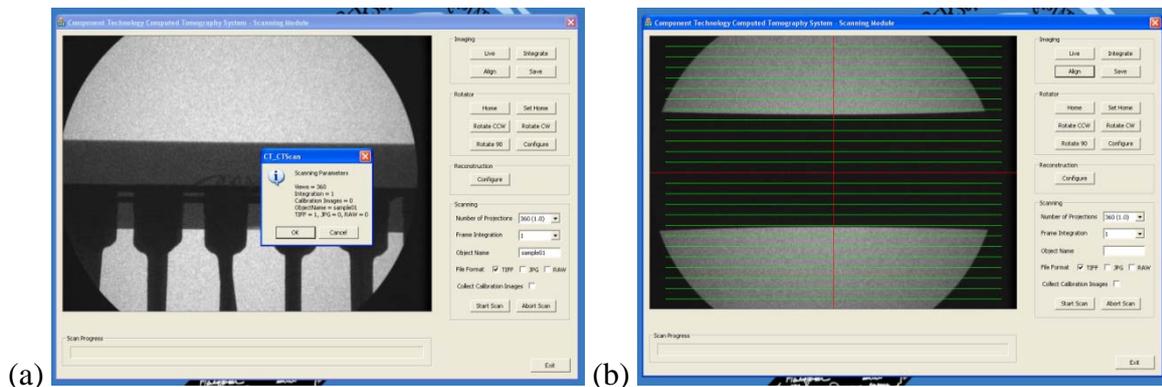


Figure 7 – Screenshots of CTScan User Interface (a) Scan Mode (b) Alignment.

During the design of the hardware, development of the software application and subsequent system integration it became necessary to identify the effect of rotation errors and axis mis-alignment. Similarly the distortion inherent in the type of image intensifier used in our base system was found to have a significant effect on the reconstruction quality and had to be addressed. These two areas are covered in the next two sections.

### 2.1 Experiments to Assess Rotation Parameters, Axis Alignment and Sample Holders

Four sets of experiments were conducted to demonstrate the effect of certain hardware-linked parameters on the reconstruction result. A standard phantom was used to allow simple visual assessment of the impact of variation in the parameters. The first three sets of experiments considered the effect of errors in the positions at which individual projection images were acquired. Errors were deliberately introduced in the angular position, the angular increment and in the orientation of the rotation axis.

Figure 8 shows the effect of random errors up to a specified level on the reconstruction quality. There is clearly almost no difference at up to 5% error in angle position.

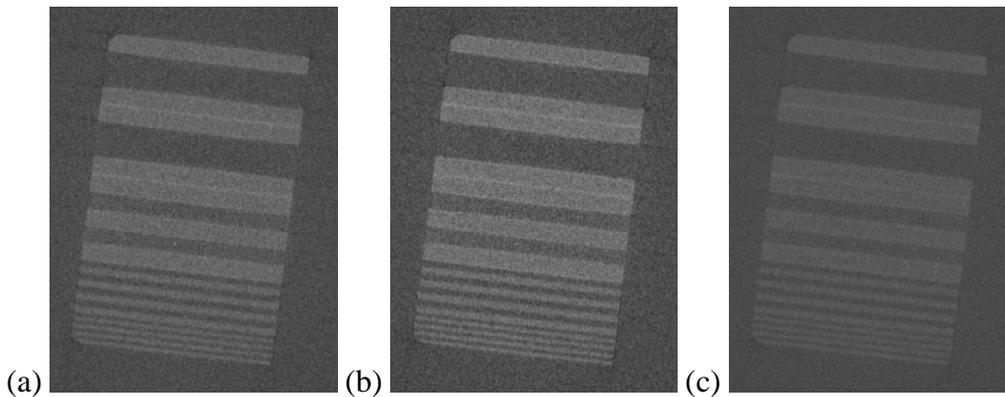


Figure 8 – Reconstruction with Errors in Angular Position of Projections (a) No Error ,(b) 5% Error, (c) 10% Error.

Figure 9 shows the effect of an error in the angular increment between adjacent projections that causes the error in angular position to accumulate during the scan. This experiment showed that the cumulative error has to be kept below 1% to avoid significant impact in the reconstruction quality.

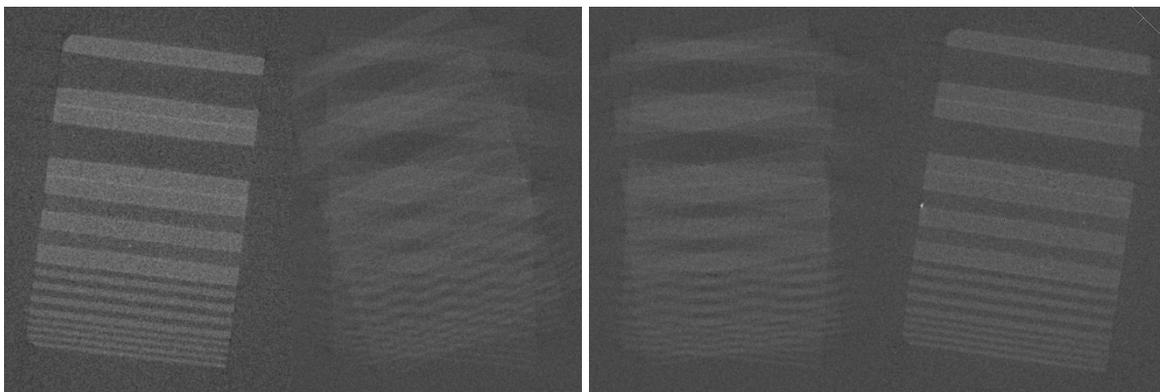


Figure 9 – Reconstruction with Cumulative Error in Angular Position (0, 10%, 5%, 1% from left to right).

The third set of experiments (not illustrated here) showed that it was necessary to be able to align the rotation axis with the pixel row axis of the CCD detector to better than 0.5 degrees i.e. tilt across the image frame should be less than 1 pixel.

The fourth set of experiments was designed to demonstrate to potential industry users the influence of different methods of mounting the sample to be inspected in the rotation unit. A sample of semiconductor IC package was mounted using four different methods; glued directly to mounting rod, embedded in resin, clamped between two rigid plates, attached to mounting rod using modelling clay. The aim was to demonstrate that provided the sample was mounted rigidly, the mounting method had marginal influence on the results generated.

## 2.2 Distortion Mapping and Correction

Image intensifiers are still widely used as a low-cost detector in many industrial X-ray systems. In terms of imaging performance, the main drawbacks of the image intensifier are its geometrical (pincushion) distortion and magnetic field distortion. With many X-ray inspection systems for industrial applications, because the image intensifier is usually fixed, and the components are properly arranged so that the magnetic field distortion is minimised, pincushion distortion generally is the main distortion issue that needs to be corrected.

Pincushion distortion is caused by the curvature of the input phosphor screen of the image intensifier. This problem has been extensively studied for tomosynthesis and quantitative digital angiography [6]. These studies are conducted based on an assumption that the curvature of the input phosphor window and the zooming magnification of the CCD camera are known.

However, in practice, in many situations, they are generally not available from the documentation of either the image intensifier or the X-ray inspection system. This leads to difficulty in implementing distortion correction methods in real inspection work. Another not sufficiently addressed problem is the variation of the total magnification of system caused by different zooming status. With a CCD that can be adjusted continuously, the exact zooming value is usually unknown. To make things more troublesome it is necessary to consider the possible slight misalignment between the optical axis of the CCD camera and the optical axis of the image intensifier tube. This leads to an uncertainty for the tube-centre's position on the image. As a combined consequence, implementing those existing geometrical distortion techniques is quite challenging and usually one has to calibrate the magnification and tube-centre position for each change of the camera zooming.

We have developed and implemented a pincushion distortion correction algorithm for use in the situation that the tube curvature, magnification and tube-centre position are unknown. Detailed theoretical background can be found in [7]. Figure 10 shows an example of an image corrected using this technique.

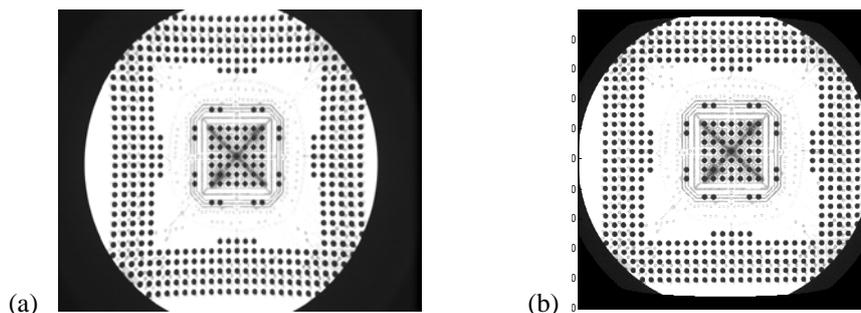


Figure 10 – (a) Original and (b) distortion corrected images.

### 3. Typical Results

Examples of results generated using the hardware and software described in this paper are shown in figures 11 and 12. Datasets can be obtained from the authors.

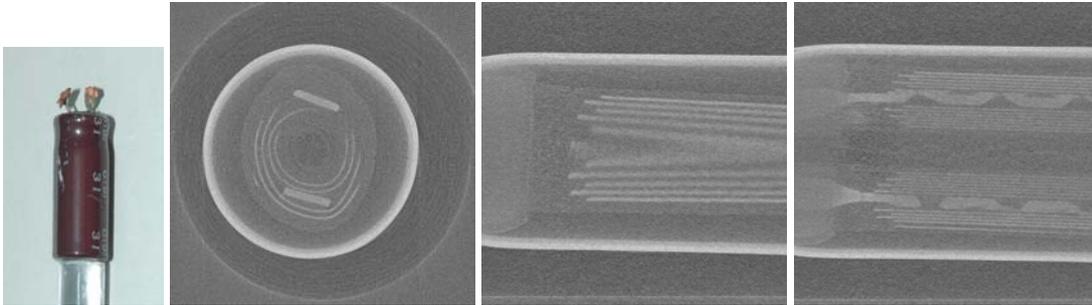


Figure 11 – Axial, Sagittal and Coronal Sections through an Electrolytic Capacitor.

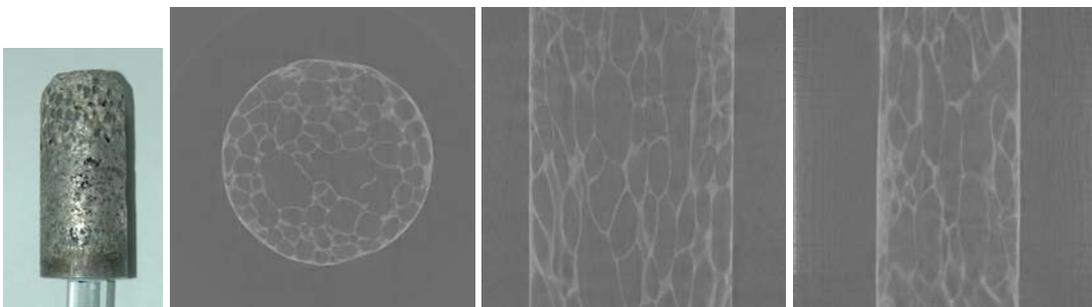


Figure 12 – Axial, Sagittal and Coronal Sections through Aluminium Foam.

### 4. Summary

A software package for CT reconstruction and visualisation has been developed. This package provides reconstruction functionality for projection image data sets from any source. Specialised or high-end hardware is not required for satisfactory performance. The output can be examined by any visualisation tool.

A basic 2D X-ray inspection system has been upgraded such that it can be used to collect projection image data sets for tomographic reconstruction. The add-on unit comprises a software application, rotation hardware and a defined set of procedures for successful operation. Enhancements have been incorporated to address identified limitations of the hardware platform including correction of distortion introduced by the use of an image intensifier.

### References

- [1] A.C. Kak and Malcolm Slaney, *Principles of Computerized Tomographic Imaging*, IEEE Press, 1988
- [2] J. Hsieh, *Computed Tomography*, SPIE Press Monograph, PM114, 2003.
- [3] L.A. Feldkamp, L.C. Davis and J.W. Kress, “Practical cone-beam algorithm”, *J. Opt. Soc. Am.*, A6, 612-619, 1984.
- [4] S.J. Liew, A.A.Malcolm, X.M.Yin and C.S.Chong, “User-friendly Visualisation of Industrial X-ray CT”, Singapore Institute of Manufacturing Technology Technical Report, December 2009.
- [5] Focalspot Inc. Home Page, <http://www.focalspot.com>, accessed October 2010.
- [6] R. Ning, X. Wang, D. Conover and Y. Zhang, “Image distortion-correction for image intensifier-based volume tomographic angiography”, *J. X-ray Sci. and Tech.* 9, 55-75, 2001.
- [7] T. Liu, A.A. Malcolm, B.S. Wong and J. Xu, “Pincushion Distortion Correction in X-ray Imaging with an Image Intensifier”, *Proc. Intl. Conf. Experimental Mechanics*, Singapore, 2009.