Design, Development and Integration of a Large Scale Multiple Source X-ray Computed Tomography System

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Abstract

X-ray Computed Tomography (CT) allows visualisation of the physical structures in the interior of an object without physically opening or cutting it. This technology supports a wide range of applications in the non-destructive testing, failure analysis or performance evaluation of industrial products and components.

Of the numerous factors that influence the performance characteristics of an X-ray CT system the energy level in the X-ray spectrum to be used is one of the most significant. The ability of the X-ray beam to penetrate a given thickness of a specific material is directly related to the maximum available energy level in the beam. Higher energy levels allow penetration of thicker components made of more dense materials.

In response to local industry demand and in support of on-going research activity in the area of 3D X-ray imaging for industrial inspection the Singapore Institute of Manufacturing Technology (SIMTech) engaged in the design, development and integration of large scale multiple source X-ray computed tomography system based on X-ray sources operating at higher energies than previously available in the Institute.

The system consists of a large area direct digital X-ray detector (410 x 410 mm), a multiple-axis manipulator system, a 225 kV open tube microfocus X-ray source and a 450 kV closed tube millifocus X-ray source. The 225 kV X-ray source can be operated in either transmission or reflection mode.

The body of the 6-axis manipulator system is fabricated from heavy-duty steel onto which high precision linear and rotary motors have been mounted in order to achieve high accuracy, stability and repeatability. A source-detector distance of up to 2.5 m can be achieved. The system is controlled by a proprietary X-ray CT operating system developed by SIMTech. The system currently can accommodate samples up to 0.5 x 0.5 x 0.5 m in size with weight up to 50 kg. These specifications will be increased to 1.0 x 1.0 x 1.0 m and 100 kg in future development. All components are housed in a custom designed 5.0 x 4.0 x 3.0 m walk-in radiation protection chamber. All set-up and operation can be controlled remotely from dual operator/supervisor workstations.

This paper provides more comprehensive details of the system and its development.

Keywords: Computed Tomography, CT, reconstruction, NDT, visualisation
1. Overview of Computed Tomography

X-ray CT is a non-destructive inspection technique which provides cross-sectional images in planes through a component. The principle of CT imaging, as used in the industrial context, is illustrated in figure 1. The component is placed on a precision turntable in the divergent beam of X-rays generated by an industrial X-ray source. A detector array is used to measure the intensities of the X-ray beam transmitted through the component, as the component is rotated in the beam. The set of images collected at angular increments is known as the projection image data set. A mathematical algorithm is then used to generate (or “reconstruct”) the CT images from the measured transmitted intensities [1-3].

The resultant CT images are true cross-sectional images perpendicular to the axis of rotation, and show the geometry of the component in the plane of the cross-section. The CT image values (grey-levels) provide information on the material’s X-ray attenuation coefficient at each point in the image. There is considerable current interest in the correction for a number of effects, including especially “beam hardening”, which would allow the CT grey levels to be converted to values which are directly proportional to the local material density.

Cabinet-based systems for real-time radiography contain suitable X-ray sources and detectors for industrial X-ray CT, and can be upgraded to provide a CT capability by addition of a precision turntable and a high-performance PC with appropriate image acquisition cards, motion control capabilities and software for image reconstruction and visualisation. This arrangement is shown schematically in figure 2.

Figure 1 – Overview of the CT inspection and measurement process.
2. SIMTech High-energy X-ray CT System

2.1 Design Criteria including required motions (System Specifications)

In order to establish appropriate initial design criteria the authors first considered the type and range of motions required to support various forms of CT including manipulation of the source, sample and detector. These are highlighted in figure 2.

![Figure 2](image)

**Figure 2** – Motion axes required for various forms of CT.

Subsequently the state-of-the-art in commercially available systems of similar class was reviewed to support specification of the physical size and resolution of each necessary motion axis. These specifications are summarised in table 1.

<table>
<thead>
<tr>
<th>Axis</th>
<th>Travel</th>
<th>Accuracy</th>
<th>Purpose</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zs (Source Vertical)</td>
<td>1000 mm</td>
<td>&lt; 50 um</td>
<td>Scan position</td>
<td>150 kg</td>
</tr>
<tr>
<td>Zd (Detector Vertical)</td>
<td>1000 mm</td>
<td>&lt; 50 um</td>
<td>Scan position</td>
<td>120 kg</td>
</tr>
<tr>
<td>Zo (Sample Vertical)</td>
<td>500 mm</td>
<td>&lt; 25 um</td>
<td>Scan position, Alternative sources</td>
<td>100 kg + Rotation Stage</td>
</tr>
<tr>
<td>Y (Object Horizontal)</td>
<td>3000 mm</td>
<td>&lt; 10 um</td>
<td>Magnification</td>
<td>100 kg + Rotation Stage + Translation Stage</td>
</tr>
<tr>
<td>Yd (Detector Horizontal)</td>
<td>1500 mm</td>
<td>&lt; 50 um</td>
<td>Magnification, multiple-point measurement</td>
<td>120 kg + Translation Stage</td>
</tr>
<tr>
<td>X (Object across beam)</td>
<td>±200 mm</td>
<td>&lt; 10 um</td>
<td>Multiple-point measurement, Radiography</td>
<td>100 kg + Rotation Stage</td>
</tr>
<tr>
<td>θ (Object Rotation)</td>
<td>360°</td>
<td>&lt; 30°</td>
<td>Scan</td>
<td>100 kg</td>
</tr>
<tr>
<td>φ (Object Tilt)</td>
<td>±45°</td>
<td>&lt; 10°</td>
<td>Inclined CT, Oblique radiography</td>
<td>100 kg + Rotation Stage</td>
</tr>
<tr>
<td>β (Source Swing)</td>
<td>±45°</td>
<td>&lt; 1°</td>
<td>Switch 225kV mode</td>
<td>45 kg</td>
</tr>
</tbody>
</table>

Table 1 – Manipulator specifications and functionality.
In addition consideration was given to the requirement for significant flexibility in both capability and configurability in order to support both existing “standard” CT operations and future research needs generating a requirement for alternative scanning geometries and protocols.

For a single X-ray source X-ray system there is an inevitable trade-off between material penetration and voxel resolution. Higher energy X-ray sources which support greater material penetration generally require a larger focal spot size which leads to a reduction in spatial resolution in the CT output. Requiring increased spatial resolution generates a need for a smaller X-ray focal spot size which limits the available energy level in turn restricting the material penetration capability.

Hence a system based on multiple X-ray sources was proposed - a 450 kV source for high material penetration and a 225 kV source for high resolution. This arrangement was further extended by selecting a 225 kV source with two interchangeable output heads. The first operates in reflection-mode (higher power and larger focal spot size) whereas the second operates in transmission-mode (lower power and smaller focal spot size).

This arrangement effectively builds three different CT systems into the same machine which, while increasing the system capabilities also, increases the design complexity.

The first major consideration with regard to the manipulator system was to maximise the available distance between X-ray source and detector in order to provide maximum available magnification. Two factors act to limit this distance – the reduction in X-ray intensity reaching a more distant detector and the physical limit imposed by the radiation protection chamber. The second factor fixed the maximum distance in the region of 2.75 m. The first factor is addressed by allowing the detector to be shifted closer to the X-ray sources when required.

The second major consideration concerned the requirement to be able to scan objects initially up to 500 x 500 x 500 mm in size (in phase 1), and subsequently up to 1000 x 1000 x 1000 mm in size (in phase 2). The general requirement for standard CT scanning is that the object should be completely within the cone formed by projecting the centre of X-ray source to the four corners of the detector array. This limits the size of object that can be scanned to a size less than the detector size. The maximum size of detector array that is currently commercially available is approximately 410 x 410 mm.

Several approaches can be taken to address this constraint. In phase 1, the system will use offset methods to allow scanning of objects up to 500 mm in size. This method requires the ability to shift the centre-of-rotation off the centre line between X-ray source and detector, i.e. object translation perpendicular to the magnification axis.

In phase 2 translation of the detector within its own plane in two directions will be provided to create a much larger virtual detector up to 1200 x 1200 mm in size. This will allow scanning of much larger objects with little reduction in image quality, but at a cost of increased scanning time.

The third major consideration addressed the use of machine baseplate produced from a solid piece of a single material (typically granite) or a baseplate fabricated in modular fashion.
The requirement for configurability and flexibility was held to be more important than absolute rigidity and a modular approach was used based on heavy-duty steel box sections.

2.2 Design – Conceptual and Detailed

Based on the identified design criteria and the evolved system specifications a conceptual design of the system was generated. This is shown in figure 3. The system can be described as a vertical rotation axis CT system with three stacked X-ray sources. The detector is mounted on a linear translation stage whose sole purpose is to centre the detector in alignment with whichever X-ray source is currently active.

Figure 3 – System conceptual design.
Figure 4 shows the detailed design of the system.

Figure 4 – Side elevation of detailed design showing maximum separation between source and detector for different X-ray source operating modes; (a) 450 kV, (b) 225 kV Transmission, and (c) 225 kV Reflection.
2.3 Components including source, detector, manipulators and chamber

2.3.1 450 kV X-ray Source

The 450 kV X-ray source was acquired from Yxlon International GmbH and comprises the Y.MG452 universal bipolar constant potential generator system to power the Y.TU 450-D09 bipolar metal-ceramic X-ray tube. This combination is targeted at the inspection of thick sections of high density materials, e.g. iron and steel castings. Due to relatively small focal spot size combined with high penetration depth it is well suited to high resolution CT.

Figure 5 shows the Yxlon Y.MG452 and Y.TU 450-D09 components.

![Figure 5 – Yxlon Y.MG452 generators, controller, power supply and Y.TU 450-D02 X-ray tube (schematic).](image)

The key features include high penetration power, high output stability, small focal spot size, long lifecycle and high reliability [4, 5]. The focal spot size is switchable between 0.4 mm and 1.0 mm with maximum output power of 0.7 kW and 1.5 kW and maximum tube current of 1.6 mA and 3.3 mA respectively. The emergent beam angle is 40° by 30°.

2.3.2 225 kV X-ray Source

The 225 kV X-ray source was acquired from X-ray WorX GmbH and comprises a Gulmay 225 kV HT generator powering the XWT-225 X-ray gun which can be fitted with either a reflection or transmission head. This multiple head arrangement allows the transmission head to be used for applications requiring high resolution analysis at very high magnifications, and the reflection head to be used for applications where higher power is needed, e.g. when analysing dense metallic materials [6].

With the transmission head installed, which can be fitted with a range of targets, detail detectability ranges from 300-500 nm depending on the target in use. The minimum focal spot size is less than 2 µm. Maximum target power varies from 10 W to 25 W. Maximum tube current is 1000 µA. Condenser lenses are used to allow stronger focusing of the electron beam.

With the reflection head installed detail detectability is estimated at less than 2 µm based on a minimum focal spot size of 5 µm. Maximum target power is 280 W with
maximum tube current of 3000 µA. Target cooling is provided to ensure stable operation at higher power.

Figure 6 shows the XWT X-ray gun fitted with either transmission or reflection head. Change-over time is approximately 30 minutes plus the time taken to evacuate the vacuum system.

Figure 6 – X-ray WorX XWT-225-XC multiple head X-ray source, (a) Transmission head, (b) Reflection head.

2.3.3 X-ray Detector

The X-ray detector was acquired from Yxlon International GmbH, but manufactured by PerkinElmer under product code XRD1621 [7]. It is an amorphous silicon (a-Si) flat panel direct digital detector. It is suitable for X-ray energies from 40 keV to 450 keV. The detector has an active area of 409.6 x 409.6 mm with a 2048 x 2048 matrix of 200 x 200 µm pixels. A/D conversion is performed with 16-bit quantisation generating output images with 65536 grey levels. Full resolution images can be acquired at 15 frames per second. The interface to image acquisition PC is via dedicated frame grabber with glass fibre optical connection. Figure 7 shows the PerkinElmer XRD1621 detector.

Figure 7 – PerkinElmer XRD1621AN X-ray detector.
2.3.4 Radiation Protection Chamber

In order to address the safety concerns associated with any form of X-ray based inspection and to meet the regulatory requirements of the Singapore Radiation Act it is necessary to enclose the CT system within a radiation protection chamber [8]. As a result of the intended location of the system on the second floor of a three-story building it was necessary to design a six-sided chamber with radiation protection in the floor and ceiling in addition to the walls. Design calculations based on European standards were used to determine the thickness of each side in terms of lead equivalence [9]. The thickest wall, directly facing the X-ray source has a thickness equivalent to 58 mm of lead. The chamber was designed in modular fashion based on a series of interlocking panels fabricated from steel-lead sandwiches. This allows the chamber to be extended by the addition of further panels or dismantled for relocation. The chamber was fabricated in China before being shipped to Singapore for on-site assembly.

Figure 8 shows the custom-designed radiation protection chamber.

![Figure 8 – Radiation Protection Chamber.](image)

The chamber is fitted with a heavy-duty centre-split two part motorised access door which provides an opening 2 m in height and 1.5 m in width. The door is fitted with a dual interlock system linked directly to the X-ray sources to ensure that they cannot be activated with the door open. Laser sensors are used to disable door movement if the opening is blocked by an operator or other obstruction.

Four cable labyrinths were installed. Two are utilised for the HT cables, control cables and cooling pipes associated with the two X-ray sources. The third is used for data, control and power cables associated with the manipulators and X-ray detector. The remaining labyrinth is used for temperature control, emergency communications and safety systems.

High voltage generators and tube chillers for both X-ray sources are located externally to the chamber. In accordance with standard metrology protocols the chamber environment is temperature controlled to 20° Celsius.
2.4 Control Software – Architecture and Interface

The software architecture is based on a multi-layered approach with hardware abstraction, machine control and user interface separated into three layers. This methodology allows easier addition of new hardware components or replacement of obsolete ones since modifications are only required at the hardware layer. New data acquisition strategies and algorithms can be quickly implemented using the extendable scripting interface which provides access to all machine control functionality.

The software was written in a combination of managed C# and unmanaged C++ with custom-developed wrapper classes where necessary. The development platform was MS Visual Studio 2012 with the target operating system being Windows 7 64-bit edition. The system runs on an industrial PC utilising an Intel Core i7 processor with 16 Gb of system memory. Dual 3 Tb hard disks provide for temporary local storage of projection image data sets which are subsequently transferred to the reconstruction system via gigabit Ethernet.

Command and control architecture for the principal hardware components is shown in figure 9.

![Diagram of Software Architecture](image-url)

Figure 9 – Software architecture.

The operator GUI is shown in figure 10. The GUI is dominated by the live image from the X-ray detector. Two versions of the live image are maintained at all times regardless of the operating or processing mode in use. The first version is always the raw image coming directly from the detector output. Only pre-processing operations conducted internally within the detector are allowed to be displayed on this version. These operations are limited to gain, offset and bad pixel correction plus image averaging. The second version shows the processed image generated by applying user-specified image processing operators to the raw image. A range of standard and custom-defined image processing operators and filters are available to
the operator. During automated CT scanning both raw and processed projection images can be saved at each angular increment.

The right hand side of the GUI is split into three sections. The upper section allows the operator to control, configure and maintain whichever of the X-ray sources is selected. The layout and content of the section changes depending on which source is in use. In the central section three tabbed panels allow the operator to control and configure the manipulators, the detector and the image acquisition (including pre-processing). The lower section displays the position of each individual motion stage within the manipulator system and a message window continuously updated with system status information.

The live output from two high-resolution webcams installed inside the chamber can be displayed in separate overlay windows (shown on the left hand side of figure 10). This allows the operator to monitor the position of the sample relative to the X-ray source and detector during set-up operations and to monitor the progress of the scan itself.

Once the operator has completed set-up procedures an automated CT scan, based on default parameters, can be initiated with a single click. The scan configuration dialog is displayed as an overlay (figure 10, lower right) which allows the operator to either proceed immediately or to specify the desired scan parameters.

More complex CT scans based on alternative scan geometries and including variation of parameters during the scan can be implemented using the scripting function.

Figure 10 – System graphical user interface for CT scanning.
2.5 Reconstruction Tools (PowerRecon and VGStudio MAX)

The output from the system (projection image data sets) is compatible with SIMTech’s proprietary reconstruction software, PowerRecon as shown in figure 11, and with industry standard packages including VGStudio MAX from VolumeGraphics GmbH [10, 11].

Figure 11 – PowerRecon CT reconstruction software from SIMTech.
3. System Performance

The figures in this section show some examples of 2D X-ray images acquired using system at the current state of development. Some preliminary 3D X-ray CT reconstructions based on initial CT scans conducted during the early development stages are also included. A more detailed performance review with analysis of reconstruction quality will be presented in a subsequent publication.

3.1 2D X-ray Image Examples (Projections)

Figures 12 to 14 show some example components imaged in 2D at static positions. Figure 12 shows an aluminium casting of approximate dimensions 100 x 100 x 75 mm.

![Aluminium casting](image)

Figure 12 – Aluminium casting (a) X-ray image (b) Photograph.

Figure 13 shows a domestic water heater element fabricated from steel comprising two half-shells plus the heating coil.

![Steel water heat](image)

Figure 13 – Steel water heat imaged from two different angles.
Figure 14 shows a steel casting imaged in two different angular orientations separated by 90°. The component dimensions are approximately 120 x 120 x 150 mm.

3.2 3D X-ray Image Examples (CT Reconstructions)

Figure 15 shows the 3D view of the CT reconstruction based on the projection image data set from which the images in figure 14 were extracted. In total 360 projection images were acquired during a full rotation of the component (1° angular increment). The model was reconstructed over a 512 x 512 x 512 voxel matrix.
Figures 16 and 17 show the 3D and cross-sectional views respectively of the CT reconstruction based on the projection image data set from which the image in figure 12 was extracted. In total 360 projection images were acquired during a full rotation of the component (1° angular increment). The model was reconstructed over a 512 x 512 x 512 voxel matrix.

Figure 16 – 3D view of reconstructed volume (aluminium casting).

Figure 17 – Axial, sagittal and coronal cross-sections through the reconstructed volume of an aluminium casting.
4. **Industrial and Scientific Impact**

From a service perspective SIMTech will utilise the system to address the scanning needs of the aerospace, precision engineering, oil and gas, and marine industry sectors within Singapore and regionally. Specifically targeted applications include:

- Assessment of porosity, internal cracks and possibly microstructure in metallic materials such as nickel and titanium
- Inspection of impact damage in multi-layered composite and ceramic structures
- Assessment of repair quality in hollow walled components such as turbine and compressor blades
- Recovery of internal shape in cast components
- Recovery of internal and external geometry in a single pass with a common reference frame
- First article inspection for injection moulded components
- Detection of defects in cast and machined components

In parallel the developed system will support further research work at SIMTech including:

- Simplification and optimisation of the CT scanning process
- Novel reconstruction algorithms for both conventional and non-conventional scanning geometries
- 3D image processing methods to support automated defect detection
- Traceable dimensional metrology with specified uncertainty of internal feature measurement
- Development of reference standards for other NDT inspection methods

The planned research work leads to enhancement of existing capabilities and the introduction of new technologies. These technologies will be licensed to system developers both directly through machine development and through extending the capabilities of software packages jointly commercialised with our collaborators and industrial partners.
5. Summary

This paper has provided an overview of the development of a high-energy X-ray computed tomography system as a tool for non-destructive testing of large scale engineering components for failure analysis, prototype evaluation and performance assessment. Figure 18 shows internal and external photographs of the completed system.

Figure 18 – Completed development with CT system inside radiation protection chamber.

This system will support both industrial applications from local industry and further research activities including simplification and optimisation of the CT scanning process, the development of novel reconstruction algorithms for both conventional and non-conventional scanning geometries and the creation of 3D image processing methods to support automated defect detection and traceable dimensional metrology.
References