final report

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Line Scan CT for Beef & Lamb by Rotating Carcass

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Executive Summary

An initial proof-of-concept cone beam system has been developed at Scott Automation and Robotics' facility in Tullamarine, Victoria. Utilising this system, the complex geometric alignment and reconstruction algorithms were able to be developed and verified. These algorithms, which convert the collection of slice images into a complete 3D CT image of a sample, were tested with great success. The system as constructed is capable of accurately imaging an object with adequate spatial resolution and grayscale contrast for this application. However, image quality issues have arisen.

With the implementation of a fully featured camera driver, and an optimised program sequence, the cycle time can be reduced by approximately 75%. Once operating within this cycle time, the limitations of the system in relation to the physics of x-rays and optical light can be properly explored, and ultimately provide a result as to whether the system architecture can be applied to a production environment.

With the solutions described in this report successfully implemented, a full assessment of image quality and useful information content must be performed. In particular, the effect on image quality of scan time must be evaluated. It is certain that the faster the scan, the poorer will be the images. Given the need for high speed in a production environment there are two methodologies that should be evaluated to determine their effectiveness in preserving information content at high scan speeds. These are dual energy CT and using less than 360 degrees of rotation to image a carcass.

Dual energy CT requires that the carcass be imaged twice at two x-ray energies but has the benefit of greatly increasing the material differentiation capabilities of the system. Consequently, it may be possible to do fat/lean/bone discrimination with much poorer quality images. The exact trade off can only be evaluated by experiment using the POC system.

It was always envisaged that in a production environment, it would be very difficult, if not impossible to perform a full 360-degree scan of a carcass at line speed. 'CT' using a reduced data set is known as tomosynthesis. It should be possible to position equipment so that only regions of interest in a carcase are reconstructed. Tomosynthesis is based on constructing a volume by iteratively comparing between simulated and measured projection images to generate corrections to the volume. Consequently, the computational requirements are much larger than those required for tomography. In addition, there is the potential to also correct for object movement, but this in itself would further increase the computational requirements.

Moving forward with the developed platform, through a combination of hardware and software improvements, the performance of the overall apparatus can be further increased, and progress the integration of the key elements into a production trial ready system. The technology demonstrated at this point plus a sub-set of the improvements mentioned in this report should enable the generation of 3D data with sufficient spatial resolution and grayscale contrast to meet requirements for the red meat processing industry

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1 Background

Eating quality and supply chain carcase data present an opportunity to significantly transform the red meat supply chain (Greenleaf 2008). Currently, data capture alternatives include: carcase sampling using a variety of manual devices, single and dual energy x-ray measurement currently under development, and helical CT data capture currently planned for further evaluation. Helical CT represents the best known technology to directly measure the highest number of carcase attributes.

This project will determine whether an industrial cone beam dual energy X-ray system generating a 3D carcase model by rotating the carcase at line speed, could provide an alternative data capture solution.

The CT scoping study will generate a set of practical specifications for a CT system for red meat processing in Australia. The specifications will be based on achievable CT configurations for carcasses and will able to operate at production rates.

The first stage of a program aimed at practical implementation of CT would consist initially, of discussions with the red meat industry including MLA, AMPC and major meat processors. These discussions will identify and prioritise those targets that CT can potentially address. These could include carcass yield data, carcass structural information for robotic cutting, etc.

The remainder of the scoping study will consider

- CT configuration options
- Single and dual energy x-ray trade-offs
- Hardware requirements for full scan rate
- Resources needed to progress to a limited experimental phase in the Scott Automation and Robotics (AST) facility, using, where possible, existing x-ray equipment (sources, detectors etc) and testing on carcass sections plus constructed targets for setup purposes
- Software resources needed for both the production of CT images in limited and full production systems as well as the potential use of these image sets for meat-works applications.
- A costed, staged plan detailing the first limited experimental phase and outline subsequent stages including some consideration of the cost of a whole carcass production rate system.

If the project proceeds beyond the Go/No Go Decision, the design and setting up of a vertical orientation rotating and translating platform able to handle eg rib sections would begin. This will be set up in the x-ray laboratory and use wherever possible existing Scott Automation and Robotics (AST) x-ray componentry with multiple passes for noise reduction and multiple energy level scanning. The aim is to produce a range of CT image sets of sections of meat carcasses for study and evaluation by industry which would be encouraged to participate in identifying commercial applications of the solution.

Hence, following the completion of the limited experimental phase, we would expect that there would be a period of industry evaluation of the outcomes of the practical scanning experiments. Decisions would then be able to be made on the possibility of full scale facility set-up and the way in which this would best be progressed.

2 Project Objectives

As written in the Research Agreement:

- The project aimed to deliver a scoping report with technical specifications of both: a proof of concept x-ray system to generate a CT 3D point cloud of a suitable bone-in beef primal, and a production system for whole lamb carcases or beef half carcases. **[complete]**
- A Proof of Concept system will be built to determine both dimensional and greyscale resolution of a 3D point cloud model of a bone-in primal (lamb and beef). **[complete]**
- A final report summarising all findings will be delivered

3 Results

3.1 Review of Scoping Report

Below are extracts from the Scoping Report completed by Scott Automation and Robotics (AST) at the conclusion of Milestone 1 for this project:

- A practical and achievable CT configuration, which could reasonably be expected to operate in a processing room at or approaching line speed, would involve a cone beam configuration. This is basically due to the cone technique involving only one full or even half rotation and potentially a single translation motion compared with more than a thousand motions that are required for a fan beam system.

- As the quality of the CT information drops off at higher cone angles, it is expected that the reconstruction will provide detailed high spatial resolution around the central field of the cone and that DEXA-style information will be obtained at higher angles which can provide useful average compositional data over the wider region covered by the cone.

- The test rig will be built with vertical and rotational movement incorporated. A separate movement axis will be provided to translate the detector horizontally in order to simulate capturing a wider horizontal field of view.

- In order to confine the scattered radiation generated by the open x-ray cone beam, we have determined that the additional lead shielding would be too heavy for the existing x-ray room so a stronger enclosure was planned.

- The project as put together by the MLA and Scott Automation and Robotics (AST) is a scoping study with the purpose of demonstrating that an “industrial” cone beam potentially dual energy x-ray system can generate a 3D carcass model at line speeds more practically than a commercial “helical” scanner. In order to get to this point we have agreed that a trial system needs to be built to verify the information obtained and assess the quality of the information as well as determining the parameters of viable plant full-scale prototype equipment.

- In summary, the Scoping Study project is the necessary initial practical step toward development of a plant-viable CT system potentially capable of providing meat quality and bone location data at line speed by rotating either carcass or x-ray source/detector in a single 180 degree rotation.

- The scanning would be done on the rib/loin area of a beef carcass or shoulder to hind lamb carcass. It would aim to sense muscle, fat, bone and possibly muscle tissue differences such as pathology and seams as well as predicting saleable meat yield.

- The immediate deliverable of the scoping project is a flexible but mechanically accurate test rig which is fully enclosed in an appropriately shielded but relocatable room. This would be capable of CT examination of sections of beef and lamb carcasses up to about 30kg weight, for purpose of quality assessment of a wide range of meat quality and cutting parameters, whilst at the same time providing hard engineering data on the CT process and critical parameters such as scan speed, X-ray power and sample stability requirements.

3.2 System Design

The cone beam x-ray apparatus consists of three main elements:

1. Source

   In this case a 160kV x-ray tube with beryllium window and 40 degree beam spread, with a High Voltage generator providing the electrical supply required to produce the x-rays.

Figure 1: X-ray source, or tube, mounted in position (Left). Opposite side of tube mount, showing stepper controlled lead shutter and filter wheel (Right)

2. Table

The table supports the object to be scanned (in this case primal meat products), and provides support and motion through the x-ray field. A 2-axis servo driven system provides vertical and rotational motion for this purpose.

Figure 2: Underside of table showing rotational servo drive and reduction gearbox (Left). Full view of table, with servo motor at top for driving vertical axis (Right).

3. Detector

In this application the ‘shadow’ of the target is projected onto an x-ray sensitive phosphor panel, mounted to the front of a sealed box. This panel generates visible light when excited by x-rays, and this light is then captured by a high performance camera within the light-proof box, digitising the projected image.

Figure 3: Hamamatsu high speed camera mounted to detector box, with lead shroud removed (Left). Full view of detector box and stand, showing horizontal positioning axis, phosphor panel fitted to front, and leaded camera shroud in place at top (Right).

3.3 System Build

3.3.1 Shielded Laboratory

Due to the use of an open field Cone Beam at this early stage of system development, a shielded room would be required to house the equipment. To comply with required safety measures for Radiation, in addition to installing lead shielding a high rated safety system was required. The completed room utilises electromagnetic door locks, keyed x-ray control, audible and visible start-up warnings, and motorised door mechanisms.

The final room footprint was increased to accommodate varied geometry for the Cone Beam apparatus if required, as well as a workspace for other open field testing, such as for calibration scanning and hardware troubleshooting.

Figure 4: View from inside x-ray laboratory (Top).

Figure 5: Outside view of room inside Tullamarine facility (Bottom).

SIEVERTS
RADIATION PROTECTION CONSULTANCY
BRISBANE . SYDNEY . MELBOURNE

Radiation Shielding Assessment Report

Scott Automation & Robotics – Melbourne

Imaging Room

10 Lillee Crescent, Tullamarine VIC 3043, Australia

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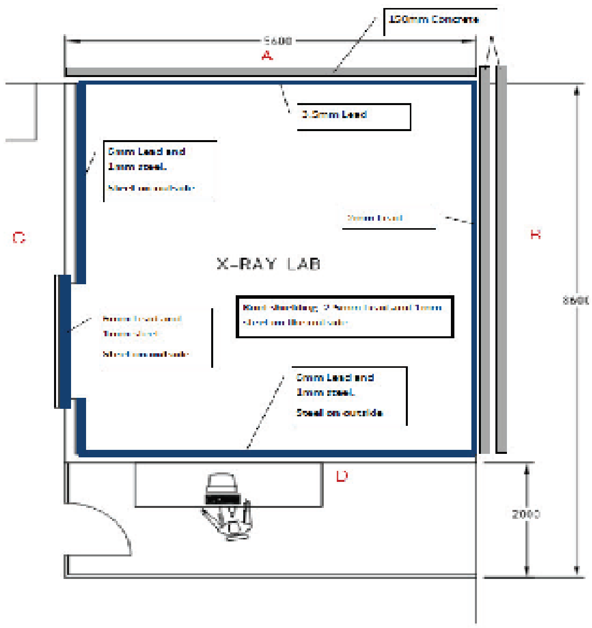
Figure 6: X-Ray lab accreditation report, completed by external third party



Point of Interest	Dose Rate(nGy/min)	Transmission Factor	Occupancy	New Dose Rate (nGy/min)
A	31.92	0.0002	0.0625	1.9
B	3.12	0.00002	0.0625	0.2
C	12.84	0.00008	0.0625	0.8
D	2.4	0.00005	1	2.4

Conclusion:

Shielding installation satisfy regulatory shielding design limit of 1mSv/year.

Inspection conducted by

William Tan – Accreditation #900059607

2

Figure 7: X-Ray lab accreditation report, completed by external third party

3.3.2 Apparatus Control

Control of system elements is completed from a single graphical user interface. From this interface the user can start the x-ray generator and adjust power settings, capture images, move the motion servos, and monitor room safety measures.

When scanning a product, parameters are setup and then the scan sequence proceeds automatically.

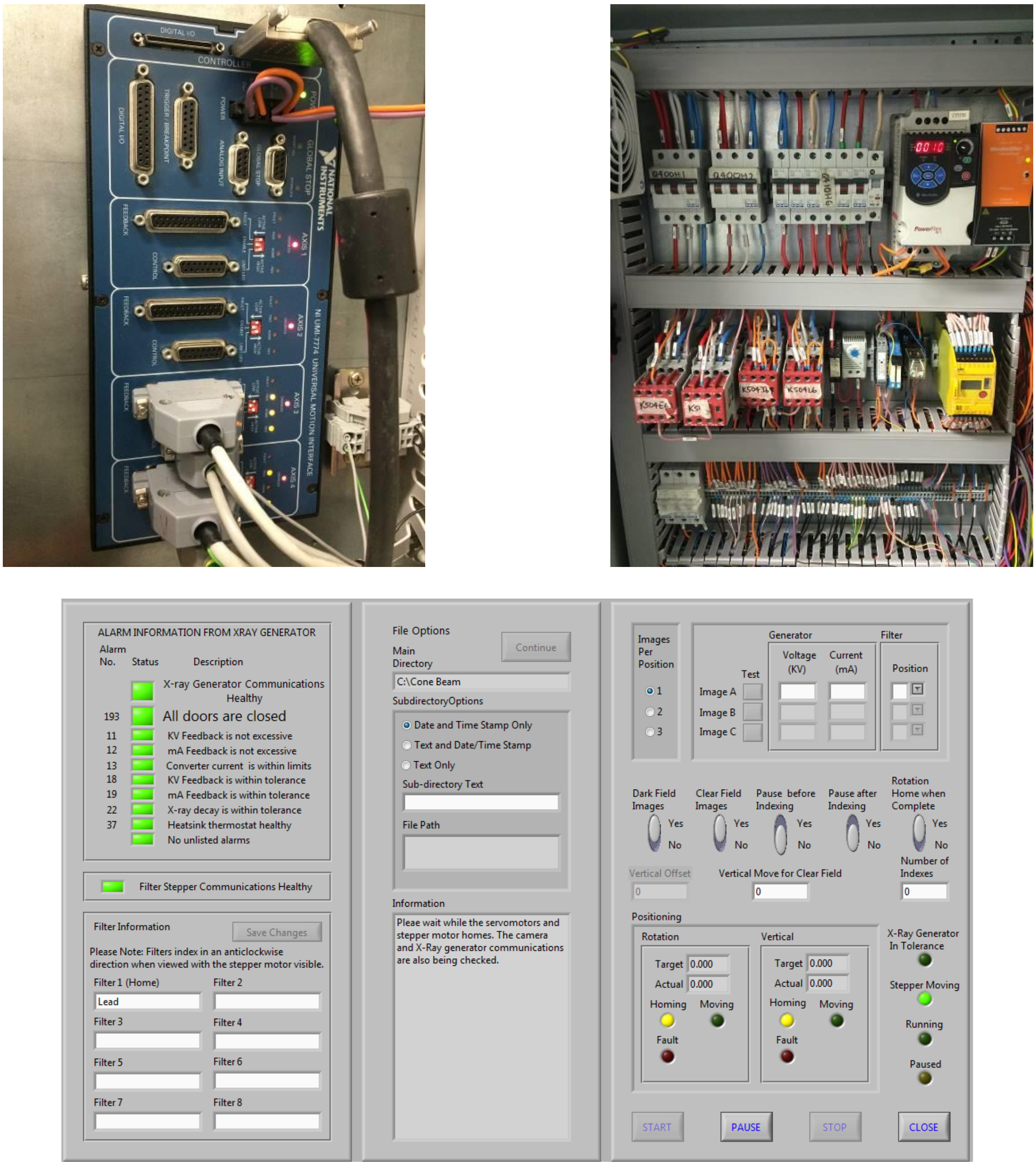


Figure 8: Universal interface boards takes outputs from the PC and controls servo drives for rotational and vertical motion (Top Left). Control cabinet, showing safety contactors and controller (Top Right). Graphical user interface for apparatus control (Bottom).

3.3.3 Reconstruction

Once a complete data set of projections is acquired, they must then be processed and arranged to form the CT model. The reconstruction software has been developed by SCOTT for use in this particular application.

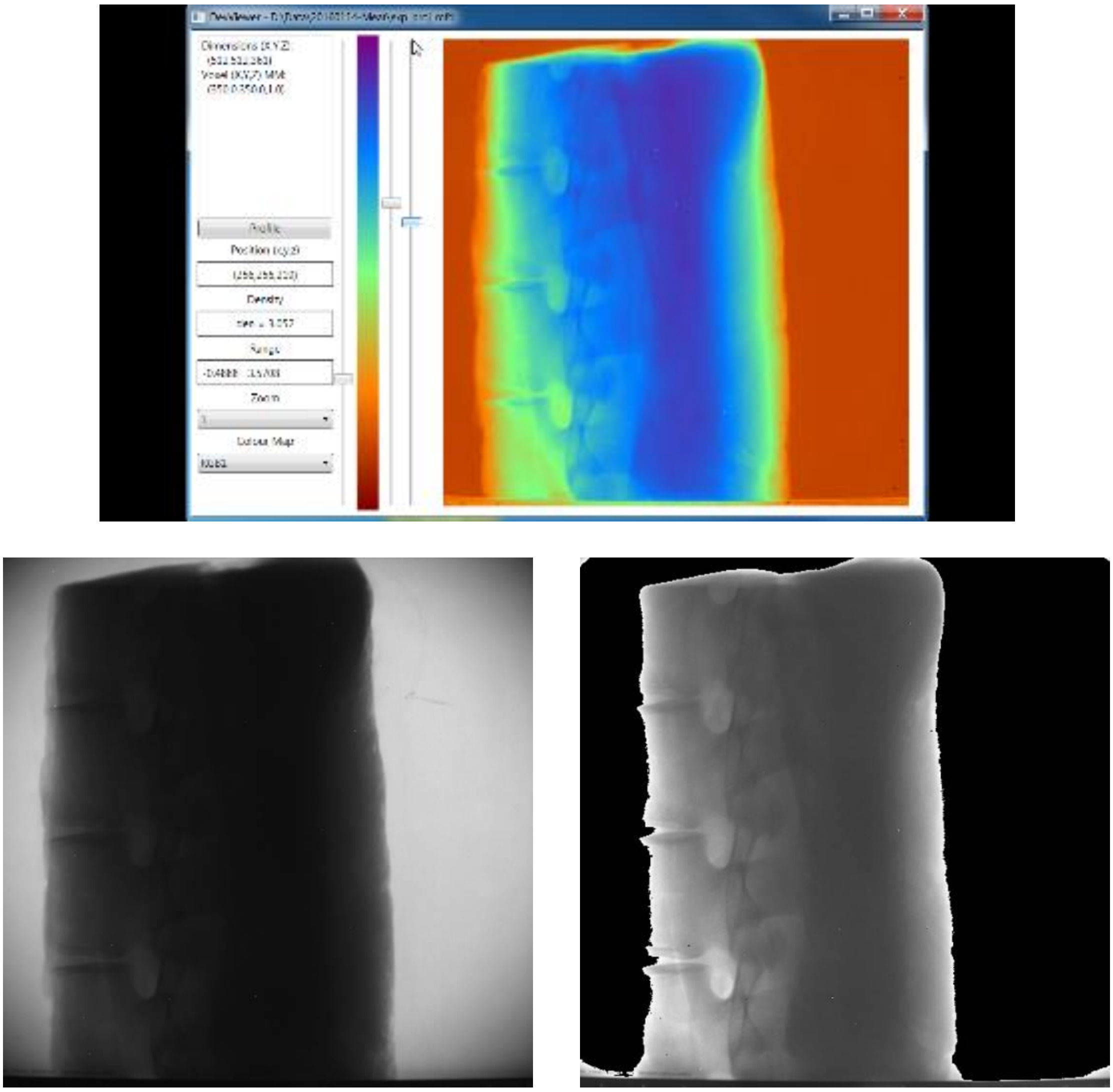


Figure 9: Reconstruction application for data review, enables variation of colours, intensity and contrasts to identify reconstruction artefacts and faults (Top). Pre and post-processing of projection images, with improved contrast and background removal (Bottom Left and Right, respectively).

3.3.4 Image Analysis and Results

Please refer A.MQA.0016 Milestone 4 Report for complete image analysis detail relevant to the following information.

Data Set One – Sample Tin

Object Description:	A steel tin (130mm diameter, 175mm height) was filled with short sections of electrical wire, a bolt and calcium carbonate powder.
Scan Parameters:	Single Energy @ 125kV, 1.0mA, Projections; 360.
Image Quality:	Excellent, with a volume element size of 0.48 mm cubed and sufficient grayscale contrast to easily delineate individual components.
Comments:	The dimensions and composition of this object were chosen to demonstrate both the dimensional and grayscale resolution capabilities of the system. The component steel, wires, bolt and powder are easily discernible and the subject geometry has been reconstructed accurately.

Reconstruction:

Figure 10a: Photo of Sample Tin.

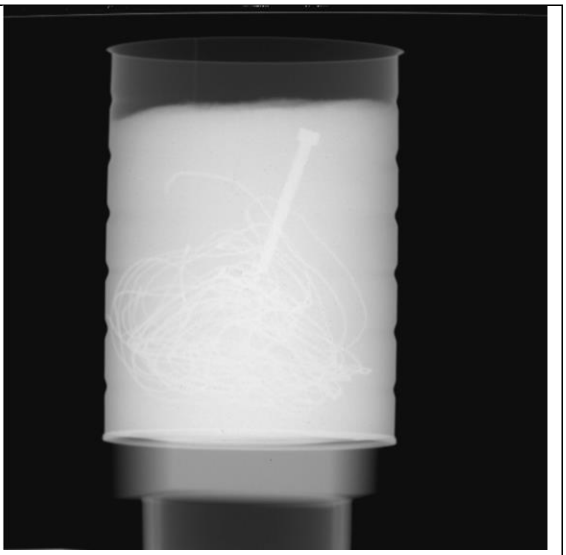


Figure 10b: Projected X-ray Image.

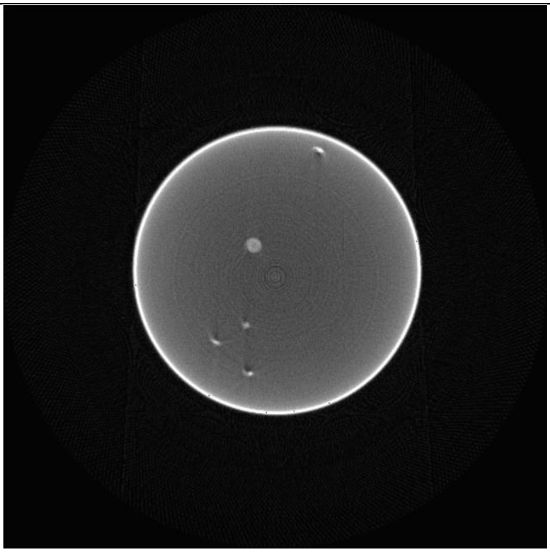


Figure 10c: A transverse cross-section.

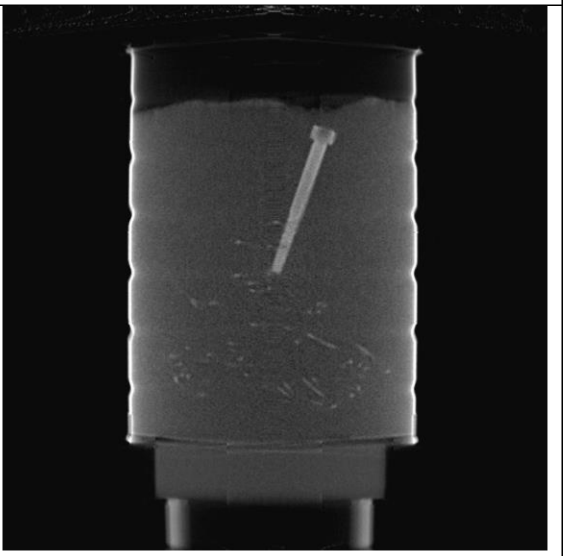


Figure 10d: A coronal cross-section.

Data Set Two – Beef Striploin

Object Description:	Frozen T-Bone section of a Beef Striploin, contained in a polystyrene box.
Scan Parameters:	Single Energy @ 100kV, 1.6mA, Projections; 360.
Image Quality:	Poor, predominately the result of: • Strip loin moving due to thawing over the 70 minute duration of acquisition leading to poor spatial resolution, seen as double imaging at edges. • A combination of beam hardening and Compton scattering reducing contrast.
Comments:	Object movement over the course of the acquisition (70 minutes) has degraded image quality and prevented effective image registration in reconstruction. The best compromise in alignment of the images between using bone and tissue edges gives the blurred results seen in figure 2.

Reconstruction:

Figure 11a: Photo of Beef Strip Loin in polystyrene box.

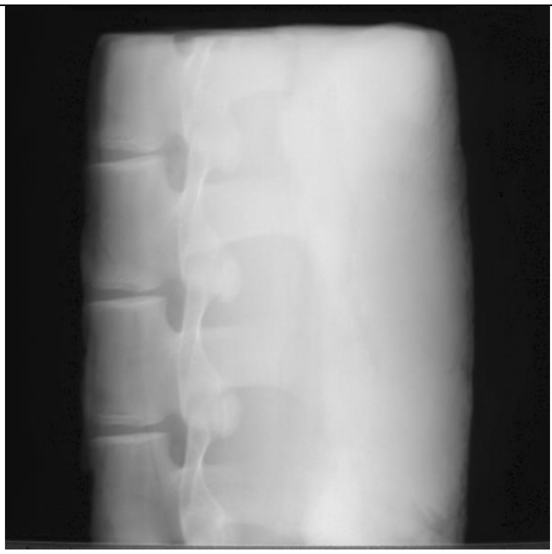


Figure 11b: Projected X-ray Image.

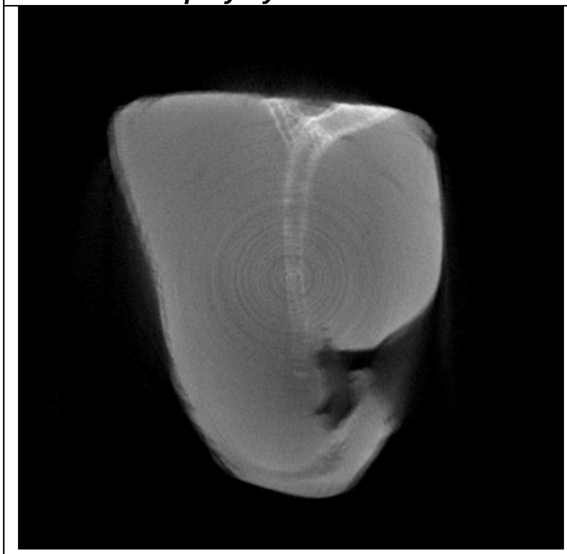


Figure 11c: A transverse cross-section.

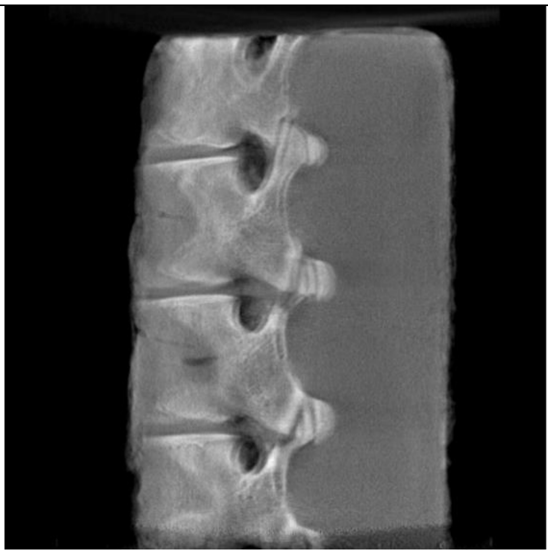


Figure 11d: A coronal cross-section.

Data Set Three – Lamb Rack

Object Description:	Frozen Lamb Rack Saddle, 9 ribs with flaps and brisket removed.
Scan Parameters:	Single Energy @ 100kV, 1.0mA, Projections; 360
Image Quality:	Almost excellent, with some spatial resolution issues at the ends of the ribs, seen as double imaging. This again is due to the rack moving as a result of thawing over the 70 minute duration of acquisition.
Comments:	Another instance of object movement creating blurring in the reconstruction. Whilst the spinal column is excellent, the tissue shows blurring at the extremities of the field of view. This is due to the optical distortion of the camera lens, an effect which can be compensated for in the image processing tasks but not yet implemented. Also of note is the lack of contrast between tissue and fat in this sample. This distinction should be obvious, however excess x-ray scattering is responsible for decreasing the signal to noise ratio and obscuring the contrast between muscle and adipose tissue.

Reconstruction:

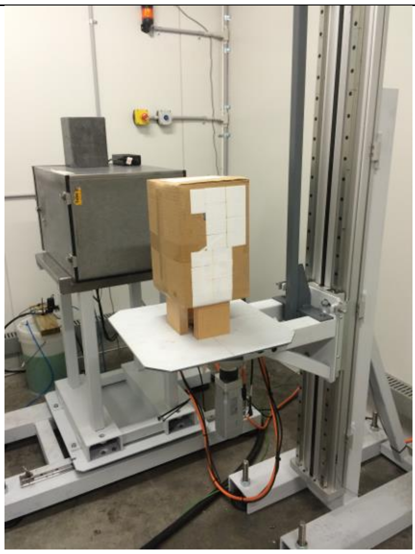


Figure 12a: Photo of Lamb Rack Saddle in Box.

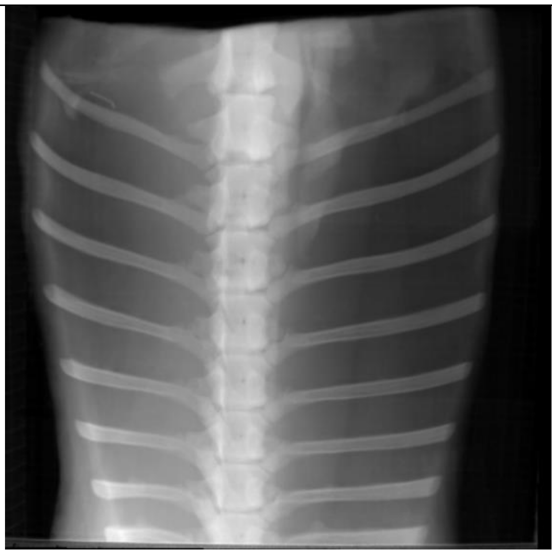


Figure 12b: Projected X-ray Image.

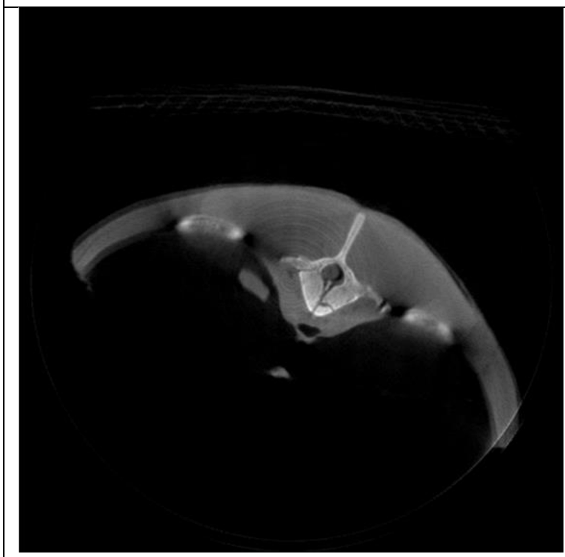


Figure 12c: A transverse cross-section.

Figure 12d: A coronal cross-section.

3.3.5 Image Quality Improvement

The quality of the current images is limited by the following factors:

1.	Acquisition time is too long
Solution 1:	Optimise the control system hardware and software to allow much faster acquisition times. This will require replacement of some hardware in order to achieve the timing and close sequencing needed for high speed imaging.
2.	There is a significant amount of scattered radiation in the current layout caused by lack of collimation of the x-ray source and a sub optimal geometry of the tube-object-detector layout. Scatter is a major cause of contrast reduction.
Solution 2a:	Collimate the x-ray source using remotely adjustable slits that will allow the beam size to be optimised for each object.
Solution 2b:	Conduct a series of experiments to evaluate various tube-object-detector layouts to minimise scatter. The exact nature of scatter is complex and identifying the optimal geometry is best done by a series of experiments.
3.	One of the effects arising from the propagation of x-rays through large objects is beam hardening which results in a reduction in image quality.
Solution 3a:	Experiment with various tube voltages and filters to minimise beam hardening for the specific case of meat primal subjects.
Solution 3b:	Introduce beam hardening reduction algorithms into the reconstruction software.
4.	The x-ray detector as built uses an optical lens to collect the light from the x-ray converter. All optical lenses have distortion. In the case of this lens it is barrel distortion as shown in figure below. The effect of this distortion is to degrade image quality at the outside edges of the frame.
Solution 4:	Introduce spatial distortion reduction algorithms into the reconstruction algorithms.

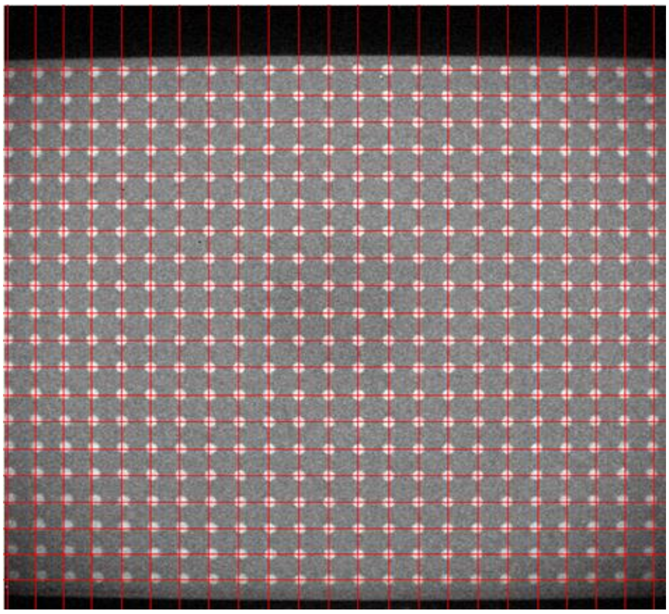


Figure 13: *X-Ray projection of the aluminium calibration plate illustrating the barrel distortion.*

The implementation of the above solutions was going to be necessary on the way to a CT system capable of operating a production environment. Through the work on this part of the project, it has become apparent that the implementation of these methodologies is required before we can make an accurate assessment of the possible performance of a potential production CT system.

The primary limiting factor of the system currently is the control system. The initial design concept of one centralised processing unit to control all hardware and image acquisition would have enabled a powerful and flexible proof-of-concept system. There have been significant ongoing issues with getting the control system to operate as specified. This has limited the potential of the proof-of-concept system. A number of workarounds have been implemented however which have enabled scans to be performed. These scans have enabled the construction, verification and evaluation of the geometric alignment and reconstruction algorithms – the key aspect of the proof of concept system. They have also enabled initial assessments to determine the aforementioned factors will be relevant (although to a lesser extent to the control system) to further developing the proof-of-concept system to enable the specification of a commercial solution.

3.3.6 Further Refinements

In addition to the immediate solutions available for improving image quality, the following items will be considered to further optimise the system.

Field of view

The size of the object able to be scanned is still relatively small (approximately 300mm x 200mm x 180mm). This can be changed by altering the object-detector distance to shrink or magnify the projection, or by positioning the detector at different locations and stitching the resultant reconstructions together.

Helical scan

At this stage of the concept, the system only uses rotational motion at a fixed vertical position. Helical scanning combines rotational with vertical motion to collect a data set over a larger area in the same time, however requires more complex reconstruction routines.

Calibration Standard

Use of a standard, stable and representative material should be considered to ensure consistency across different scans of red meat products.

Multiple Energy Exposures

In the same way that DEXA for line scan x-ray can be used to increase contrast, use of different energies for the Cone Beam system will improve contrast resolution. The system has capacity for this but has not been tested at this time.

Automated Reconstruction

At this stage the reconstruction software stands alone and is not part of the system control software. Once the stability of this software is proven over a number of scans, it may be integrated into the acquisition system to automatically provide an output from the scan.

Automated Measurement/Feature Extraction

Further to the point above, the scan output may be further processed to provide dimensional information or statistical data on the scan subject.

4 Conclusions/Recommendations

An initial proof-of-concept cone beam system has been developed at Scott Automation and Robotics' facility in Tullamarine, Victoria.

- A purpose built x-ray laboratory was constructed. This facility was constructed with lead shielding and air-conditioning to ensure safety of personnel and optimal operation of the x-ray hardware.
- The mechanical concept for product movement to enable cone beam scanning was designed, constructed, installed and commissioned within the laboratory.
- The required x-ray hardware, including x-ray tube, generator, cooling unit and detector panel were purchased, mounted, installed and commissioned.
- An interchangeable filter mechanism was also designed and constructed to allow for up to three different x-ray images to be acquired per slice if required.
- A high-end high-speed camera was selected and mounted within a specially designed lead-lined box to enable digital image capture of the slices.
- Finally, a high-end integrated control system was selected and specified with a supplier and purchased to enable centralised control of product movement, dynamic x-ray parameter control and image capture.

Utilising this system, the complex geometric alignment and reconstruction algorithms were able to be developed and verified. These algorithms, which convert the collection of slice images into a complete 3D CT image of a sample, were tested with great success.

The system as constructed is capable of accurately imaging an object with adequate spatial resolution and grayscale contrast for this application. However, image quality issues have arisen when imaging meat in part due to the long scan acquisition times and the tendency of these objects to move as they thaw out, and also due to the occurrence of the physics phenomena of Compton scatter and x-ray beam hardening.

The first instance where significant gains can be made in the time taken to acquire a complete data set is the control system. The initial design concept of one specialised, centralised processing system to control all hardware and image acquisition would have enabled a powerful and flexible proof-of-concept system. Unfortunately, on-going issues have been experienced in attempting to operate the system to specification. Despite attempts to address these, there have been significant delays and challenges in completing a functioning proof of concept system. In order to progress the project to develop and test key reconstruction algorithms the overall system in its current form utilises a number of secondary measures to provide the functionality that should have been included in the 'plug and play' control hardware. With the implementation of a fully featured camera driver, and an optimised program sequence, the cycle time can be reduced by approximately 75%. Once operating within this cycle time, the limitations of the system in relation to the physics of x-rays and optical light can be properly explored, and ultimately provide a result as to whether the system architecture can be applied to a production environment.

With the solutions described in this report successfully implemented, a full assessment of image quality and useful information content must be performed. In particular, the effect on image quality of scan time must be evaluated. It is certain that the faster the scan, the poorer will be the images. Given the need for high speed in a production environment there are two methodologies that should be evaluated to determine their effectiveness in preserving information content at high scan speeds. These are dual energy CT and using less than 360 degrees of rotation to image a carcass. Dual energy CT requires that the carcass be imaged twice at two x-ray energies but has the benefit of greatly increasing the material differentiation capabilities of the system. Consequently, it may be possible to do fat/lean/bone discrimination with much poorer quality images. The exact trade off can only be evaluated by experiment using the POC system.

It was always envisaged that in a production environment, it would be very difficult, if not impossible to perform a full 360-degree scan of a carcass at line speed. 'CT' using a reduced data set is known as tomosynthesis. The technique actually pre-dates tomography and has recently undergone a resurgence in the fields of musculoskeletal imaging and mammography. It is similar to tomography with the main difference being it generates volumes with a limited depth of field from fewer projections over a limited angular range. Thus it should be possible to position equipment so that only regions of interest in a carcase are reconstructed. Of relevance are the improvements to musculoskeletal imaging where it should be pointed out that for the application of this project, the lack of organs would render this renewed technique as a viable alternative to tomography. Tomosynthesis is based on constructing a volume by iteratively comparing between simulated and measured projection images to generate corrections to the volume. Consequently, the computational requirements are much larger than those required for tomography. In addition, there is the potential to also correct for object movement, but this in itself would further increase the computational requirements.

Moving forward with the developed platform, through a combination of hardware and software improvements, the performance of the overall apparatus can be further increased, and progress the integration of the key elements into a production trial ready system. The technology demonstrated at this point plus a sub-set of the improvements mentioned in this report should enable the generation of 3D data with sufficient spatial resolution and grayscale contrast to meet requirements for the red meat processing industry.