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X-ray development trials

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Abstract

This report outlines the results of the x-ray trialling performed to determine the feasibility of utilising x-ray imaging as a sensing technology for four red meat industry applications:

- Beef Scribing
- Beef Feather Bone Processing
- Beef Spinal Cord Removal
- Ovine Primal Cutting

It was found that single-energy x-ray imaging would not be suitable for any of these applications. Dual energy x-ray imaging however lent itself well, especially to beef scribing and ovine primal cutting, which require the identification of sub-surface features. There was a high level of confidence that a good result could be obtained for the feather bone processing application, but it was felt other sensing technologies may be more suitable. The beef spinal cord removal seemed more challenging but potentially possible using x-ray. Again, it was felt that alternative sensing technologies may be more suitable.

Executive Summary

X-ay imaging is a sensing technology which exhibits a significant level of promise with meat industry automation projects. The reason for this is its ability to detect sub-surface features. There are essentially two methods widely used to obtain x-ray images – single energy and dual energy imaging. Single energy imaging involves imaging the object using a single x-ray spectrum. The advantage in this method lies in its simplicity. It does however demonstrate drawbacks when processing objects of varying sizes with similar materials (i.e. varying beef carcasses with bone, muscle, fat and cartilage which all present similarly to x-ray). Dual energy imaging involves imaging the object using two different x-ray spectra to isolate certain materials of interest (i.e. bone vs muscle/fat/cartilage) regardless of relative thicknesses.
This project investigated the potential to use x-ray imaging for four meat industry applications:

- Beef Scribing
- Beef Feather Bone Processing
- Beef Spinal Cord Removal
- Ovine Primal Cutting

Initial x-ray trials were performed in-house at MAR. These trials were able to give a good idea on the capabilities of using single-energy imaging for these applications. The results demonstrated that the aforementioned limitations associated with single-energy imaging meant it wasn't a viable option for these applications. Dual energy trials were also attempted at MAR with limited success. It was determined that external assistance would be required and Applied Sorting Technologies (AST) in Melbourne was engaged as a partner to conduct the x-ray trials. These trials would be done in conjunction with work relating to a project on Beef Rib Cutting which was looking to use x-ray (the scope of which is a subset of the "Beef Scribing" requirements).
AST conducted an in-depth theoretical analysis and simulation into the Rib Cutting requirements in order to determine the ideal x-ray configuration required. This step exhibited the limited understanding of dual-energy x-ray imaging possessed early in the project. As such analysis wasn't allowed for in the project for each application, data was taken using the x-ray setup for the rib cutting which was then analysed to gauge potential for x-ray use as the primary sensing technology and what optimisations could be applied to achieve better images.
The beef scribing application gave promising results and appeared to lend itself well to the x-ray task at hand. Isolation of one of the key features of interest (the intersection of rib 1 and the sternum) was achieved with a high level of contrast. The other key feather, the individual vertebrae, did not present well in this setup. However, there is a high level of confidence that with a higher power tube (thus providing greater penetration), perhaps a different type of detector and changing the calibration procedure slightly would provide an immediate improvement in the raw image. By adding another level of data processing, the scapula can also be essentially removed from the image to give greater visibility of the spine towards the cranial end of the carcass. For these reason, it is believed that dual energy x-ray would be an ideal sensing technology for the beef scribing application.
The beef feather bone trials provided less than ideal images which was to be expected given the lower density of feather bones versus ribs (which the x-ray setup is optimised for). Even in this case, the images presented fairly well. It was felt that the feather bones would be able to be imaged clearly by simply modifying the calibration procedure for feather bones and cartilage and by modifying the dual energy recombination algorithm to isolate bone **and** cartilage versus muscle/fat. This latter modification would prevent the tips of the feather bones from being washed out in the x-ray image. While there is a high level of confidence that an ideal x-ray configuration could be found, it is felt that other sensing technologies may be more suitable for this application – namely vision and 3D - and should be investigated first.

The beef spinal cord removal application showed some promise through the visibility of the spinal cord channel in the tailbone section of the carcass. This wasn't visible throughout the entire length of the spine as the x-ray configuration wasn't optimised to give high visibility of the spine. It is felt though that, using similar proposed modifications as the beef scribing application, the spinal channel may be able to be isolated using the same method envisaged for removing the scapula from the image. The level of confidence for this application however is not as high as the other applications. As with the feather bone processing, it is recommended that other sensing alternatives be investigated first.

The ovine primal cutting application was one which also lent itself well to dual energy x-ray. Even with the sub-optimal x-ray configuration, the results obtained were positive. Given the less challenging nature of ovine carcasses in terms of thickness and size variation (in comparison to beef), there was a high degree of confidence that high-quality results are attainable. This would allow for simple processing to identify the ribs, vertebrae and joints of interest to perform the required cuts.

Contents

1 Background

1.1 X Ray Introduction

X-rays are a form of electromagnetic radiation like light, UV, infra-red etc. Each 'particle' of x-ray radiation is called a photon. Each photon has an associated energy level, which is measure is eV (electron-volts). When x-rays are produced by an x-ray tube, a range of different energy x-rays are produced in what's known as a spectrum. This is similar to how visible light consists of a spectrum of different energy light particles (photons) which gives rise to the different colours we see.

The spectrum produced by the x-ray tube is defined by a number of characteristics, the key of which is the operating voltage which defines the maximum energy of the x-rays produced. For instance, an x-ray tube operating at 90kV may produce the spectra shown in Figure 1. It can be seen that operating a tube at 90kV (kilo-volts) will produce x-rays with energies less than or equal to 90keV (kilo-electron-volts). Controlling and matching the spectra for an x-ray imaging application is equivalent to selecting the correct lighting for a machine vision setup.

The spectrum is also defined by the target material used in the tube as well as what filtration is used. Filters can be placed over the x-ray tube window and may be constructed by any material required (e.g. copper). These affect the shape of the x-ray spectra again in a similar fashion to light filters used in lighting setups for conventional imaging.

X-ray tubes can also be run at different current levels (mA levels). Increasing the mA to an x-ray simply increases the number of photons exiting the tube. The spectrum itself is unchanged.

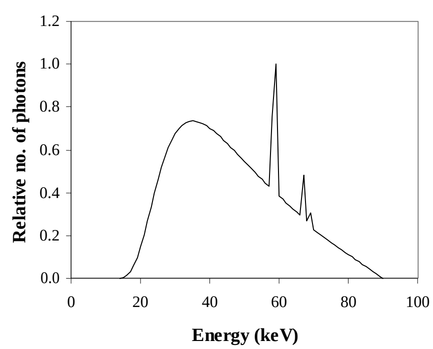


Figure 1 - Example X-ray Spectra

When an object is imaged using x-ray, the x-rays hit the object are some are reflected/scatter, some are absorbed and some are transmitted. The x-rays transmitted then pass through to some form of detector which collects the x-rays to produce an image. Areas in the object in which a lot of x-rays are absorbed will appear different to areas in which most x-rays are transmitted.

There are two main methods of x-ray imaging: single-energy and dual-energy. Single-energy imaging involves taking an image at a single kV setting (ie with one x-ray spectrum). Dual-energy imaging involves taking two images – one with a low kV setting and one with a high kV setting (ie with two distinctly different spectra).

The purpose for doing this is that different materials have different absorption characteristics to x-rays at different energy levels. The absorption characteristic graph for water is shown in Figure 2. It can be seen for instance that significantly more x-rays with an energy of 1keV are absorbed than with an energy of 1MeV. Using this fact, certain materials are then able to be isolated from surrounding materials in a dual-energy x-ray image. For example, an image can be optimised to accentuate bone while removing muscle, fat and cartilage mass. The main motivator for using single energy x-ray is its relative simplicity.

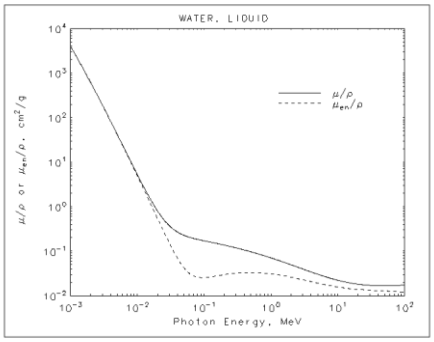


Figure 2 - Absorption coefficient graph for water

Thus imaging with x-rays provides the opportunity to identify subsurface features in an object – features which aren't externally visible and therefore able to be sensed with other sensing technologies such machine vision. This is where x-ray represents its value as a possible sensing technology for meat industry automation projects.

1.2 Work Completed to date

As part of another meat industry project on automated rib cutting, some work has already been completed on x-ray sensing. During this project, a number of x-ray trials were completed. Firstly, beef carcass sections were x-rayed at two different facilities to gain an idea of the potential for using the technology for this application. These trials gave initial insight into whether x-ray would be a feasible option while also showing the difference in single energy versus dual energy results.
X-ay equipment was then rented from a supplier and set up in MAR's workshop. Using a conveyor, a beef fore-quarter was scanned under a number of different conditions in order to determine which x-ray settings would be required to obtain an optimal image. These trials investigated single energy imaging and dual energy imaging; as well as a number of x-ray technology integration issues such as beam collimation and alignment, intensity loss and x-ray scatter (to determine shielding requirements). The key deliverables from these trials would be what kV and mA will be required and what shielding would be needed.

Figure 3 - MAR X-ray Trial Setup

The single energy trials conducted included:

- Trialling different kV at maximum mA capable
- Trialling different kV at maximum mA with different detector settings
- Trialling different kV at reduced mA to emulate expected intensity loss from the layout
- Trialling different kV with extra meat added behind rib 1

These trials were performed with some success, but the limitations of a single energy solution for beef became quickly apparent. More details on these trial results are provided in the Section **Error! Reference source not found.** of this report.

The dual energy trials were trialled using a dual energy detector and a single source. The methodology used was the same as with the single energy trials, except for each kV trialled, there would be two sets of data produced (a low energy (LE) and high energy (HE) dataset). This data would then be combined using a particular algorithm to create the dual energy image. Thus, the dual energy trialling also investigated the use of a different number of algorithms to stitch together these two sets of the data to produce the optimal image. The ultimate goal was to accentuate bone and remove muscle and fat from the image. The main benefit of this is the ability to differentiate thin bone from thick muscle – something that isn't possible with single energy x-ray imaging.

These trials however did not meet the same level of success. No matter what was attempted, the bone could not be successfully isolated. Results mirroring those achieved in the initial dual energy trials using a baggage scanner, as well as those observed from medical images, weren't able to be attained. It was determined that the capabilities in-house were reached and that outside assistance would be required.

MAR then partnered with Applied Sorting Technology (AST) who possess extensive experience both in x-ray technology and the meat industry, making them an ideal partner. Their initial approaches to the problem were also met with limited success proving the non-trivial nature of the task. They then enlisted the assistance of an external consultant whose expertise lay in dual energy x-ray. His initial approaches to the project displayed immediately the shortcomings in MAR's understanding of dual energy applications. By initially performing complex theoretical analysis and computer simulations on the task, he was able to determine first and foremost that a single dual energy detector would not be able to be used for the application. What would be required were two separate detector/x-ray tube pairs. He also calculated the optimal kV and mA to use, as well as what filtration would be required. He was also then able to apply a complex dual energy imaging algorithm to the data to obtain results much more promising in nature. These results are outlined in section **Error! Reference source not found.**.

With the results obtained from this trialling, it became clear that the nature of dual energy x-ray is far from intuitive. Trialling is unfortunately not simply a case of iterating through a number of different energy levels to determine an 'optimal' energy – significant theoretical work must be conducted on the application in order to determine not only energy level, but equipment requirements (e.g. a dual energy detector versus multiple detectors), filtration and appropriate calibration and imaging algorithms.

The methodology for the trials conducted as part of this project were envisaged to be of the nature of examining multiple energy levels and developing conclusions based on the images produced. However, it is now known that such an approach will not work. As a result, the dual energy trials for the applications covered in this project are conducted with a setup which is optimised for the Beef Rib Cutting project. The large amount of pre-work required by the consultant to identify the optimal setup for each application was not able to be accommodated in a project of this size. However, it must be stressed that the data provided are still indicative of the potential of using x-ray as a sensing technology for each respective application. The images produced using this setup are then analysed and discussed, with possible improvements and considerations moving forward being outlined. As the x-ray system to be provided by AST for rib cutting is quoted as a whole, the potential cost for each application is given relative to the Rib Cutting system cost quoted.

2 Project Objectives

This project aims to investigate the possibility of using x-ray as a sensing technology for the following meat industry applications:

- Beef Scribing
- Beef Feather Bone Removal
- Beef Spinal Cord Removal
- Robotic Ovine Cutting

3 Methodology

The trials were conducted using the setup pictured in Figure 4. A carcass side was sourced which was divided into sections in order to fit within the testing rig. The carcass side sourced was a bull with a dress weight of 230kg and reflected the largest and thickest carcass sides processed at Swift. For each carcass side section, a number of both low-energy and high-energy images were obtained from the sample. A number of low-energy and high-energy images from each respective set were then averaged together. The data from these images were then combined using a dual energy algorithm to provide the final dual-energy x-ray image. By averaging different numbers of low-energy and high-energy datasets, a more powerful x-ray setup was able to be emulated.
The x-ray configuration used for the trialling is as follows:

- Low energy image – 70kV, 9.0mA, GOS filter
- High energy image – 140kV, 4.6mA, 1.6mm Cu filter
- Carriage speed – 400 mm/s
- Dual energy imaging algorithm – Base Material Decomposition
- Detector Normalisation with 50mm Perspex
- Calibration Phantom – Perspex 0mm to 80mm in 10mm steps; Aluminium 0mm to 3mm in 0.3mm steps

Figure 4 - AST Trialling Setup

4 Results and Discussion

4.1 Beef Scribing

4.1.1 Overview

The beef scribing operation consists of placing the first cuts to a side of beef in its preparation for boning activities. This process involves placing one or two vertical cuts across the carcass's ribs. It

generally also involves a number of horizontal cuts to be performed across the spine of the carcass side.
Examples of beef scribing specifications for Australian processors are shown in **Error! Reference source not found.** and **Error! Reference source not found.**. Images showing these cuts on actual carcasses are shown in **Error! Reference source not found.**.
The first vertical cut runs along the line which generally starts at the junction of the first rib and the sternum, and extends up to the reflection of the diaphragm and rib 11 and continuing through rib 13. The second vertical cut line runs parallel to the first cut line, at a specified distance towards the spine from the first cut.
The horizontal cuts are placed between two adjoining vertebrae as specified and run horizontally between the edge of the carcass and the chest cavity. It can be seen from the aforementioned specifications that a number of different horizontal cuts can be required along the spine of the carcass, extending from as low as the bottom of rib one, to as high as the last vertebrae.
Thus, for the vertical cuts, the key point of interest is the intersection of rib 1 and the sternum. For the horizontal cuts, the key points of interest are the individual vertebrae in the spinal column along the entire length of the carcass. The most challenging horizontal cut appears to be that which is located just below rib 1 due to the thickness of the carcass in this area, as well as the existence of the scapula.

4.1.2 Industry Benefit

It can be seen that a fundamental flaw exists with the current manual process – the cut specifications are determined by the positions of bones and joints which may not be immediately visible to an operator. As a result, manual operators often perform cuts based on other visual cues on the carcass resulting in cuts which don't strictly meat the required specification. This also results in different operators having different opinions of where the cut should be placed on any given carcass. Identification of the required points of interest lends itself well to a technology such as x-ray which is capable of identifying sub-surface features. The result of this is an anticipated benefit of 2.0% yield improvement (for selected cuts). As well as a significant improvement in yield, other benefits would include:

- Labour replacement
- Potentially increased throughput
- Reduction in OH&S costs
- Reduction in staff training costs

4.1.3 Energy Trialling – Single Energy

Initial x-ray trials were conducted to investigate the suitability of utilising a single-energy x-ray setup for this application. The benefits of using single energy include a simpler setup with lower equipment costs. It was expected however that single energy would not be sufficient to see through the junction of the sternum and rib 1 as this is one of the thickest areas on the carcass. It was also expected that single energy x-ray penetration would be insufficient to isolate individual vertebrae along the spinal column. However, due to the potential benefits and for completeness of trialling, single-energy trials were conducted.

4.1.3.1 Images and initial observations

Single energy x-ray images were obtained for a beef carcass from a previous meat industry projects. The results of these trials are shown below.

Figure 5 - Scribing - Single Energy 80kV (Rib 1 circled)

Figure 6 - Scribing - Single Energy 120kV (Rib 1 circled)

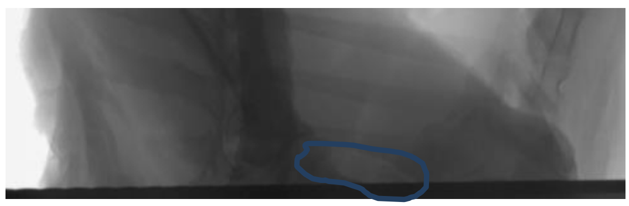


Figure 7 - Scribing - Single Energy 160kV (Rib 1 circled)

It was found that a much less pronounced progression in image quality expected. This particular carcass sample was on the 'smaller' side, with a thickness of approximately 170mm through the sternum and rib 1. Even so, it can be seen that rib 1 'disappears' as it passes across the thicker sections of meat towards the sternum.

Single energy trials were also performed focussing on the vertebrae. Given the challenges experienced with the visibility of rib 1, the expected results for the spinal column weren't expected to be of useable quality. The results can be seen below.

Figure 8 - Scribing - Single Energy 80kV (Spine)

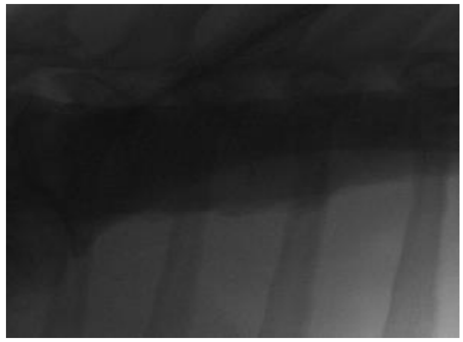


Figure 9 - Scribing - Single Energy 120kV (Spine)

Figure 10 - Scribing - Single Energy 160kV (Spine)

Again, it can be seen that isolating individual vertebrae was extremely challenging with a single-energy solution. The 160kV case looks somewhat promising, but still extremely challenging from a X-ray image analysis perspective.

4.1.3.2 X-ray image analysis

The single energy images were then visioned in an attempt to isolate the targeted features. The results for the rib 1 visibility are shown below.

Figure 11 - Scribing - Single Energy 80kV (Rib 1 circled) - X-ray image analysis

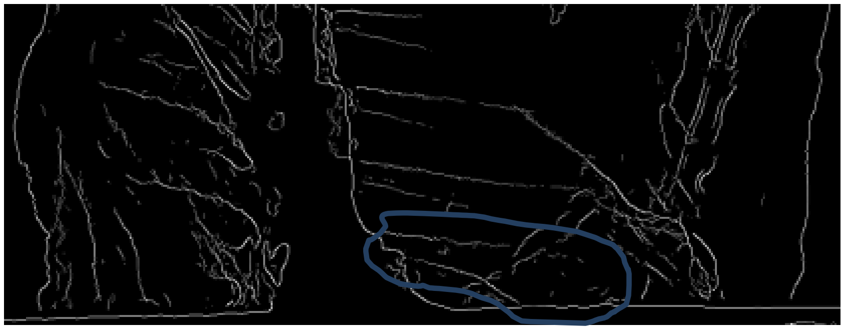


Figure 12 - Scribing - Single Energy 120kV (Rib 1 circled) - X-ray image analysis

Figure 13 - Scribing - Single Energy 160kV (Rib 1 circled) – X-ray image analysis

It can be seen that the while the beginning of the rib is fairly visible, the rib becomes lost as it moves past the thicker muscle around the chest of the beast. Where rib 1 finishes and meets the sternum is thus impossible to find under these conditions. The muscle also provides quite a bit of noise and false features.

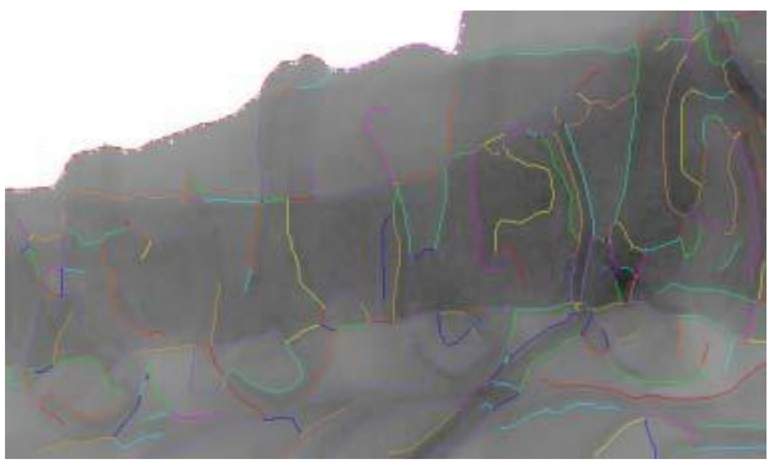


Figure 14 - Scribing - Single Energy 160kV (Spine) – X-ray image analysis

It can be seen that despite aggressive attempts to vision the sample, each individual vertebrae was unable to be isolated. There were also an excessive number of unwanted features which were unable to be filtered out.

4.1.3.3 Discussion

It can be seen from both the rib and spine images that significant difficulty was encountered in providing clear visibility of the features of interest for the beef scribing application. This difficulty could be attributed to a number of different factors which can be attributed to the inherent limitations associated with single-energy x-ray imaging.
The primary reason for this is difficulty penetrating the most challenging areas of the carcass – the intersection of rib 1 and the sternum, and the spine. This lack of penetration is visible to the eye for the given x-ray results. This translates to the poor results obtained by the vision algorithms which were not able to isolate the targeted points of interest.
Given the varying ratio of meat/fat to bone across not only different carcasses, but within the same carcass across different spinal and rib sections, the fundamental issue of separating thin bone from thick muscle also becomes a significant issue. This can be seen by comparing the presentation of rib 3 (green) and rib 1 (yellow) with thin and thick levels of meat behind each respective rib in Figure 15 below.

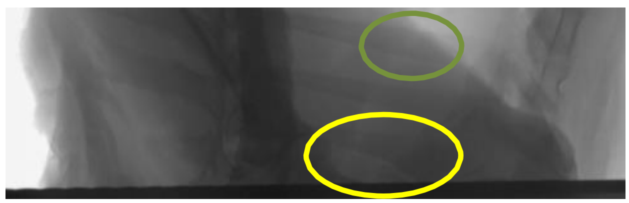


Figure 15 - Comparison of thick muscle and thin muscle

4.1.3.4 Conclusion

Both key features of interest proved to be too challenging to identify reliably using a single energy setup. As initially expected, a single-energy solution would not be suitable for the beef scribing application.

4.1.4 Energy Trialling – Dual Energy

Given the results of single-energy trialling, it was determined that a dual-energy x-ray would provide the best opportunity to identify the key features required: namely the intersection of rib 1 and the sternum; and the individual vertebrae.

4.1.4.1 Images and initial observations

Dual energy x-ray images for a couple of carcasses were taken. The results are shown below.

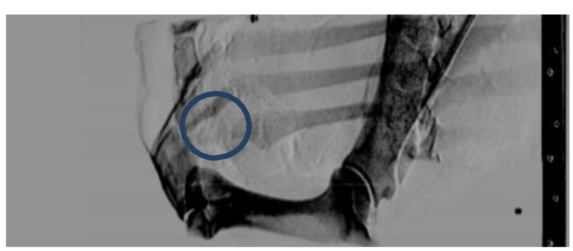


Figure 16 - Scribing - Dual Energy (Ribs 1-3)

This particular body was on the larger side, with a thickness of approximately 210mm through the intersection of rib 1 and the sternum. It can be seen that the intersection of rib 1 and the sternum is clearly visible to the eye. Although there is some noise in the area, most of the muscle in the area has been removed through the dual energy algorithm. This is in stark contrast to the single energy results.

On the other hand however, there is extremely low visibility of the vertebrae. The high amount of noise in the area shows there was an issue with insufficient penetration. More mA would be required in order to penetrate the area. It can also be seen that the scapula provides a significant challenge in this area.

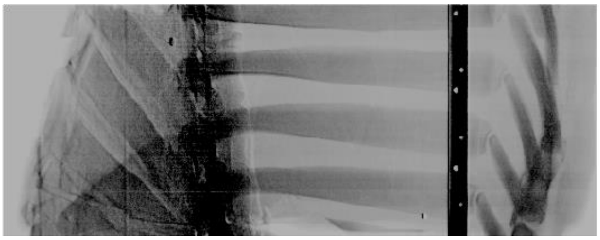


Figure 17 - Scribing - Dual Energy (Ribs 4-7)

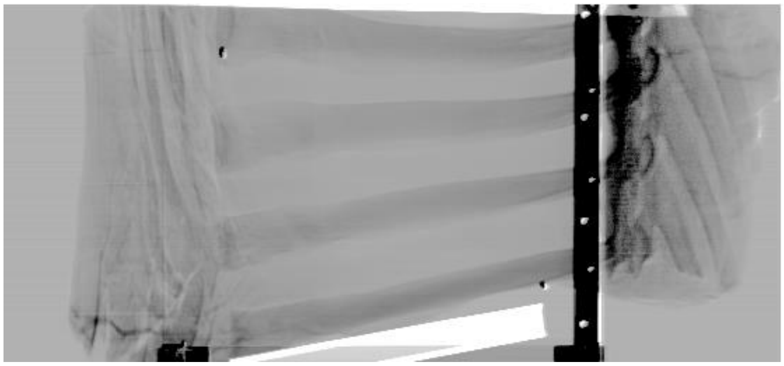


Figure 18 - Scribing - Dual Energy (Ribs 8-11)

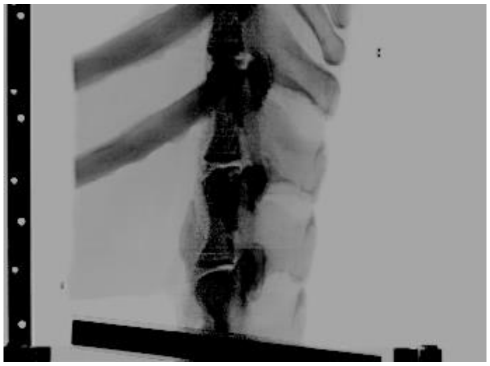


Figure 19 - Scribing - Dual Energy (Ribs 12-13)

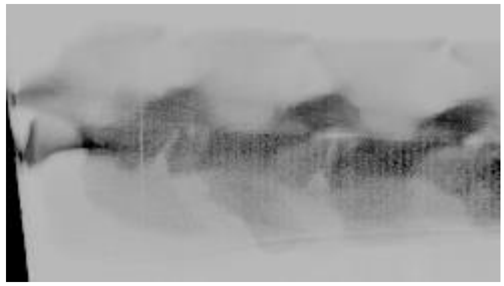


Figure 20 - Scribing - Dual Energy (Spine above Rib 13)

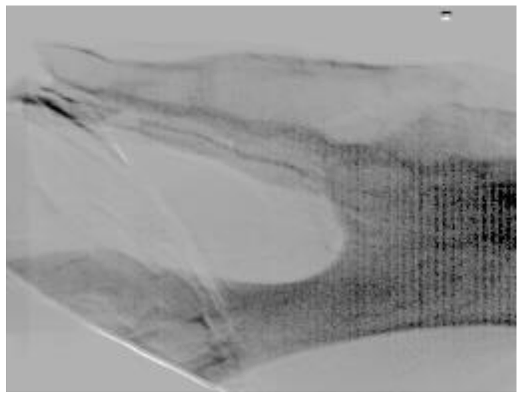
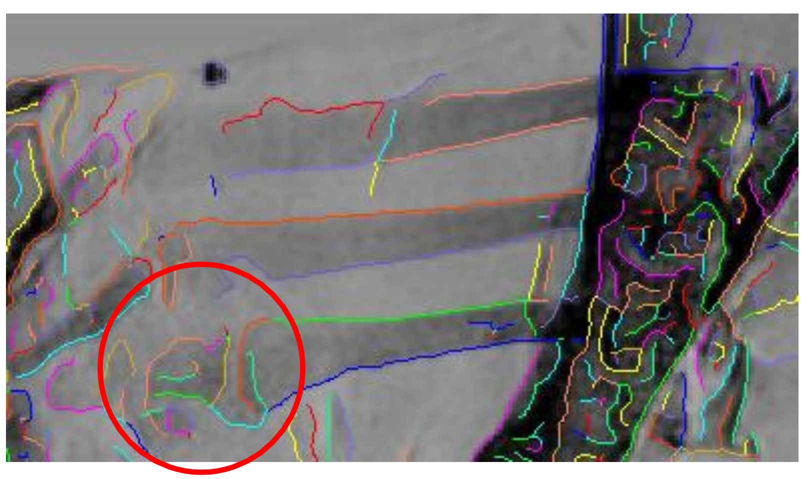


Figure 21 - Scribing - Dual Energy (Tail Bone)

It can be seen that the visibility of the vertebrae becomes less challenging up the length of the carcass, as expected. The presentation of the ribs are also quite clear, especially rib 11 – one of the features of interest.

4.1.4.2 X Ray Image Analysis

The image in Figure 16 was visioned using an edge detection filter in order to isolate where rib 1 joins with the sternum.



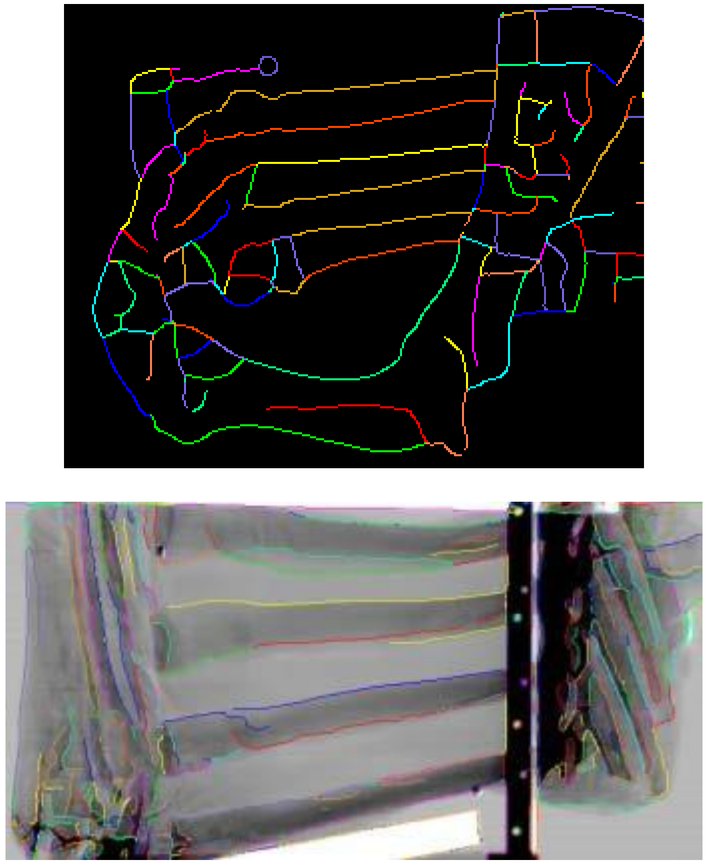


Figure 22 - Scribing - Dual Energy (X-ray image analysis)

It can be seen that the intersection between rib 1 and the sternum is able to be isolated quite clearly (as shown in the red circle). The visibility of the ribs is also quite straight forward. The spine section however is far too noisy to be able to isolate any meaningful features in that area.

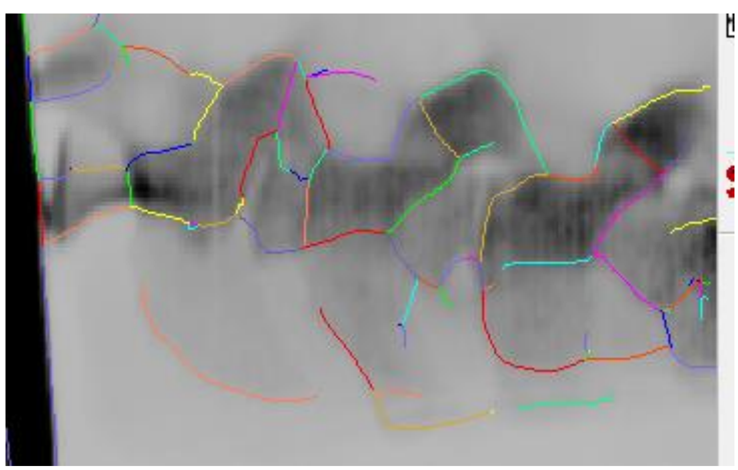


Figure 23 - Scribing - Dual Energy (X-ray image analysis - spine)

Even visioning of one of the better presented images proved challenging, but displayed much more promise. An optimised setup would provide greater visibility of this area. It is also envisaged that extra information such as rib location would be used to narrow down particular regions of interest in which to locate the vertebrae joint of interest.

4.1.4.3 Discussion

The results for identifying the intersection of rib 1 and the sternum (the key feature for the rib cuts) are very promising. The x-ray setup has been optimised to view this area of the carcass and it can be seen that, even with the large amount of meat in behind the area of interest, the ribs are able to be isolated with a relatively high level of contrast

While these results are particularly promising for the rib cuts associated with the beef scribing, it can be seen that the isolation of the vertebrae in this area was unable to be achieved with this x-ray setup. However, there is promise that the correct x-ray setup would be able to provide sufficient visibility of individual vertebrae.

In moving forward with identifying the x-ray requirements for this application, a detailed theoretical analysis and simulation would need to be conducted.

4.1.4.4 Conclusions

It was able to be seen that the optimisations calculated for the rib cutting application were able to enable a high quality image of the key feature of interest (the intersection of rib 1 and the sternum) to be identified, even for the worst-case situation anticipated. While this setup is not able to provide the required results for the full beef scribing specification, it appears as though a solution is able to be calculated for this application for the reasons outlined in Section **Error! Reference source not found.**.
Therefore, based on the results achieved, it is felt that dual-energy x-ray would be able to address the shortcomings associated with single-energy imaging. Dual-energy x-ray can be identified as the ideal sensing technology able to be utilised for beef scribing automation. In moving forward with x-ray, in-depth technical analysis and simulation of the application would be required, but there is a high level of confidence that an ideal configuration would be able to be found.

4.1.5 Sensing Alternatives

There are a number of potential sensing alternatives which may be considered for the beef scribing operation.

4.1.5.1 Vision

There is potential to be able to use conventional vision to perform the operation as it is primarily performed by manual operators by sight. However, as aforementioned in Section **Error! Reference source not found.**, this process is flawed. Operators also use other information to help locate cuts, such as touch. This information becomes imperative for carcasses possessing fat-covered rib cages, “red ribs” and low-visibility cartilage between vertebrae. As a result, conventional computer vision possesses significant limitations in its application to beef scribing. Attempts in previous projects to utilise conventional vision for beef scribing have vindicated these conclusions.

4.1.5.2 Vision + High-resolution 3D

In theory, coupling vision with high-resolution 3D data may provide the information required to identify ribs by identifying their protrusion. However, it has been found through previous trialling that this method is unreliable due to considerations such as the low relative protrusion of the ribs and the existence of fatty deposits (especially around rib 1). It also doesn’t help with issues associated with vertebrae identification.

4.1.5.3 3D modelling

Carcass modelling is a method which has found success with some lamb applications. Investigations into its application for beef operations however displayed limited success due to the larger variation experienced amongst beef.

4.1.5.4 Conclusion

Given the sensing alternatives, x-ray appears to be the ideal technology to use for beef scribing. Ultimately, the specification for the cuts derives from sub-surface features and the most accurate way to reliably identify such features is using x-ray imaging.

4.1.6 Accuracy and Resolution Requirements

The dual energy trials for the rib cutting application utilised a detector with a 1.6mm resolution. It is envisaged that such a resolution would be suitable for identifying the vertebrae as well. Using a finer resolution would increase the cost of the detectors by a considerable amount without a perceivable level of benefit.

4.1.7 Shielding Requirements

Shielding requirements must first be calculated with extensive theoretical analysis once the operating voltage and power has been ascertained, upon which a conservative safety factor is added. Using the rib cutting shielding costs as a baseline, the following points can be considered to extrapolate an approximate shielding cost for the complete beef scribing system.

- Dual energy would be required utilising two separate detectors rather than a single dual-energy detector as per the rib cutting system.
- Dual energy would be required for essentially the entire carcass length.

- It is anticipated that higher energy levels will be required for the complete beef scribing application as opposed to the rib cutting application.
- X-ray layout and equipment scope may change which would have to be taken into consideration.

Based on these considerations, the shielding requirements would be expected to be slightly heavier than for rib cutting. There would still need to be shielding in place blocking all lines of sight to where the x-ray beam penetrates the carcass meaning a rail kink or carcass indexing would be required on the chain to allow for a lead-lined shutter to be utilised.

4.1.8 Equipment Costs

The equipment would be very similar to that required for rib cutting. It is envisaged that a dual-energy setup will be used requiring two tubes and detectors. These will be mounted on a gantry moved by a linear drive to scan down a carcass as it is moving along a stabilisation conveyor. A breakdown of expected major cost items is as follows:

- Detector –
    - A two-detector setup would be required with the same detector lengths as the rib cutting application. However, a different type of detector which possess a logarithmic response rather than a linear response may be required. This would add some cost.
- X-ray tube and generator –
    - A higher power generator and tube would likely be required for the beef scribing applications. The issue with going with higher power equipment is availability, cost and mechanical issues. For instance, going from a 3kW to a 4.5kW tube means an increase in weight from 10kg to 95kg, an increase in length of 600mm and an increase in diameter of 90mm and may require two generators for each tube. However, it isn't expected that a significantly higher level of power would be required and layout modifications could be made to increase scanning time rather than increasing power. Thus there's a potential for an increase in cost of these components, but shouldn't be significant.
- Shielding
    - As mentioned in the previous section, shielding costs would be expected to be similar to the rib cutting application, depending on how much extra power is needed.
- Mechanical Considerations
    - A gantry with a linear drive to move the x-ray and 3D equipment to scan the carcasses as with the rib cutting application.
    - Lead-lined shutters will also be required to shield the entrance and exit to the cell while the x-rays are on.

Image analysis software would also be required. For this application, it is recommended that MVTec Halcon be utilised. The licensing cost associated with this software package is around €5500 for the development license, plus €1350 for the run-time license.

4.1.9 Layout

The sample layout shown in Figure 24 is envisaged for the application. In order to safely accommodate an x-ray system in the cell, some form of active shielding will be required along any

possible line-of-sight from outside the cell to where the x-ray beams intersect the carcass. It is proposed that the most efficient way to achieve this is by decoupling carcasses from the client's existing chain and indexing it onto an MAR-controlled chain for passage through the system. This will allow a set of lead-lined shutters to be used to ensure the entire cell is shielded whilst the x-rays are energised. It will also allow carcasses to pass through the cell continuously, within being affected by any stoppages occurring elsewhere on the client's chain.
The X-ray and 3D components will be mounted on a gantry driven by a linear drive to move down along the carcass as it scans across it. This will allow the x-ray tube to be mounted as close as possible to the source and will also allow the x-rays to scan slightly slower over the thicker, more difficult rib 1 section. It will also allow one 3D scanner and x-ray setup to be used while catering for all carcass sizes.

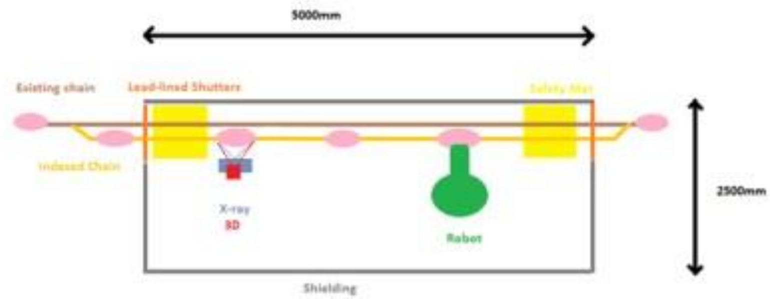


Figure 24 - Beef Scribing - Sample Layout

4.1.10 Conclusion

Beef scribing is an application which could realistically benefit from using dual-energy x-ray imaging as a sensing technology. In moving forward, it is recommended that the theoretical and simulations be conducted to identify the optimal operating range for the application.

4.2 Beef Feather Bone Processing

4.2.1 Overview

Feather bone processing involves the separation of the specified feather bones on the carcass from the surrounding meat. Figure 25 shows a carcass which has had its feather bones processed. This involves running a tool (similar to that shown in Figure 26) around each feather bone. The feature of interest for this application is the feather bones themselves. This includes both the bone itself as well as the cartilaginous tip at the end of the feather bone.

Figure 25 - Feather Bone Processing

Figure 26 - Feather Bone Removal Tool

4.2.2 Energy Level Trialling – Single Energy

4.2.2.1 Images and initial observations

Initial single energy trials show fair visibility of the feather bones from as low as 40kV. However, it can be seen that the contour of the muscle in behind the feather bone is quite obvious. A thicker amount of muscle behind the feather bones at this energy level would almost certainly render them invisible to image processing software.

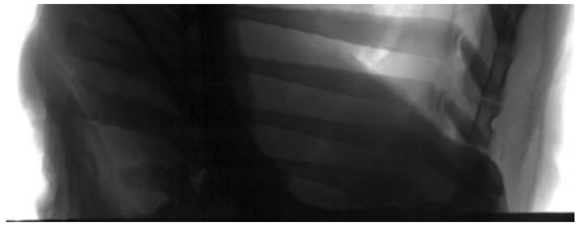


Figure 27 - Feather Bones - Single Energy 40kV

As higher kV's are used, the feather bones begin to wash out – especially the cartilaginous tips. The contour of the underlying muscle however stays quite prominent.

Figure 28 - Feather Bones - Single Energy 130kV

The 'sweet spot' appears to be around 60-80kV energy level. However, at these levels the issue of washing out the feather bone tips also become significant. Thinner carcasses may exhibit an issue with this at these energy levels whereas a thicker carcass would make them difficult to differentiate.

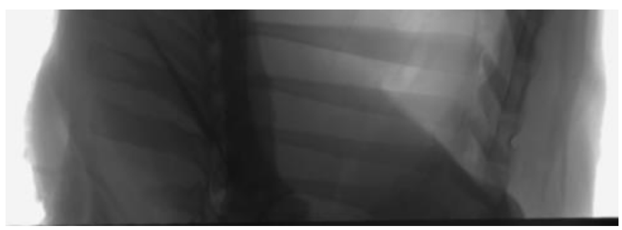


Figure 29 - Feather Bones - Single Energy 70kV

4.2.2.2 X-ray image analysis Results

Attempting to apply an edge detection algorithm to the image demonstrates the challenging nature of the images presented. The contrast of the feather bones make them appear somewhat visible to the eye, image processing algorithms have difficulty reliably identifying these features. It can be seen that the noise produced by the muscle contour also presents as a significant issue.

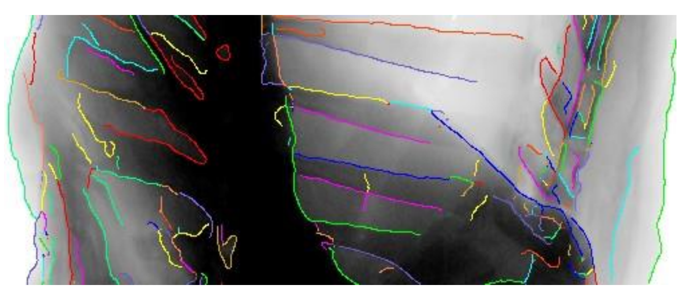


Figure 30 - Feather Bones – Single Energy - X-ray image analysis

4.2.2.3 Discussion

As with any single energy application, the robustness of the results must be questioned due to:

- the varying thicknesses of material encountered in beef behind the feather bones across different carcasses;
- the varying thickness of material encountered in beef behind the feather bones as you move up the body for the same carcass; and
- the varying composition and structure of the material in behind the feather bones (as can be seen by the muscle contours in Figures Figure 27 - Figure 29.; and
- the varying thickness and composition of each individual feather bone.

While an adequate solution may be found for an individual carcass case, it would be different to find a single energy which would provide a satisfactory solution for the expected range of carcass sizes expected to be processed.

4.2.2.4 Conclusion

The considerations discussed in Section 4.2.2.3 suggest a robust single energy solution may not even be able to be found for a single complete carcass let alone all carcass sizes expected to be encountered.

4.2.3 Energy Level Trialling - Dual Energy

4.2.3.1 Images and initial observations

The dual energy images were obtained with an x-ray setup optimised for the beef rib cutting application. However a number of valid observations are still able to be made regarding the results. It can be seen that the feather bones present themselves with a fair level of contrast. However, there is a high level of noise which affects the image quality. The tips also appear to be washed out.

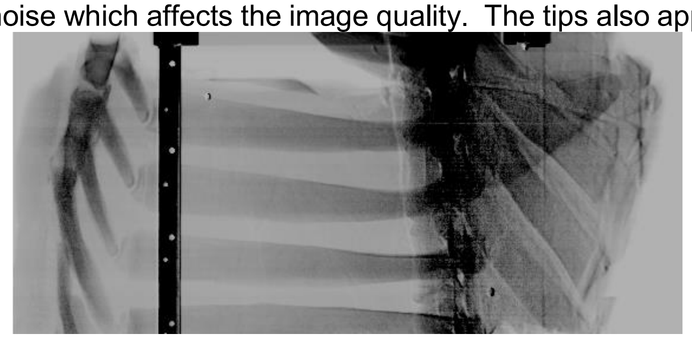


Figure 31 - Feather Bones - Dual Energy 70kV/140kV

4.2.4 X-ray image analysis Results

In attempting to process the feather bone image, the level of noise becomes a noticeable issue. The features were able to be identified at a greater success level than expected, but still not acceptable.

Figure 32 - Feather Bones – Dual Energy - X-ray image analysis

4.2.5 Discussion

As aforementioned, the dual energy setup is optimised for the identification of the junction of rib 1 and the sternum. Thus, the images are optimised to maximise contrast between bone and muscle/fat/cartilage. As a result, the raw images from the current dual energy setup aren't ideal for this application

It is envisaged that a similar spectra and power would be used to the rib cutting application. With these changes applied, it would be less challenging to accentuate the feather bones than identifying the junction of rib 1 and the sternum.

4.2.6 Conclusion

As the dual energy setup was optimised for isolating rib 1 through the thickest part of the carcass, the results are far from indicative of the potential of using dual energy for this application. In order to optimise the setup for feather bones, significant theoretical work would have to be performed to get a fair idea.
However, given the analysis of the images obtained in the trialling, there is a high level of confidence that an ideal x-ray configuration is able to be found for this application. In theory, this application presents fewer challenges than the rib cutting application.

4.2.7 Sensing Alternatives

4.2.7.1 Vision

It is thought that this particular application would lend itself well to traditional computer vision. However, some significant challenges which may present themselves are:

- Inconsistent colouring of the feather bones and tips; and
- Similar colouring of feather bones and surrounding muscle.

These issues are shown in Figure 33. It is still a technology which should be investigated first due to the price benefits as well as fewer layout and safety considerations.

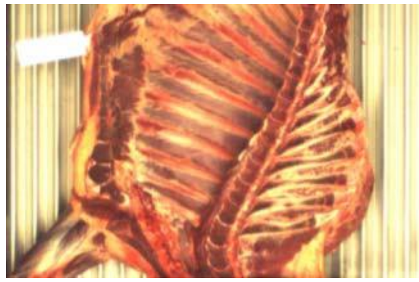


Figure 33 - Feather Bones - Vision Challenges

4.2.7.2 3D profiling

Another technology which should be investigated is high-profile 3D profiling. All the data currently possessed has the required feather bones already processed. However, it is evident from the smaller remaining feather bones in the 3D in Figure 34, that there is some potential to identify them based on their protrusion from the carcass.

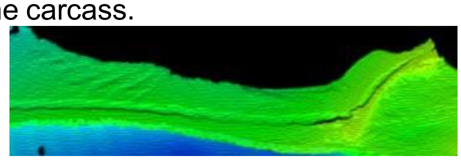


Figure 34 - Feather Bone - 3D Profile

4.2.7.3 Conclusion

While there is potential to apply x-ray to this application, it is felt that alternative technologies should be explored first given that x-ray's true benefit comes in identifying sub-surface features. Both the vision and 3D profiling alternative suggested possess their respective weaknesses, but are still alternatives that should be investigated. They could potentially be used in tandem - for example using the 3D profile to generate an area of interest on the colour image to process.

4.2.8 Accuracy and Resolution Requirements

Single energy results were obtained using 0.8mm resolution whereas the dual energy results were obtained with a 1.6mm resolution. It can be seen from the single energy images that 0.8mm is much finer than is required. It is reasonable to assume a similar resolution required to accurately view the ribs would be required for feather bone identification. Observing the dual energy images, it can be seen than a 1.6mm resolution would be ideal.

4.2.9 Shielding Requirements

Shielding requirements must first be calculated with extensive theoretical analysis once the operating voltage and power has been ascertained, upon which a conservative safety factor is added. From the results achieved in the trialling, some points can be made regarding the shielding:

- Dual energy would likely be required
- Similar power x-rays will be required for the application than for rib cutting

- X-ray layout would likely be similar so percentage scatter should be on a similar level to rib cutting

Based on these considerations, the shielding requirements would be expected to be very similar to that required by rib cutting – perhaps a little lighter. There would still need to be shielding in place blocking all lines of sight to where the x-ray beam penetrates the carcass meaning a rail kink, diversion or shutters would be required on the chain.

4.2.10 Equipment Costs

The equipment would be very similar to that required for rib cutting. However, it is hoped that the features required to be sensed lie within a small enough window between the smallest and largest carcasses that the x-ray tube and detector can be kept stationary. A breakdown of expected major cost items is as follows:

- Detector –
    - A two-detector setup with the same detector types used for the rib cutting application would be required. A larger field of view may be required from this x-ray setup to cover the required area of interest for all carcass sizes required. This will require slightly longer detectors which would increase costs slightly.
- X-ray tube and generator –
    - The lower power requirements (if any) would not be expected to result in a significant saving in tube or generator costs compared to the rib cutting application.
- Shielding
    - As mentioned in the previous section, shielding costs would be expected to be similar to the rib cutting application.
- Mechanical Requirements
    - While a moving gantry would not be required, the mechanically actuated shutters would still be required to seal the cell while the x-rays were scanning a carcass.

Image analysis software would also be required. For this application, it is recommended that MVTec Halcon be utilised. The licensing cost associated with this software package is around €5500 for the development license, plus €1350 for the run-time license.

4.2.11 Layout

The sample layout shown in Figure 35 is envisaged for the application. It can be seen that this is the same setup as that proposed for the Beef Scribing application owing to the fact that the implementation, including all equipment, will be very similar. Again, the X-ray and 3D components will be mounted on a gantry driven by a linear drive to move down along the carcass as it scans across it.

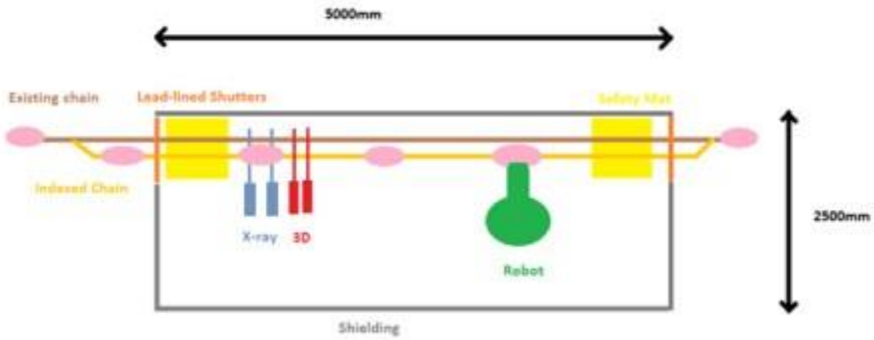


Figure 35 – Feather Bones - Sample Layout

4.2.12 Conclusion

Beef feather bone processing, while able to use dual-energy x-ray as a sensing technology, may be better suited to other sensing technologies. It is recommended that vision and 3D trials be conducted first before further investigating dual-energy x-ray.

4.3 Beef Spinal Cord Removal

4.3.1 Overview

The spinal cord removal process involves using a tool to suck out the entire length of the spinal cord from the channel in the spine in which it sits. In order to perform this application, either the spinal cord itself, or the channel in which it sits, must be located for the entire length of the spinal cord. Figure 36 illustrates an example spinal cord removal tool. Such a tool must track the spinal cord from the end of the tailbone down to the end of the neck.

Figure 36 - Spinal Cord Removal Tool

4.3.2 Energy Level Trialling – Single Energy

4.3.2.1 Images and initial observations

The carcass sample processed already had its spinal cord removed. However, it was hoped that the channel in which it sits would be able to be located. At low energy levels, the spine profile is too saturated to distinguish. However, as the energy increases, the line of the vertebrae becomes clearer, but the individual vertebrae still remain hidden.

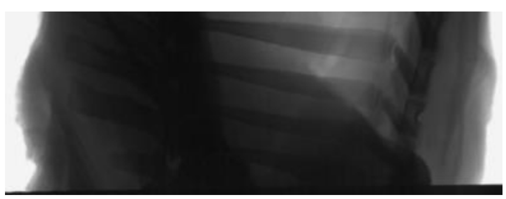


Figure 37 - Spinal Cord - Single Energy 40kV

Figure 38 - Spinal Cord - Single Energy 80kV

Figure 39 - Spinal Cord - Single Energy 160kV

4.3.2.2 Discussion

As initially expected and covered in section **Error! Reference source not found.**, the vertebrae aren't able to be identified using a single energy solution. There may be a possibility of inferring the location of the channel in which the spinal cord sits based on the homogenous blob that the spine presents itself as. However, it is thought that this method would not provide the value to justify the cost of an x-ray solution.

4.3.2.3 Conclusions

The limitations of single energy processing for this application are similar to those outlined in the beef scribing and feather bone processing. It is unlikely that the spinal cord itself could be directly sensed using single energy x-ray and processing based on inferring the spinal cord channel's position is not likely to succeed.
Hence, it is recommended that single any x-ray would not be suitable for this application.

4.3.3 Energy Level Trialling - Dual Energy

4.3.3.1 Images and Initial Observations

As with the other applications discussed in this report, the x-ray setup has not be optimised for this particular application. The image shown in Figure 40 demonstrates the challenges in visibility with the spinal section around the lower ribs due to the extra meat thickness and presence of the scapula. Figure 41 shows a scan of the tail bone section – the end of the spinal cord where the tool would enter. It can be seen from this image than the channel in which the spinal cord sits it fairly visible (circled in red). Figure 42 shows the other key area of interest – the end of the neck where the tool would exit the carcass. Observing this image doesn't appear to show this channel clearly however.

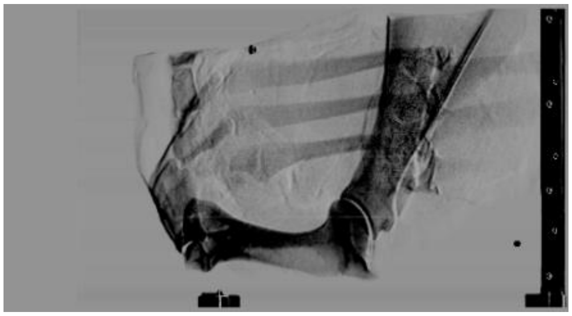


Figure 40 - Spinal Cord - Dual Energy (Ribs 1-3)

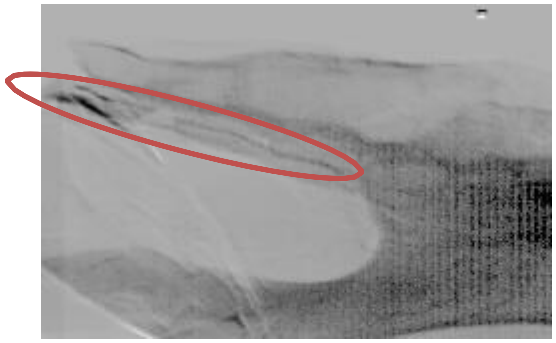


Figure 41 - Spinal Cord - Dual Energy (Tailbone)

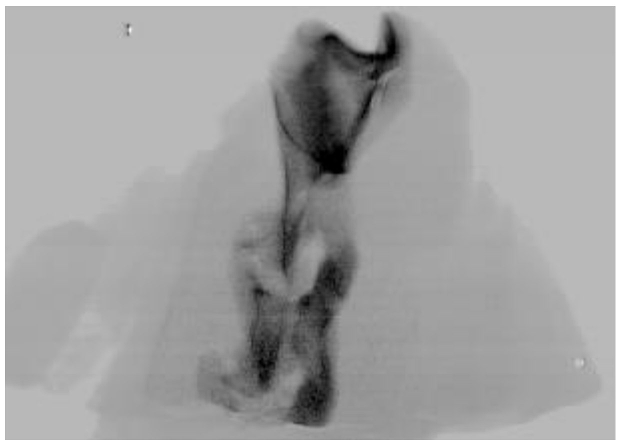


Figure 42 - Spinal Cord - Dual Energy (Neck)

4.3.3.2 X-ray Image Analysis

In analysing the most promising image – the tail bone section – it can be seen from Figure 43 that the low level of contrast and high level of noise presents a challenge. It remains difficult to isolate this channel using image analysis with the image presented as it is which, realistically, isn't surprising.

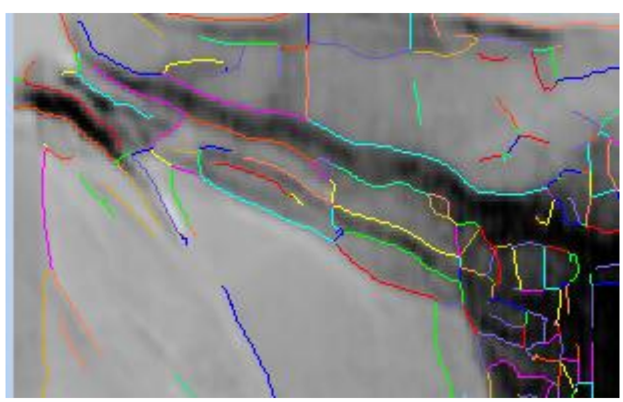


Figure 43 - Spinal Cord – Dual Energy - X-ray Image Analysis

4.3.3.3 Discussion

In approaching this application, it is believed that the key feature to identify will be the channel in which the spinal cord sits for the entire length of the carcass. While the carcass imaged didn't have its spinal cord present, it is felt that directly isolating the spinal cord material would be extremely difficult given its similarity to muscle. Research into medical applications for spinal cord imaging suggests that, in order to view the spinal cord with x-ray, a radioactive dye must be injected into the spinal cord first. Alternatively, an MRI image is taken instead.

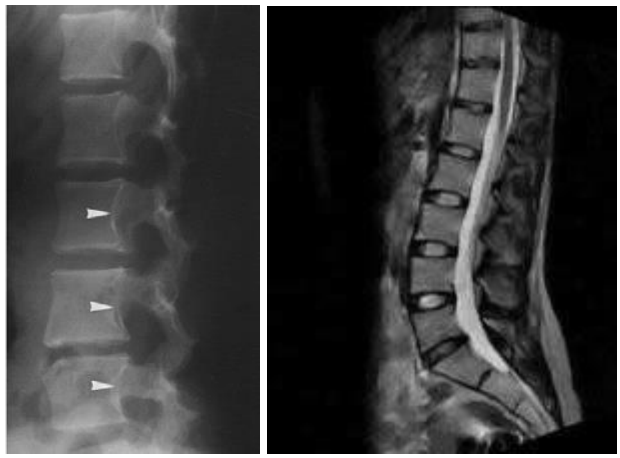


Figure 44 - Medical Spine Image - X-ray (left) vs MRI (right)

It is felt that the best way to approach this problem would be to optimise the x-ray to isolate the vertebrae, similar to the beef scribing setup that would be required. The calibration and dual energy recombination algorithms would aim to maximise contrast of bone versus muscle/fat/cartilage. A second layer of data processing will then be added to after the dual energy recombination to quantify the thickness of the bone along the spine. Using this technique, the scapula can essentially be 'subtracted' from the appropriate section of spine. It can also be used to isolate the thinner section of the vertebrae in which the spinal cord sits.
In order to achieve this, the spinal cord channel will have to be presented well to the x-ray setup. That is, the spine shouldn't be tilted at an angle which causes the spinal channel to be occluded by the spine. Observing the high-resolution 3D profile of a carcass shown in Figure 45 shows that the spinal channel is expected to present itself well.

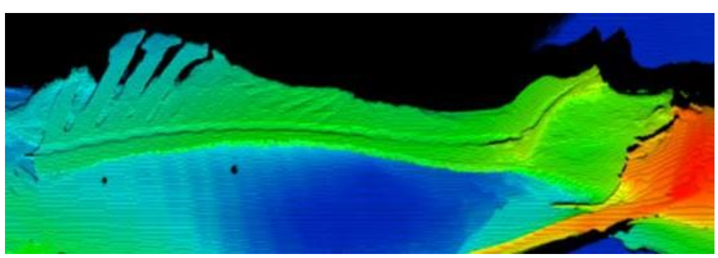


Figure 45 - Spinal Cord - 3D Profile

4.3.3.4 Conclusions

Dual energy could be used if it is determined that the spinal cord position can be suitably determined from the positioning of the vertebrae. There may be potential to directly identify the spinal cord, but this would likely be a challenge, especially around the scapula area, but it is felt there is greater opportunity in directly identifying the channel in which the spinal cord sits. It is felt that this method would show promise in successfully sensing the spinal cord for removal.

4.3.4 Sensing Alternatives

4.3.4.1 Vision

It is thought that this particular application would lend itself well to traditional computer vision given that the spinal cord should be visible. However, some significant challenges which may present themselves are:

- Inconsistent colouring of the spinal cord material; and
- Similar colouring of spinal cord material and surrounding vertebrae and cartilage.

These issues are shown in Figure 46. It is still a technology which should be investigated first due to the price benefits as well as fewer layout and safety considerations.

Figure 46 – Spinal Cord - Vision Challenges

4.3.4.2 3D profiling

Another technology which should be investigated is high-profile 3D profiling. All the data currently possessed has the spinal cord already removed, as can be seen in Figure 45. However the possibility that the spinal cord is able to reliably present itself to a high-resolution 3D scan should be investigated.

4.3.4.3 Conclusion

While there is potential to apply x-ray to this application, it is felt that alternative technologies should be explored first given that x-ray's true benefit comes in identifying sub-surface features. Both the vision and 3D profiling alternative suggested possess their respective weaknesses, but are still alternatives that should be investigated. They could potentially be used in tandem if the reliably for each technology is not sufficient individually.

4.3.5 Accuracy and Resolution Requirements

Single energy results were obtained using 0.8mm resolution whereas the dual energy results were obtained with a 1.6mm resolution. Again it can be seen that 0.8mm is likely to be a finer resolution than is required. Depending on which method is used to locate the spinal cord, it is envisaged that a resolution of 1.6mm or greater would be sufficient for this application.

4.3.6 Shielding Requirements

Shielding requirements must first be calculated with extensive theoretical analysis once the operating voltage and power has been ascertained, upon which a conservative safety factor is added. From the results achieved in the trialling, some points can be made regarding the shielding:

- Dual energy would likely be required
- Higher power x-rays may be required for the application than for rib cutting
- X-ray layout would likely be similar so percentage scatter should be on a similar level to rib cutting
- There is potential to use a smaller field of view which focuses on the width of the vertebrae which may allow for slightly lighter shielding

Based on these considerations, the shielding requirements would be expected to be very similar to that required by rib cutting. There would still need to be shielding in place blocking all lines of sight to where the x-ray beam penetrates the carcass meaning a rail kink, diversion or shutters would be required on the chain.

4.3.7 Equipment Costs

The equipment would be very similar to that required for rib cutting. It is envisaged that a dual-energy setup will be used requiring two tubes and detectors. These will be mounted on a gantry moved by a linear drive to scan down a carcass as it is moving along a stabilisation conveyor. A breakdown of expected major cost items is as follows:

- Detector –
  - A two-detector setup would be required with the same detector lengths as the rib cutting application. However, a different type of detector which possess a logarithmic response rather than a linear response may be required. This would add some cost. Conversely, there is the opportunity to scan a smaller field of view which is focused on the carcass's spinal column rather than the entire carcass width. This presents an opportunity to use a shorter (and hence, cheaper) detector.
- X-ray tube and generator –
  - A higher power generator and tube may be required than for the rib cutting application. The issue with going with higher power equipment is availability, cost and mechanical issues. For instance, going from a 3kW to a 4.5kW tube means an increase in weight from 10kg to 95kg, an increase in length of 600mm and an increase in diameter of 90mm and may require two generators for each tube. However, it isn't expected that a significantly higher level of power would be required and layout modifications could be made to increase scanning time rather than increasing power. Thus there's a potential for an increase in cost of these components, but shouldn't be significant and may be designed around.
- Shielding
  - As mentioned in the previous section, shielding costs would be expected to be similar to the rib cutting application, depending on how much extra power is needed and how much the x-ray field of view can be reduced.
- Mechanical Considerations

- A gantry with a linear drive to move the x-ray and 3D equipment to scan the carcasses as with the rib cutting application.
- Lead-lined shutters will also be required to shield the entrance and exit to the cell while the x-rays are on.

Image analysis software would also be required. For this application, it is recommended that MVTec Halcon be utilised. The licensing cost associated with this software package is around €5500 for the development license, plus €1350 for the run-time license.

4.3.8 Layout

The sample layout shown in Figure 24 is envisaged for the application. The layout is identical to that proposed for beef scribing. Again, some form of active shielding will be required along any possible line-of-sight from outside the cell to where the x-ray beams intersect the carcass. It is proposed that a set of lead-lined shutters be used to ensure the entire cell is shielded whilst the x-rays are energised.
The X-ray and 3D components will be mounted on a gantry driven by a linear drive to move down along the carcass as it scans across it. This will allow the x-ray tube to be mounted as close as possible to the source and will also allow the x-rays to scan slightly slower over the thicker, more difficult rib 1 section. It will also allow one 3D scanner and x-ray setup to be used while catering for all carcass sizes.

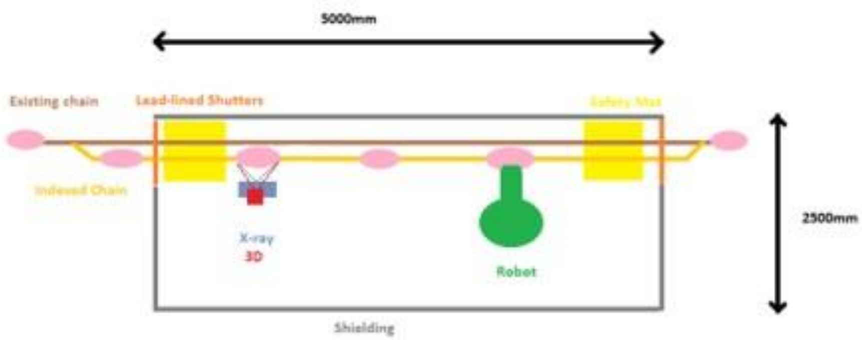


Figure 47 - Beef Scribing - Sample Layout

4.3.9 Conclusion

Beef spinal cord removal poses some significant challenges in utilising dual-energy x-ray imaging. While there is a moderate level of confidence at this stage that it can be used successfully, it is recommended that vision and 3D be investigated first.

4.4 Ovine Primal Cutting

4.4.1 Overview

The ovine primal cutting operation requires placing a number of cuts across an ovine carcass to divide it into the required sections for boning. The specifications for some of the different primal cuts required are shown in **Error! Reference source not found.**. When performed manually, these cuts are performed using a bandsaw.

MAR has developed a robotic ovine cutting system to automatically perform these cuts. The cut locations are currently determined using a vision system which utilises a carcass modelling system. Accuracy data for this current system is shown in

Table 1. It can be seen that for the data which was acquired, the vision system operated with an accuracy of less than 70% (within ±5mm of the ideal cut location).

Cut	Accuracy (within ±5mm)
1st Cut (between Forequarter and Loin)	65.08%
2nd Cut (between Rack and Short Loin pair)	NA
3rd Cut (between Loin and Chump)	68.72%
4th Cut (between Leg and Chump, or Chump and Loin)	NA

Table 1 - Ovine Primal Cutting - Vision Accuracy

The features of interest for these cuts are as follows (refer to **Error! Reference source not found.**):

- The ilium
- The acetabulum
- All vertebrae
- All ribs

4.4.2 Energy Trialling – Single Energy

4.4.2.1 Images and initial observations

Single energy imaging is expected to present fair results for lamb given the more favourable bone:muscle ratio. The carcass was scanned in two orientations – from the side and from the back of the carcass.

It was found that good visibility of the ribs from the side view was achieved from as low as 50kV. The ideal energy range for rib visibility appeared to be between 70-100kV. Higher than this, the ribs start to become washed out. This is shown in Figure 48. It can also be seen that the vertebrae are difficult to distinguish, even at the highest energy level trialled.

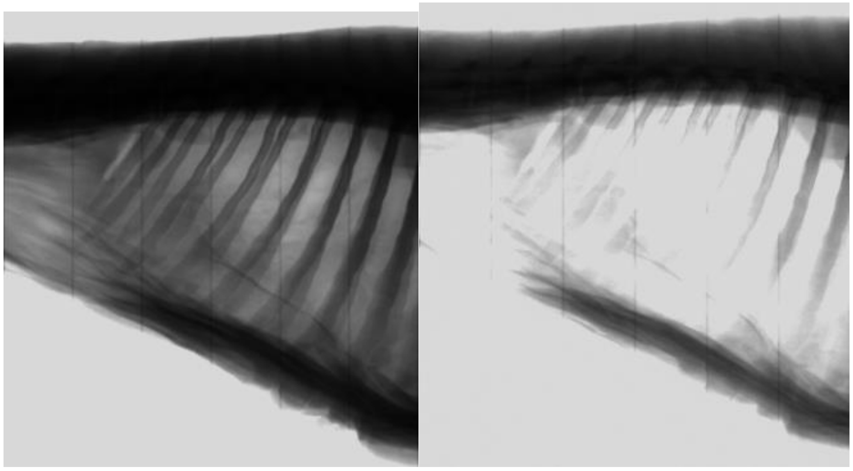


Figure 48 - Ovine Cutting - Single Energy (Side) 70kV and 150kV

With the spine facing the x-ray tube, the benefits of using a higher kV become apparent. At energies lower than 100kV, the costal cartilages come through too prominently. Higher kV x-rays do a better job at washing these out, at the expense of losing the ribs. It can be seen that the vertebrae are at least visible in this orientation, even at lower energy levels. However, the visibility of the individual vertebrae becomes more challenging towards the cranial end of the carcass.

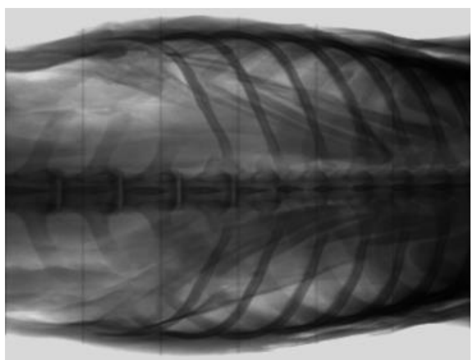


Figure 49 - Ovine Cutting - Single Energy (Front) 70kV

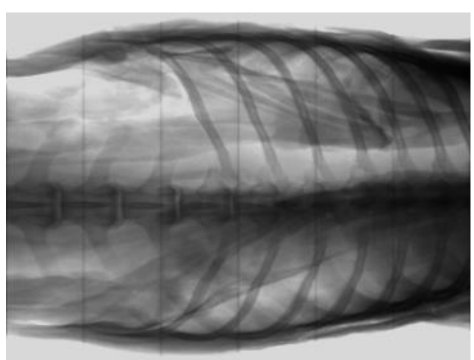


Figure 50 - Ovine Cutting - Single Energy (Front) 100kV

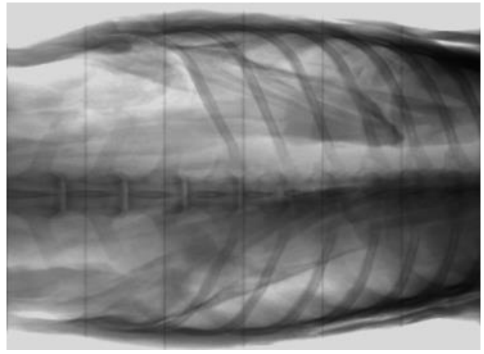


Figure 51 - Ovine Cutting - Single Energy (Front) 150kV

4.4.2.2 X-ray image analysis

With the side profile, fairly good separation of the ribs is able to be achieved. However there is an issue with picking up artefacts from the muscle structure. It can be seen that there is some issue with differentiating between left- and right-side ribs. However, rib position can be identified using the back view of the carcass. The rib angle for each given rib is still able to be accurately identified, regardless of this interference from the opposite rib.

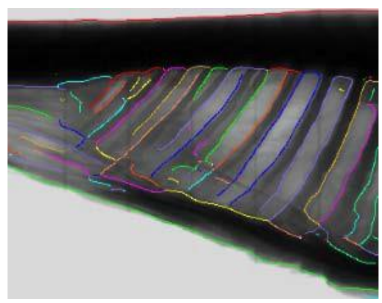


Figure 52 - Ovine Cutting – Single Energy - X-ray image analysis (Side)

The back view of the carcass shows some promising results in being able to isolate the ribs. Reliable isolation of the vertebrae still looks challenging however. It can be seen that there is a significant amount of noise from muscle the muscle structures. On a cleaner image, directional filters could probably be used to accentuate the ribs.

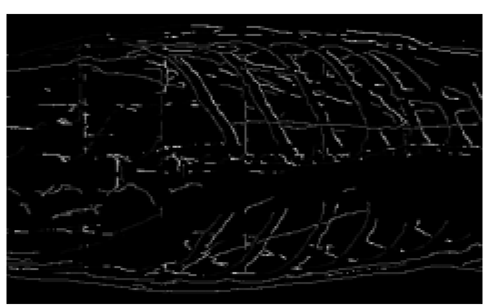


Figure 53 - Ovine Cutting – Single Energy - X-ray image analysis (Back)

4.4.2.3 Discussion

It can be seen that a number of issues present themselves for the single energy images. At the same time, there is opportunity for such a setup.

It is felt that a solution may be able to be found which can minimise these challenges, but such a solution may not be robust when presented with carcasses which differ significantly in weight. Thus, while single energy may be further investigated, it is felt that the aforementioned challenges may inherently limit the robustness of a single-energy system.

4.4.2.4 Conclusions

For lambs, there isn't as much of an issue with distinguishing between thick muscle and thin bone. However it is something that does bring about some noise in the image. Considering other lamb projects involving single energy x-rays, there are some reports stating different sized carcasses posed significant issues with a single energy solution. Observing the images obtained during the trials suggests that a single-energy solution may not be robust for varying carcass sizes.

4.4.3 Energy Trialling – Dual Energy

4.4.3.1 Images and initial observations

A lamb was sectioned in half and scanned with a dual energy setup to give three images:

- A back view of the forequarter;
- A side view of the forequarter; and
- A back view of the hindquarter.

Again, the x-ray setup was optimised for beef rib cutting. This is quite clearly obvious from the presentation of the images and isn't surprising given the significantly different nature between scanning a big beef side and a relatively small lamb carcass. The high level of visibility of the muscle in the images is a key indicator of this. However some key observations are able to be made about the presentation of these three images. Firstly, the visibility of the vertebrae for both the side and back views of the carcass is apparent. Secondly, it can be seen that clear presentation of the ilium and acetabulum has been provided in this setup. Finally, the issue of the trussed legs occluding visibility of the ribs in the side view would not be expected on-site.

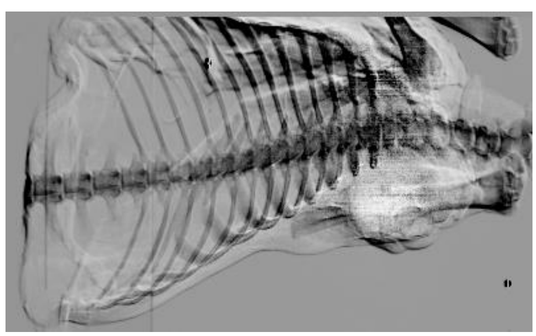


Figure 54 - Ovine Cutting - Dual Energy (Fore - Back) 70kV, 140kV

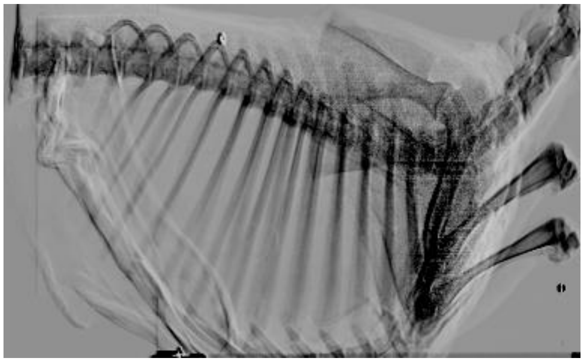


Figure 55 - Ovine Cutting - Dual Energy (Fore - Side) 70kV, 140kV

Figure 56 - Ovine Cutting - Dual Energy (Hind) 70kV, 140kV

4.4.3.2 X-ray image analysis

The images were individually analysed and gave surprisingly promising results given the less-than-ideal x-ray calibration.

4.4.3.2.1 Forequarter – Back

The back view of the forequarter of the carcass was analysed with edge detection filters. It can be seen that the ribs were isolated fairly successfully given the amount of noise in the image. The vertebrae didn't present quite as well, but still looked promising. Another positive sign is the fact that the costal cartilages affecting the edge detection didn't appear to be an issue.

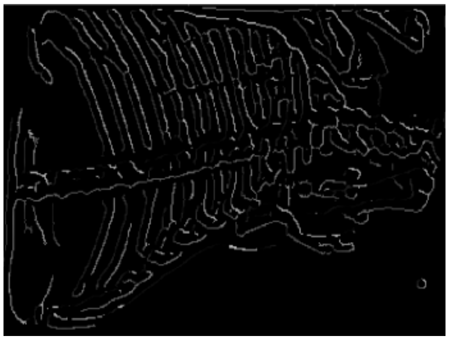


Figure 57 - Ovine Cutting – Dual Energy - X-ray image analysis (Fore – Front)

4.4.3.2.2 Fore-quarter – Side

The side view of the carcass also demonstrated a higher than ideal level of noise but was still able to segment the ribs quite successfully. The potential for vertebrae isolation in this view is also apparent – something that didn't appear promising with the single energy images from this view. The issue of the opposite lateral ribs causing significant noise in the image also didn't seem as apparent.

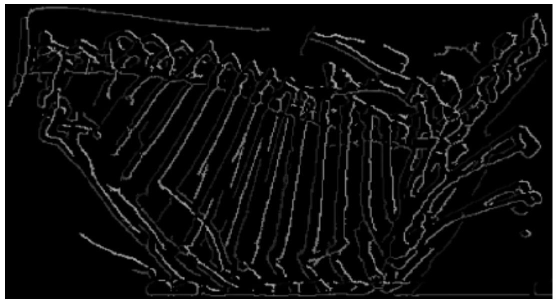


Figure 58 - Ovine Cutting – Dual Energy - X-ray image analysis (Fore – Side)

4.4.3.2.3 Hindquarter

The image for the back view of the hindquarter actually presented relatively well which isn't surprising given the fewer number of biological features in this area. It can be seen from the image analysis that the ilium is quite easy to distinguish. The acetabulum appears more challenging to isolate, but optimal calibration would be expected to increase the visibility of this joint.

Figure 59 - Ovine Cutting – Dual Energy - X-ray image analysis (Hind)

4.4.3.3 Discussion

The ovine primal cutting operation is one which lends itself well to dual energy x-ray. The results obtained, while based on images with a sub-optimal x-ray setup, were promising. The ribs still presented quite well and the vertebrae were also slightly visible in both forequarter views. The hindquarter view gave good visibility of the remaining vertebrae as well as the ilium. While the acetabulum demonstrated some challenges, it was still visible after the image processing was performed.

It can therefore be reasoned that this application shows a particular level of promise with using dual energy x-ray. Given the biology of ovines, a result similar to what can be achieved with medical dual energy imaging isn't unreasonable.

Figure 60 - Human Chest Dual X-ray Image

The challenges experienced with the images acquired all possess potential solutions. Occlusion of some of the rib features caused by the trussed legs would not be experienced on-site at a processing facility. The amount of noise provided by the muscle contours is something that would be eliminated by optimising the x-ray spectra used as well as the calibration and dual energy recombination procedures for this application. The potential issue of overly visible costal cartilages can also be addressed by optimising the dual energy combination to maximise contrast between bone and muscle/fat/cartilage for ovine carcasses.

4.4.3.4 Conclusions

Even with a sub-optimal calibration, the dual energy images looked promising. In terms of distinguishing between muscle and bone, there should be no reason why a result close to a medical image can't be achieved with an ovine carcass due to its more similar biology (compared with beef).

4.4.4 Accuracy and Resolution Requirements

The dual energy trials for the rib cutting application utilised a detector with a 1.6mm resolution. It is envisaged that such a resolution would be suitable for identifying the vertebrae as well. Using a finer resolution would increase the cost of the detectors by a considerable amount. It is believed that such a resolution would be more than adequate to allow an x-ray solution to outperform the vision system used with the current robotic ovine cutting system.

4.4.5 Shielding Requirements

Shielding requirements must first be calculated with extensive theoretical analysis once the operating voltage and power has been ascertained, upon which a conservative safety factor is added. From the results achieved in the trialling, some points can be made regarding the shielding:

- Dual energy would likely be required
- Lower power x-rays will be required for the application than for rib cutting, but likely not significantly enough to have a large effect in shielding requirements
- X-ray layout may have to be modified to enable imaging from two different perspectives

Based on these considerations, the shielding requirements would be expected to be similar to that required by rib cutting – likely somewhat lighter. There would still need to be shielding in place blocking all lines of sight to where the x-ray beam penetrates the carcass meaning a rail kink or diversion would be required on the chain.

4.4.6 Equipment Costs

The equipment would be very similar to that required for rib cutting. A breakdown of expected major cost items is as follows:

- Detector –
    - If a two-detector setup is be used, the costs would be very similar to the rib cutting application as the same detector setup would likely be used. A slightly smaller field of view, and therefore slightly shorter detector, would likely be required which may recover a small amount of cost. There is a chance a more expensive detector design may be required however, to give better dynamic range and increase visibility of the vertebrae.
- X-ray tube and generator –
    - If using a two-detector setup, the costs would be very similar to the rib cutting application as the same x-ray tube/generator setup would likely be used (two tubes and one high-power generator). The lower power requirements would not be expected to result in a significant saving in tube or generator costs.
- Shielding –
    - As mentioned in the previous section, shielding costs would be expected to be similar to the rib cutting application.
- Mechanical Requirements –
    - A moving gantry upon which the x-ray equipment is mounted may be required
    - A means for stabilisation of the carcass during scanning and cutting would also be required.

4.4.7 Layout

The potential layout for the system is highly variable, depending on a number of factors:

- Required cycle
- Variation of carcass sizes
- Which cuts have to be performed

Some significant consideration will have to be given to how the carcass is scanned by the x-ray. One possible scenario is to index the carcass onto an MAR-controlled chain and stop the carcass. A clamp could then stabilise the carcass from the ground while the x-ray moved down the carcass to perform one x-ray scan of the carcass. The clamp could then rotate and the second view of the carcass be scanned as the x-ray gantry moves back up the carcass. A robot could then grasp the carcass and hold it while a second robot performs the cuts in a similar process to the current robotic ovine cutting system.

Alternatively, a four-detector/x-ray tube setup could be used whereby the carcass was scanned in both orientations simultaneously. The gantry could alternate between scanning up and down carcasses for each successive carcass to maximise cycle time. While such a setup wouldn’t double the equipment cost of the x-ray, it would represent a significant increase in cost.

4.4.8 Conclusion

Ovine Primal Cutting is another application which lends itself well to dual-energy x-ray imaging. There is a high level of confidence that an x-ray configuration is able to be found. It is recommended that the theoretical analysis and simulation be performed on the application to discover this configuration. One major challenge to the application however may be cycle time and associated equipment costs due to the requirement of scanning in two orientations.

5 Conclusions and Recommendations

X-ay is a sensing technology which presents significant opportunities for MAR's meat industry projects. It is one of the few sub-surface sensing able to be utilised while maintaining commercial viability in the application. This presents as a significant over technologies such as traditional machine vision, 3D imaging and thermal imaging which must infer the positions of features which are not immediately visible.
In this report, four applications in particular were investigated:

- Beef Scribing
- Beef Featherbone Processing
- Beef Spinal Cord Removal
- Ovine Primal Cutting

As part of the trialling, both single-energy and dual-energy imaging was investigated for each application. The single-energy trialling gave less than ideal results, especially for the beef applications. Key challenges encountered included:

- Distinguishing between thin bone and thick muscle;
- Noise caused by varying muscle thickness and muscle contours; and
- Inability to see through challenging areas without washing out other areas of interest.

These challenges were common between all these applications and are inherent to single energy imaging. A robust single-energy solution is unlikely to be found when processing beef and ovine carcasses of significantly different sizes.
The dual energy trials were conducted with an x-ray configuration which was optimised for Beef Rib Cutting. The reason for this is that dual energy imaging isn't as simple as single energy imaging – it isn't a matter of taking scans at a number of different energy levels and seeing which two fit together the best. Significant theoretical analysis must be performed on each application to determine the required:

- X-ray spectrum required for the low-energy and high-energy components;
- Resulting kV, mA and filtration;
- Detector normalisation technique;
- Calibration phantom design and calibration technique; and
- Dual energy recombination technique.

Scope for this work wasn't included in the project. Thus the data were taken with an x-ray setup not optimised for each respective application. Despite this, the images were still able to be analysed to determine the feasibility of using x-ray and what would be required to optimise the setup.
The beef scribing application was seen to lend itself well to dual energy x-ray. While extra power and perhaps more expensive detector technology may be required, there was a high level of confidence that an optimised dual energy x-ray setup would be able to meet sensing requirements.
The beef featherbone processing application was another application with a high level of confidence that an ideal dual energy x-ray configuration would provide the required images. However it was also thought that, while able to be used, x-ray may not be the ideal sensing technology to use for this particular application. This was primarily due to the fact that the featherbones are exposed and therefore some opportunity exists to sense them with a less expensive and cumbersome technology.
The beef spinal cord removal application appeared to pose some challenges. While there is a level of confidence that x-ray may be used for this application, it would be quite complex in its

implementation. Again, it was thought that due to the spinal cord being exposed, another sensing technology may be better suited for the application.
The ovine primal cutting application is another one which seemed to strongly lend itself to dual energy x-ray imaging. Given the biological similarity between ovines and humans (especially compared to beef), there's no reason that a result close to what's achievable with medical x-rays can't be reached. Even with the sub-optimal x-ray configuration, the images were able to be processed with a degree of success. It is felt than an ideal x-ray configuration would outperform current vision methods used to perform the application in terms of sensing accuracy. Considerations such as cost-benefit regarding equipment cost and achievable throughput, and required footprint would have to be analysed.
Thus it can be seen that x-ray sensing is a technology which provides significant opportunity to red-meat industry automation projects.