Final report

LEAP 4 Beef Sub project 1 – Automated Chine, Button and fat trim proof of concept for the Striploin and Cube Roll – MLA Confidential

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Abstract

Without the ability to see internal bone structures and fat/meat boundaries, butchers must estimate cut paths for chine removal, button removal and fat trimming; resulting in poor yields and exposing operators to cut hazards. However, with the use of CT scan data it was proposed that these cut paths could be automated using vision analysis and robotic cutting/clamping means, greatly improving yield and operator safety.

Potential candidate solutions for chine removal, button removal and fat trimming were investigated, trials jigs were built, tested, and the results analysed. Promising candidate solutions were developed further until a production prototype was designed. However, after a variation to the contract, the further development of chine removal automation was prioritised over button removal and fat trimming. The new scope involved developing test rigs for clamping the ‘chuck/rack/loin’ product in such a means that enables the separation of the chuck from the rack and the rack from the leg.

The key results from this project are as follows:

- CT data can reliably be analysed to generate cut paths using vision analysis
- Clamping the chine during cutting is essential to guarantee accurate chining results
- A robotic bandsaw was most effective for both chine removal and fat trimming
- A robotic knife was developed which removed the button bones effectively

A chine clamp and automated chine removal was developed and demonstrated. The results from this report outline many benefits for the red meat industry. The main benefit is the reduction in yield loss due to the accurate cut paths generated from the CT data. Other benefits include increased operator safety (operators isolated from bandsaw blades), reduction of the requirement to engage skilled bandsaw operators and improved production rates.

Executive summary

Background

The main purpose for this research is to evaluate and understand how CT data along with clamping and robotic cutting means, could be utilised for automating beef middle processing. It was hypothesised that 3D models of bone and meat structures, created by the CT sensing, could be used to generate 3D cut paths to increase yield in beef processing.

Findings from this report will primarily be used by the beef industry, where there is drive for automation due to safety concerns and a shortage of skilled workers. These results will be used to develop automated prototype machines for future projects and demonstrate to industry the potential benefits and limitations of using CT data to automate beef processing.

Objectives

1. Evaluate the capability and benefit of a CT variant to provide sensing for Beef rack and loin bone in and boneless processing.
2. Develop a "knife and fork" cutting rig and demonstrate the ability to apply the sensing to cutting the chine bone from beef loin and rack primals. (Demonstration in factory or at a processor)
3. Develop a "knife and fork" device and demonstrate the ability to apply the sensing to removing chine buttons from beef chine off loin and chine off rack sub primals. (Demonstration in factory or at a processor)
4. Develop a "knife and fork" device and demonstrate the ability to apply the sensing to trimming fat to a defined depth over the length of a beef loin and off rack primal.
5. By option of SCOTT and MLA Develop a prototype that can prove and demonstrate the technology in-plant

Variation agreement #2 modified project objectives

1. Concept development of clamping and datuming means, suitable for CT scanning and enabling the cross cuts.
2. Design and build to integrate the standalone trial assemblies to form a concept test bed for testing chine removal from the rack and the loin, combined or individually.
3. Trial of “Rackloin” chine removal of up to 5 “Rackloins” in the SCOTT factory.

The work done from milestone 1 to 15 addresses each of these objectives successfully. A test rig that enabled the removal of the chine and ‘button’ bone as well as the trimming of fat was achieved. A second set of test rigs also enabled the clamping, separation, and removal of the chine bone for the “chuck/rack/loin” product. CT data and 3D camera vison analysis created during this project made it possible to generate the cut paths needed to perform each of the objectives above.

Methodology

The following methodologies ensured all paths and options were assessed and trialled when completing the project objectives:

- Perform background research and product investigations
- Develop programs that can generate cut paths from CT data

- Create a list of candidates and perform preliminary tests
- Design clamping and cutting means of suitable candidates
- Build trial test rigs in the Scott factory
- Trial tests rigs and review performance
- Determine the effect clamping has on product movement during and after cutting
- Measure movement during and after cutting/clamping to verify the cut accuracy achieved with the test rig

Results/key findings

The key findings from this project are that CT data analysis can successfully generate a cut path to remove the chine bone with minimum yield loss.

The developed clamp is the best option for future refinement due to its ability to hold the product stationary during the sensing and cutting process. This approach results in no deformation of the product between CT scanning and chine removal.

Benefits to industry

The development work done in this report will help shape the way for automating beef processing in the future. If these standalone trial assemblies are developed further into working prototypes, there will be many benefits for the red meat industry.

- Increased yield gain from accurate cut paths generated from CT data.
- Operator safety.
- Less difficulty recruiting skilled workers.
- Improved production rates and reliability.

Future research and recommendations

Throughout this research, various aspects of beef processing automation have been demonstrated to be achievable using CT data. It was determined that button removal and fat trimming were possible, but due to the potentially significant yield improvements chine removal is the most promising candidate for initial automation. The next steps required to fully automate this process are:

- Integration with Rapiscan industrial CT scanner.
- Further investigation into manual vs automated clamping.
- Finalisation of clamp/pallet material and shape.

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1 Background

In the beef industry, there is a drive to get butchers away from dangerous devices and ease the shortage of skilled meat workers. This can be achieved with the use of automation in specific areas of the carcase breakdown. This research investigated the use of CT data to develop automation in the breakdown, and removal, of the chine bone for a chuck rack and short loin. This research investigated an automated process for fat trimming, removal of the chine bone, and removal of articular processes. At present, the removal of the chine bone is performed with a bandsaw, which endangers workers.

An initial investigation determined that the processing of the loin section has the greatest potential for automation. This would potentially involve an automated line to trim the fat, remove the chine bone, and then remove the buttons. The current optimum manual benchmark loin deboning process is:

- Remove the chine bone with a bandsaw. A second cut is often used to refine the first cut and ensure that the bones are separated.
- Remove buttons with a Bettcher 'Whizard' trimming knife.
- Fleece spinous process, ribs, and the transverse processes.

Figure 1: Loin deboning with a bandsaw to remove the chine to maximise yield.

The profile of the fat cover varies significantly between products. For a striploin, the fat depth can vary from 2 mm to 75 mm and up to 50 mm within a single product. This profile is non-uniform (shown in Figure 2**Error! Reference source not found.**) and requires significant guesswork to create an even fat cap when performed manually. For this project, it was determined that a 5 mm fat cover was ideal for the product.

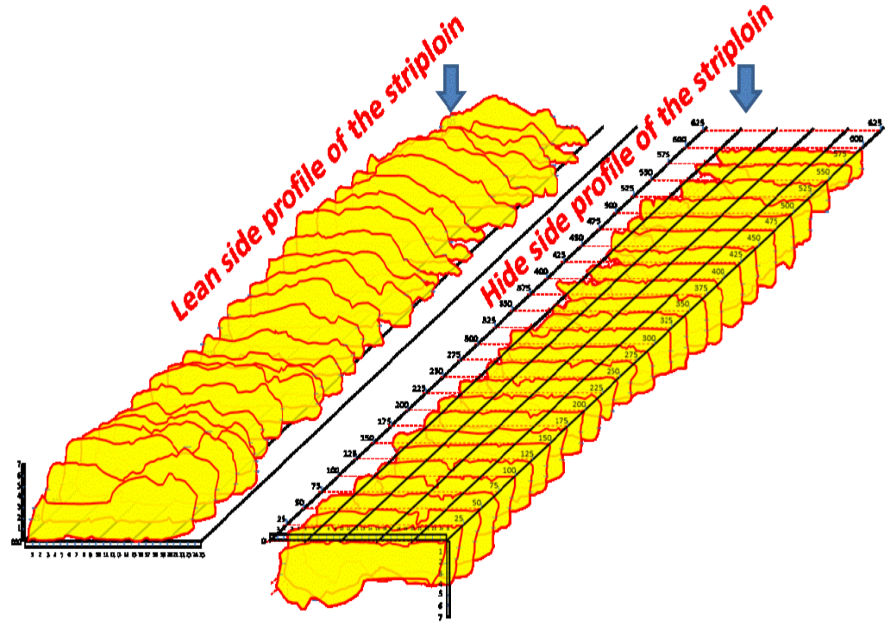

Figure 2: Sliced layers from above, emphasising the differences in the lean muscle – fat boundary in different parts of the product, compared to the hide side of the fat cap (Khodabandehloo, 2016).

The buttons are bony nodules left on the product after removing the chine. These are shown in **Error! Reference source not found.** and **Error! Reference source not found.**. In an unchined product, the spinous process, button and transverse process are connected. Removing the chine should sever these connections, and the buttons are removed in a separate process.

Figure 3: The cut surface on a loin after chine removal. The buttons (articular process) are separate to the other bones and there is enough clearance around them for clean removal.

Figure 4: Button removed from the loin product

1.1 Variation agreement #2

In a subsequent variation, this research was re-scoped to align with an automated boning room process defined in P.PSH.1199 LEAP4Beef Verify Proposed Cutting. P.PSH.1200 evaluated the feasibility of applying DEXA and 2D camera data to perform the spine cross cuts. The re-scoped process for this research investigated the removal of the chine bone from a rack and loin (‘rackloin’) product after cuts the cross cuts.

Two parallel paths were investigated for this research. Alternatively removing the chine before or after the grading cut. This corresponds to the input product being the combined rack and loin, or the input product being separated into rack and loin parts.

Figure 5**Error! Reference source not found.** shows the optimal straight cut on a lumbar vertebra. This removes the maximum amount of lean muscle while separating the buttons from the transverse and spinous processes (feather bones). With the existing process, human operators need to estimate this cut path. With CT data, a 3D model of the bone structure can be created, and the optimal cut can be determined before the product is cut.

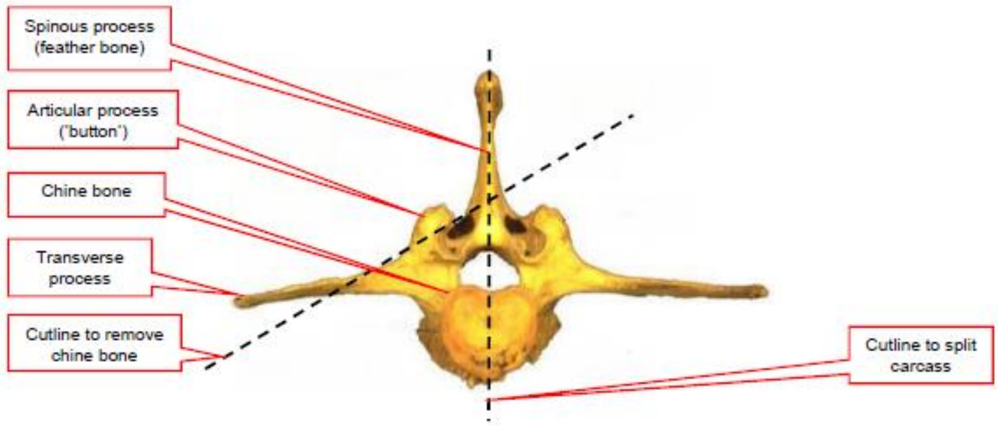

Figure 5: Lumbar vertebra for loin cross-section showing optimal cut. Product is assumed to be split along the midline.

Error! Reference source not found. shows a similar diagram for a thoracic vertebra on the rack section. The rack section has two differences compared with the loin: the optimal angle for the rack is generally much steeper and the cut line needs to avoid the end of the ribs, shown in Figure 6.

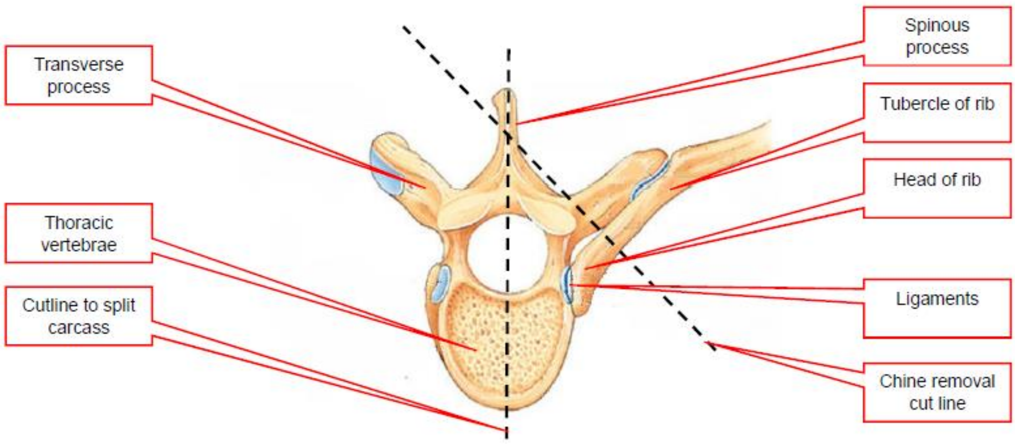

Figure 6: Thoracic vertebra for rack cross-section showing optimal cuts.

These differences highlight the purpose of the inclusion/exclusion of the grading cut. If the loin and rack are attached, the optimal angle changes abruptly at the end of the rack. This change is likely to result in a decrease in yield.

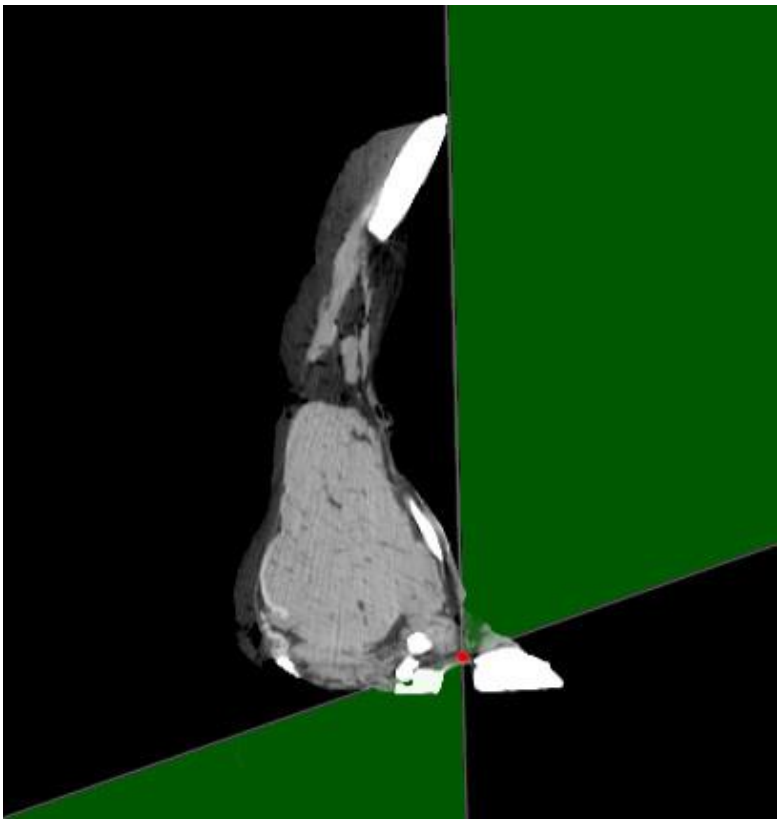

Figure 7: A cross section of a rack from CT data. For a cut passing through the red point, the plausible angles are shown in green. This region avoids the tip of the rib and separates the vertebra, rib and spinous process.

1.2 Significance to Industry

The main projected benefits to the beef industry are increased yield, safer environments and increased data about the product.

Increased yield: With CT data, cuts can be performed closer to the optimal cuts instead of relying on an estimation. The potential value per head is projected to be between $2 and $3.

Safer environments: Currently chine removal is one of the greatest hazards for beef processing due to bandsaw operation. Automating this process alleviates this.

Increased data: A CT scan provides a full 3D model of each product. This may be used for research purposes, identifying internal defects, or providing consumer or farmer information.

2 Objectives

2.1 Objective 1 – Sensing evaluation

Evaluate the capability and benefit of a CT variant to provide sensing for beef rack and loin, bone-in and boneless processing.

2.2 Objective 2 – Chine removal

Develop a "knife and fork" cutting rig and demonstrate the ability to apply the sensing to cutting the chine bone from beef loin and rack primals. (Demonstration in factory or at a processor)

2.3 Objective 3 – Button removal

Develop a "knife and fork" device and demonstrate the ability to apply the sensing to removing chine buttons from beef chine off loin and chine off rack sub primals. (Demonstration in factory or at a processor)

2.4 Objective 4 – Fat trimming

Develop a "knife and fork" device and demonstrate the ability to apply the sensing to trimming fat to a defined depth over the length of a beef loin and off rack primal.

2.5 Objective 5 – Prototype development

By option of SCOTT and MLA Develop a prototype that can prove and demonstrate the technology in-plant

2.6 Variation agreement #2 modified project objectives

- Concept development of clamping and datuming means, suitable for CT scanning and enabling the cross cuts.
- Design and build the standalone trial assemblies to form a concept test bed for testing chine removal from the rack and the loin, combined or individually.
- Trial of “Rackloin” chine removal of up to 5 “Rackloins” in the SCOTT factory.

3 Methodology

3.1 Objective 1 – Sensing evaluation

3.1.1 CT variant

The primary purpose of Objective 1 is to evaluate the capability and benefit of a Computed Tomography (CT or CAT) variant to provide sensing for beef rack and loin processing. CT is a method of combining several x-ray scans into cross-sectional slices. An x-ray scan measures radiodensity; the amount the material absorbs x-rays. Dense objects absorb x-rays more strongly. Figure 8 shows an x-ray of a beef carcase. In this image, the dense areas, such as bone, appear bright. CT combines the information from several similar scans to measure the internal structure of a material. This is shown in Figure 9Figure 9, where a slice of the loin is shown. Combining these slices can generate a 3D model of the bone or meat structure, as shown in Figure 11Figure 11.

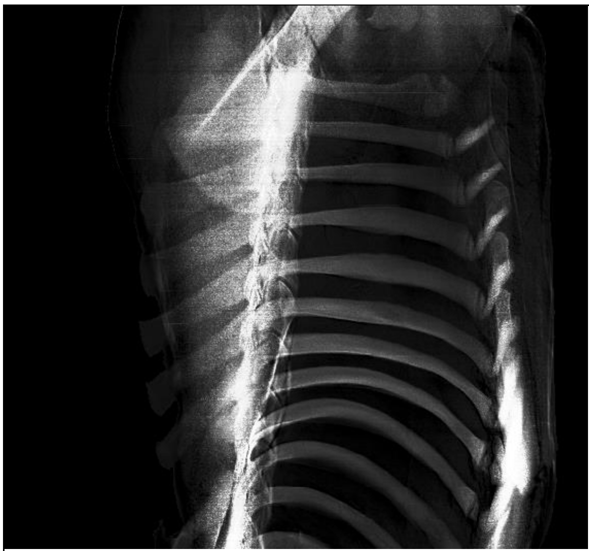

Figure 8: Beef rack x-ray. The denser areas absorb more x-rays and become bright on the screen. The rib shapes are clearly visible, but the detail around the vertebra is unclear.

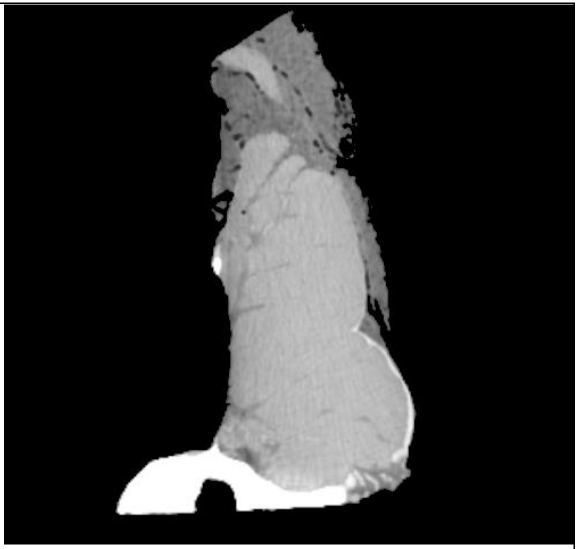

Figure 9: Internal structure of loin. Cross-section generated from CT data. The bone is clearly distinguished from the meat.

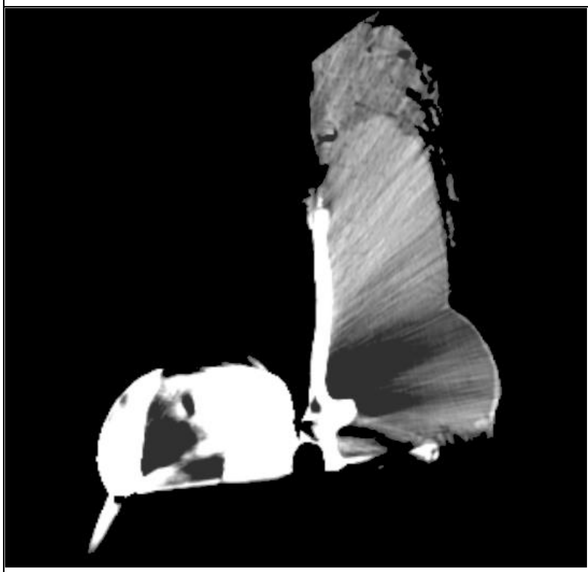

Figure 10: CT scan with a stainless steel clamp. Streak artefacts and false dark regions are visible.

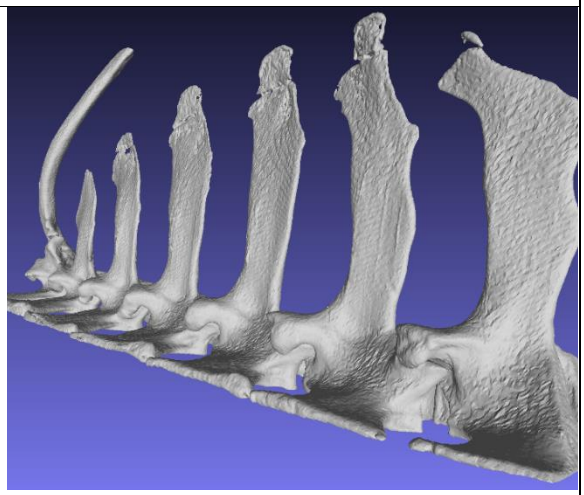

Figure 11: Loin bone surface generated from CT data.

Using a CT scan has two hurdles for beef processing. First, there is presently no commercial machine capable of performing a CT scan at line speed. Second, any deformation or uncontrolled movement of the product after the scan compromises the utility of the scan.

To minimise product deformation or movement several methods were investigated. The main approach for minimising product movement has been different clamping methods to hold the product in place. However, this is complicated by material design because metal objects can distort CT data, as shown in Figure 10.

CT scanners come in several variants including axial, helical, cone beam, multi-tube, and fixed gantry. All these variants use the same principal of combining many x-ray images from different angles to create an internal 3D view. However, the way this is accomplished varies considerably. Each variant was evaluated in a theoretical context to determine its effectiveness.

Another proposal was to supplement CT or x-ray imaging with additional sensing technology. The additional sensing candidates were ultrasound and 3D scanners.

3.2 Objective 2 – Chine removal

This section details the initial investigation into automated chine removal of beef racks and loins using information from CT data. This work was primarily undertaken in milestones 1-5. The methods for further development of the automated chine removal are contained in sections 3.5 and 3.6.

3.2.1 Build

A chine removal test cell was designed and built which used a Kuka KR90 R2700 robot, bandsaw end effector and plastic clamps for product, the design of which is shown in Figure 12. The Kuka robot served as a highly accurate (sub-millimetre) moving base for the bandsaw which allowed simple program execution of computer-generated cut paths. By changing out the end effector the robotic test cell could be easily adapted to the other milestones in the project.

The bandsaw end effector used the wheels and motor from an AEW 400 bandsaw, giving a throat width of 400mm. A new frame was designed to reduce the weight of the original and add a mounting ad for the robot flange. The overall bandsaw design was optimised for testing and development.

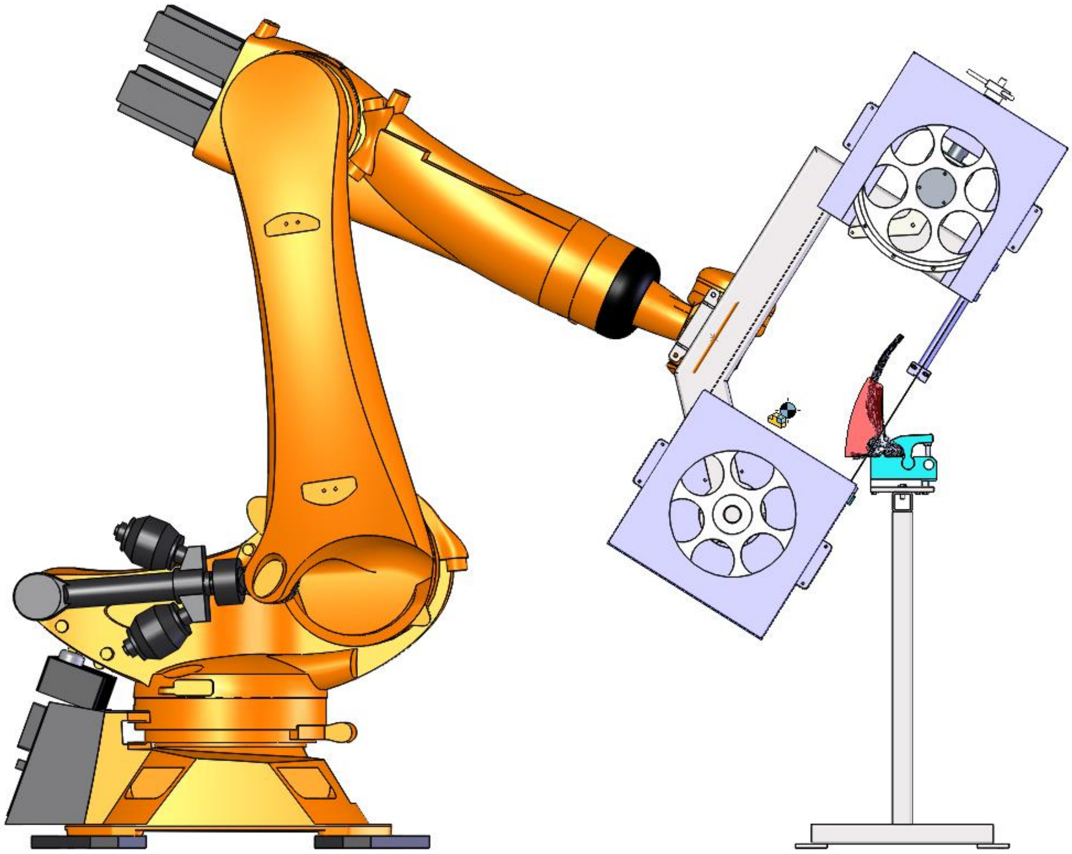

Figure 12: Design of chine removal test cell with bandsaw end effector for Kuka robot and base to support clamped product.

3.2.2 CT Scanning

For the chine removal tests clamped beef loins was CT scanned remotely at AgResearch's Invermay campus, within short driving distance. The base of the clamp provided a coordinate system in the CT data. Care was taken to avoid any movement of the loin in the clamp after CT scanning and during transit. Each loin was located by the clamp base against reference blocks on a cutting table in the test rig. The CT scan was analysed and the cut path was determined relative to the coordinate system.

3.2.3 Vision Analysis

Once the product has been CT scanned the data was analysed by vision software created by Scott. From this an optimised cut path was derived for the bandsaw.

The chine removal process for beef currently occurs through the placement of a cut using a bandsaw across the chine bone to remove it from the rest of the primal. Along this path, there are intermittent bulbous protrusions into the longissimus dorsi muscle (commonly referred to as buttons). The ideal cut path to perform is thus variable based on a trade-off between maximising yield and further processing of the primal by removing the buttons left within the primal. It is proposed that an automated solution would allow for an adjustable parameter to define this.

This application is suited to a 3D technology as the cut is defined by the subsurface 'buttons' along with the chine bone. While this is currently being investigated, CT would be the ideal sensing technology as it provides detailed and complete 3D information for the profile that is looking to be cut. This complete information enables a more robust automated solution, a higher level of accuracy as well as a greater level of customisation for defining the cut.

CT technology offers an opportunity to perform an accurate chine removal cut along with the ability to adjust it for maximal removal of the buttons, minimal loss of yield or somewhere in between. This could be done dynamically, based on the value of the primal.

3.3 Objective 3 – Button removal

To successfully automate the removal of buttons from beef primals two independent but related tasks must be achieved. The first task is to develop a removal tool that, if positioned correctly, can successfully remove the buttons present. The second necessary task is the accurate identification of the buttons to allow automated positioning of the removal tool. To combine the removal tool and sensing data the Kuka KR90 R2700 robot cell from section 3.2 was reused, with the bandsaw replaced with a button removal mechanism, as illustrated in Figure 13.

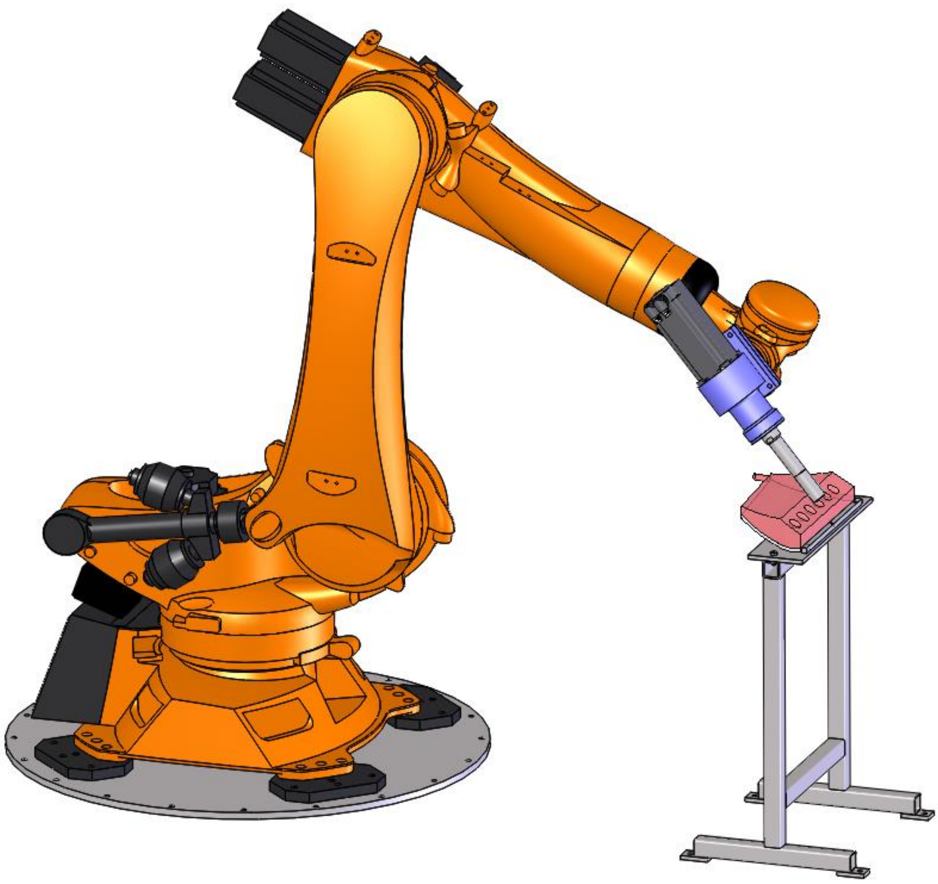

Figure 13: Button removal test rig with annular knife cutter shown as the particular button removal tool.

3.3.1 Cutting Implement

A test rig was built to allow various cutters and tools to be manually trialled for button removal. These broadly covered four candidates; annular knife, whizard knife, vibration knife, and button removal pliers. Of the candidates only the whizard knife was an existing product, a Bettcher Mach III 620 was used, shown in Figure 14.

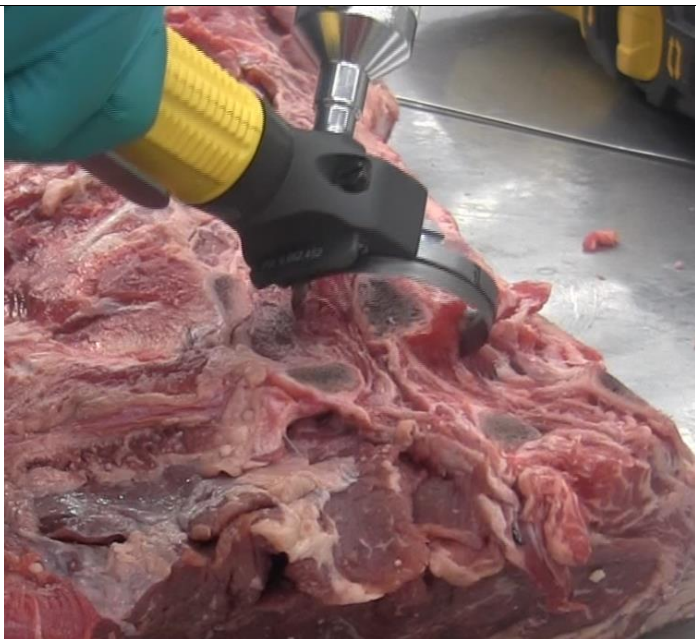

Figure 14: Bettcher Mach III 620 whizard knife, candidate 1.2.2, shown removing a button.

3.3.2 Button detection and path generation

Successful button bone removal requires accurate information about the 3D position and shape of the button. This information must be known relative to the location of the product at the stage in the process when the button is removed.

Several clamping systems were designed and tested with the aim of minimising movement during cutting. However, there remains a significant amount of product movement and deformation after the chine is removed as well as during the button removal process. This suggests that the position of the button will require re-referencing before any of the original CT data can be used for automated removal.

3.4 Objective 4 – Fat trimming

There was a need identified for a solution that would ensure that the resulting fat layer of boneless Striploin and Cube Roll on trimming are at a consistent fat depth according to each customer specification. This project investigated the viability of sensing such as CT or one of its variants that can provide tomography plus a machine to fat trim to depth to ensure an evenly distributed fat depth across the whole fat cap.

In (Khodabandehloo, 2016), the following was found:

> The fat cover on striploins observed in Australia can be 75 mm in thickness down to 2 mm, with changes in height of fat over meat, within the same primal piece, being as great as 50 mm over a 25 mm distance both along the length and along the width of a striploin primal. (pp. 3)

CT data allowed the creation of a 3D model of the fat surface. A fat surface of a beef loin generated from CT is shown in Figure 15. This shows the interface between the meat and fat is lumpy. If a fat cap of a consistent depth is required, a cutting implement that can perform concave cuts is required. Figure 16 illustrates the difference between convex and concave cuts. A bandsaw can cut convex shapes like Figure 16 (a) but if a concave cut is required then an additional tool is required, in addition, processors are unlikely to want a surface that matches this shape.

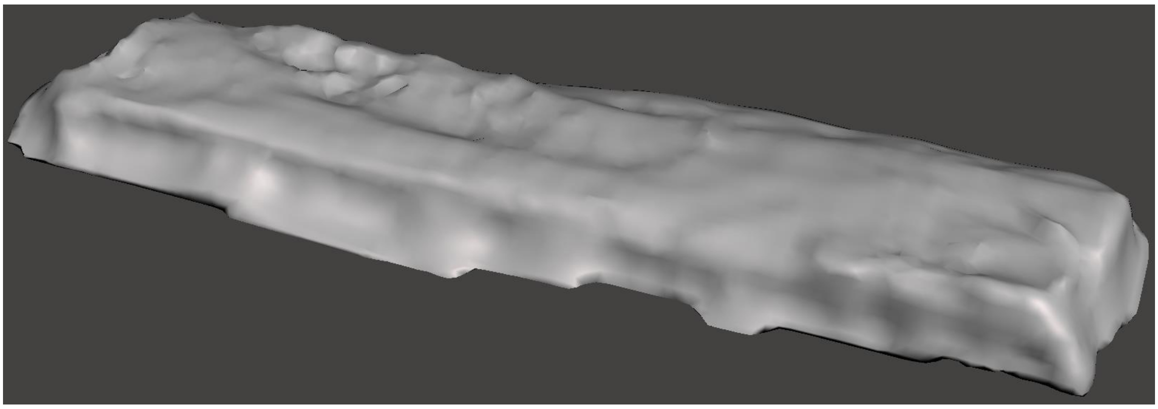

Figure 15: Beef loin meat surface (below the layer of fat) extracted from a CT scan. Viewed from the split chine side, caudal end on the left.

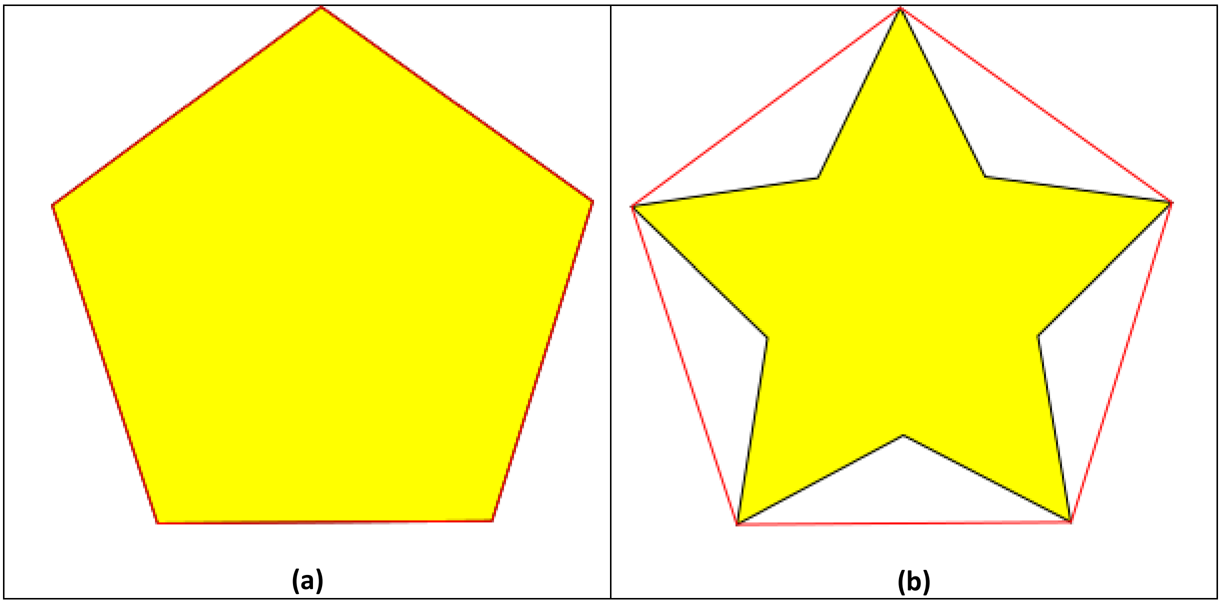

Figure 16: a) Shows a convex cross-section. b) Shows a concave cross-section. For this purpose, a bandsaw could perform several cuts to create the cross-section shown in (a) but could not create the cross-section shown in (b).

An issue for using a CT scan is the boundary between fat and muscle is not well-defined. Determining the composition requires a threshold; a range of values that distinguish which areas that are fat, and

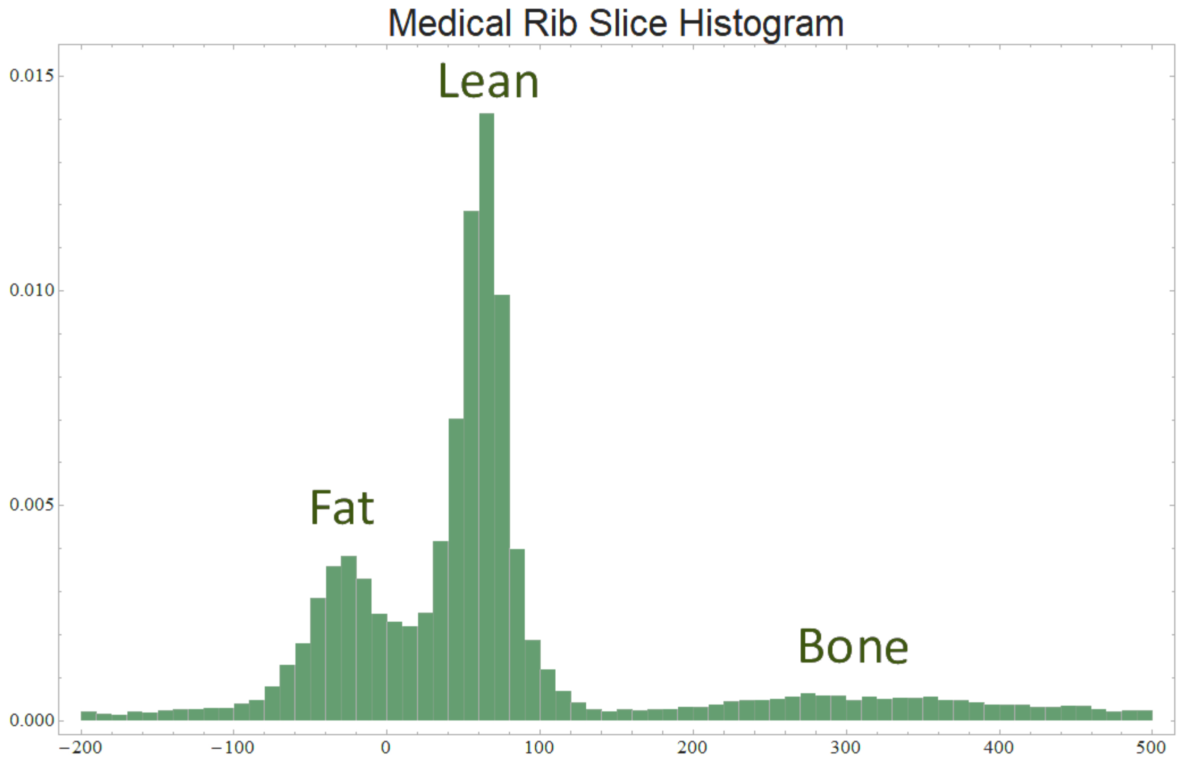

Figure 17: Sample x-ray absorption. The boundary between fat and muscle is not well-defined and classification depends on the threshold used.

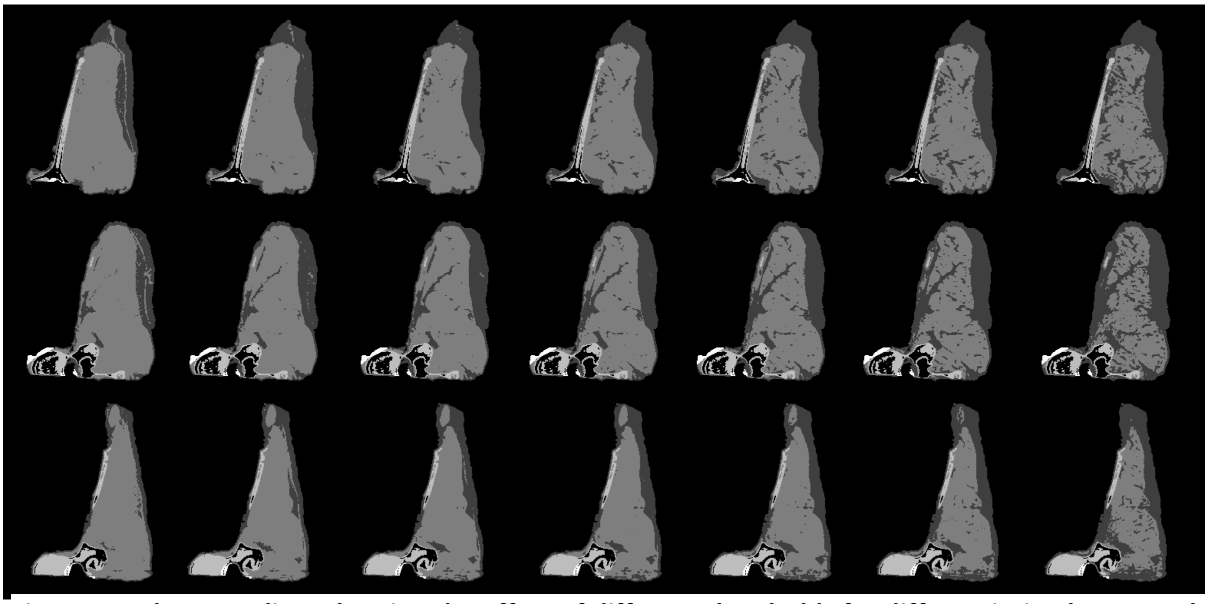

Figure 18: Three CT slices showing the effect of different thresholds for differentiating lean muscle and fat. When the threshold is higher, a larger area is considered to be lean muscle. The left side shows the lowest threshold, right has the highest.

which are muscle. Figure 17 shows a histogram of the absorption for a rib. The three peaks represent fat, muscle and bone. Fat and muscle strongly overlap making the boundary less distinct than the lean—bone boundary. Figure 18 shows the effect of using different thresholds for the fat—

lean boundary. As there is variation between products, this range may also vary. This was identified as an area that could be improved upon with a larger dataset to ensure the fat classification thresholds accurately cover the full range of variation for a beef product.

Trials required two parts: deciding the instrument to use for fat trimming, and the vision systems to determine the path of the cutting implement and automate the removal of the fat cover.

For cutting trials, two orientations were tested. The main development path considered was clamping on the spine with the halving plane parallel to the floor (straight datum). Alternative path of development, was where the product was laid fat side down on the conveyor (natural datum). In the natural datum there is the potential for the product to oscillate or deform during conveying, this must be minimised to ensure the CT data can be matched with the physical product.

3.4.1 Cutting implement

In the initial investigation, a proprietary Bettcher 'Whizard' trimming knife was tested, as used by some processors. This produced a good result manually but was very limited to the thickness of fat it could remove cleanly in one pass. It was considered a reasonable solution for fine fat trimming, but duty cycle and reliability are a concern, and a more robust option is necessary for automation. In addition, different instruments were necessary for heavy fat removal. For the clamped fat trimming trials, several custom tools were developed.

3.4.2 Path generation

To automate the fat trimming process, the movement profile for the given tool needs to be generated. Once an ideal fat profile is created, the path to direct the robot's end effector needs to be generated.

3.5 Objective 5 – Prototype development

3.5.1 Clamping

For the original specification, the primary focus involved clamping on the spine. This attached a set of clamps before the CT scan. Following variation agreement #2, further investigation was put into alternative clamping methods for processing a chuck/rack/loin product.

To minimise movement through an automated machine, a clamp needs to perform these functions:

- Enable separation and removal of the chuck
- Enable separation of the rack and loin
- Enable chining of the loin
- Enable chining of the rack
- Location of loin to enable referencing off CT scanned data

For testing the movement caused by a process using a particular type of clamp, a dial test indicator (DTI) was used. These can measure small changes in position and angle from a reference point. To test whether a clamping method was viable, an operation such as separating rack and loin sections was performed and measured using a DTI.

For these tests, only plastic clamps were used if the product was put through a CT scan to avoid artefacts. This limits the strength and durability of clamping. An initial investigation has been conducted into the feasibility of alternative materials and clamp shapes that limit CT artefacts.

3.5.2 Bandsaw limits

To maximise yield and to ensure fidelity of chine cuts, it was important to establish the limits of the bandsaw. A sharper turning radius widens the possible paths that can be performed. The rotational axes are shown in Figure 19. Adjusting pitch is the most natural rotation for the bandsaw. Roll is possible but with a shallower radius. Only a fixed yaw was considered.

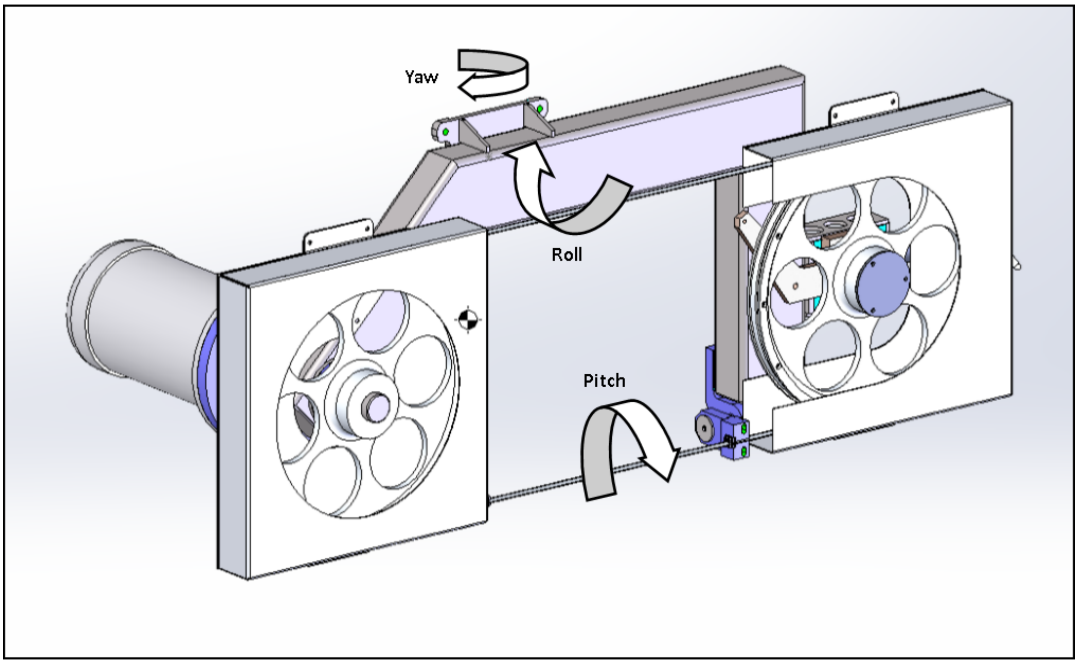

Figure 19: Model of bandsaw and the associated axes.

3.5.3 Prototype process

The original research problem was to design a prototype, to demonstrate the innovated technology in a processing plant. This was to automate the fat trimming, chine bone removal and button bone removal. While maximising the yield achieved. The return on investment is to be supported from the improved yield over the manual process and the labour savings.

The overall methodological approach is to use the outcomes from milestones 1 -11 as inputs to the designing of the Alpha prototype. The previous milestones involved development of “knife & fork” test rigs and subsequent trials. A suitable target production cycle time of 10 seconds was proposed.

The following evaluation criteria was established:

1. Value added due to Accuracy – maximising value of each resultant piece
2. Yield (Scaping benchmark)
3. Capital cost per carcass production rate
4. Labour saving

5. Cycle time – ability to achieve 10 second
6. Footprint/Ability to be retrofit
7. Health & Safety
8. Reliability – confidence in achieving performance requirements
9. Collected Data Value – value for downstream analysis or decision making
10. Potential for Intramuscular measurement

A cycle time chart is developed to define the series or parallel logic, assess the cycle time of each action, and therefore establish a prediction for the overall machine cycle time. For an alpha prototype, the focus was to demonstrate the feasibility of the process without the 10 second cycle time requirement.

3.5.4 Re-scoped process

The project was re-scoped to suit the proposed TEYS Automation process laid out in P.PSH.1199. In this process a beef side is manually prepared by removing the foreleg (4), inside skirt (1) and flank (2). The brisket and rib strip are removed with cuts A and B where the chuck, rack and short loin (chuck/rack/loin) is then removed by cutting along line E. This product called the 'chuck/rack/loin' is then input into the beef middle machine.

The tenderloin is either in place (head dropped) or removed. The tenderloin is primarily left in for creating T-bone steaks. After a CT scan, the chuck is removed with the spine crosscut between the chuck and the rack. The rack and loin are then separated. The chine bone is optionally removed for both the rack and loin; depending on whether the tenderloin is still attached and whether oven prepared racks are required. There is an option to bypass the separation of the rack and loin and chine the rack/loin as one piece.

3.6 Variation agreement #2 modified project objectives

3.6.1 Process

For this variation, the automated processing was moved to focus on a chuck/rack/loin section. For this option, the chuck would be first separated. Then the remaining rackloin would either be separated and chined individually, or chined together before separation. The main path of development has been the candidate where the product is clamped during the CT scan.

4 Results

4.1 Objective 1 – Sensing evaluation

4.1.1 CT variant

The foundation of this project has been to test whether CT data could be used for rack and loin processing. CT technologies were evaluated across several categories, shown in Table 1. The combination of CT or 2D x-ray and supplementary techniques is given in Table 2

Table 1: Evaluation of CT scanning setups. FBCT refers to a Fan Beam CT variant while CBCT refers to a Cone Beam CT variant.

	Cost	Speed	Effectiveness	Reliability	Installation	Safety	Quality Assurance	Collected Data Value	Marbling Measurement	Fat Covering Measurement	Resolution	Bone Definition
Axial FBCT	Acceptable	Not Acceptable	Acceptable	Not Acceptable	Acceptable	Acceptable	Good	Good	Good	Good	Acceptable	Good
Helical FBCT	Acceptable	Not Acceptable	Good	Acceptable	Acceptable	Acceptable	Good	Good	Good	Good	Good	Good
Cone Beam CBCT	Acceptable	Acceptable	Good	Acceptable	Acceptable	Acceptable	Good	Good	Acceptable	Good	Acceptable	Good
Multi Tube Fixed Gantry	Acceptable	Good	Good	Acceptable	Acceptable	Acceptable	Good	Good	Good	Good	Good	Good
CNT Fixed Gantry	Acceptable	Good	Good	Acceptable	Acceptable	Acceptable	Good	Good	Good	Good	Good	Good

Legend	
Green	Good
Yellow	Acceptable
Red	Not Acceptable

Table 2: Evaluation of sensing methods.

	Cost	Speed to process	Overall Effectiveness	Reliability	Installation	Safety	Chine Bone Removal Accuracy	Loin Fat Trimming capability	Ability to further process after first cut	Button Removal	IMF Detection
CT Only	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Good	Acceptable	Acceptable	Good	Good
CT + Ultrasound	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Good	Good	Good	Good	Good
CT + 3D Scanners	Acceptable	Acceptable	Good	Acceptable	Acceptable	Acceptable	Good	Good	Good	Good	Good
2D Xray + 3D Scanners	Good	Good	Not Acceptable	Acceptable	Good	Acceptable	Not Acceptable	Not Acceptable	Good	Not Acceptable	Not Acceptable
2D Xray + Ultrasound	Good	Good	Not Acceptable	Acceptable	Good	Acceptable	Not Acceptable	Good	Good	Not Acceptable	Not Acceptable

Legend	
Green	Good
Yellow	Acceptable
Red	Not Acceptable

There exist several methods of CT scanning, these are detailed in Appendix 7.1. In an early milestone, it was determined that any of the existing methods would provide sufficient precision for this project.

However, most of these methods are unlikely to be fast enough to perform at line speed. As such, there are no commercially available scanners with the required speed and dimensions. In principle, this could be addressed using multiple scanners, but this would be cost-prohibitive.

As part of MLA project P.PSH.0930 Rapiscan is developing a CT scanner (RTT110) with the required properties for beef processing. This prototype is adapted from airport baggage scanners with a tunnel size of 1000mm x 650mm and conveyor speed of 0.5ms^{-1}.

4.2 Objective 2 – Chine removal

Throughout this project, methods for chine removal for rack and loin were tested. This was possible to achieve using CT data. The results in this section primarily concern the initial trials into automated chine removal using CT, largely completed in milestones 1-5. The results for further development of the automated chine removal are contained in results sections 4.5 and **Error! Reference source not found.**.

4.2.1 Build

A robotic test cell was built to allow high accuracy cutting based on CT data. This consisted of a 6-axis robotic arm with an attached bandsaw, shown in Figure 20. This setup allowed accurate positioning while also being highly configurable to allow rapid prototyping of different cutting techniques. This chine removal cell was used for many of the chine removal candidates. Additionally, by swapping the end effector the setup was easily adapted to the other objectives of the project, i.e. button removal, and fat trimming.

Figure 20: Robotic tool used for the removal of chine bone.

4.2.2 CT Scanning

To allow for accurate chine removal with CT information a base is needed to support the product during transport, scanning, and chine removal. The base had to support the product during transport from the Scott factory to the CT scanning facility at AgResearch's Invermay campus, approximately a 10-minute drive from the Scott facility.

4.3 Objective 3 – Button removal

Methods for button removal from the loin were developed using CT data to identify the buttons.

The original objective specified removing buttons for the rack and loin. In the original scoping, removing the buttons from the rack was difficult, messy and did not contribute additional value. With agreement from MLA, it was decided to focus on removal of the buttons from the loin.

4.3.1 Cutting implement

Initial button removal tests were performed with various implements

4.3.2 Button detection and path generation

Manual trials led to a reliable template for a cut strategy that gave robust and efficient button removal. The surface entry and exit points and the button depth from CT are combined to produce a cut path for each button.

4.3.3 Results

Sample results are shown Figure 21 and Figure 22.

This method produced promising results for a prototype however, some of the buttons were incorrectly removed, such as in Figure 23.

Figure 21: Loin after automated button removal.

Figure 22: Button bones resulting from the automated removal process.

Figure 23: Topside of removed button on test loin. The cut path produced a close cut around the perimeter of the button.

4.4 Objective 4 – Fat trimming

4.4.1 Cutting implement

Several different options were tested for removing a layer of fat.

The bandsaw was effective at coarse fat removal as the blade cut through thick fat with minimal disturbance to the loin. The finish was generally smooth but produced saw dust and can only cut convex surfaces.

The alternative development path with fat face down was trialled. Shaving fat strips of constant thickness using a fixed blade and infeed belts was successful for thin strips. This method required a strong force to guide the product through the blade, which causes deformation of the fat. This modifies the orientation and shape of the product, compromising the utility of any prior scan.

4.4.2 Trials

4.4.2.1 Chilled loin trimmed with bandsaw

The lack of fat cover on the test product limited the cut depths that could be tested. For this reason, the fat trimming was set to 0mm, with a maximum of 6 passes over the loin with the bandsaw.

Figure 24: Left: Chilled product before fat trimming. Right: Product after fat trimming with the bandsaw. Six passes were used along the length of the loin. The cut specification had to be set at 0mm due to the light fat cover on the loin.

4.4.2.2 Frozen product trimmed with bandsaw

To minimise product movement two loins were fitted into the chine clamp and frozen. The frozen loins were CT scanned and processed in a frozen state. This required alterations to the voxel classification due to changes in x-ray absorption. It also meant the x-ray attenuation properties of meat and fat (voxel intensity values) became more similar and the boundary was less pronounced.

Figure 25: Left: blade deflection visible in frozen product. Right: Frozen loin after seven passes by the bandsaw.

The product was more robust to movement, but the previously tested cut constraints were no longer applicable due to the stiffer product. This introduced a significant amount of blade deflection and led to poor cut path adherence.

4.5 Objective 5 – Prototype development

4.5.1 Clamping

Spine clamps were developed and evaluated. The spine clamp was evaluated and movement determined as minimal and would contribute insignificantly to cut path error.

4.5.2 Process

4.5.2.1 Original process

Two systems were developed, the “10 second cycle time concept” and the “Alpha prototype” machine. Where the “Alpha prototype” machine was fully designed for manufacture. Figure 26.

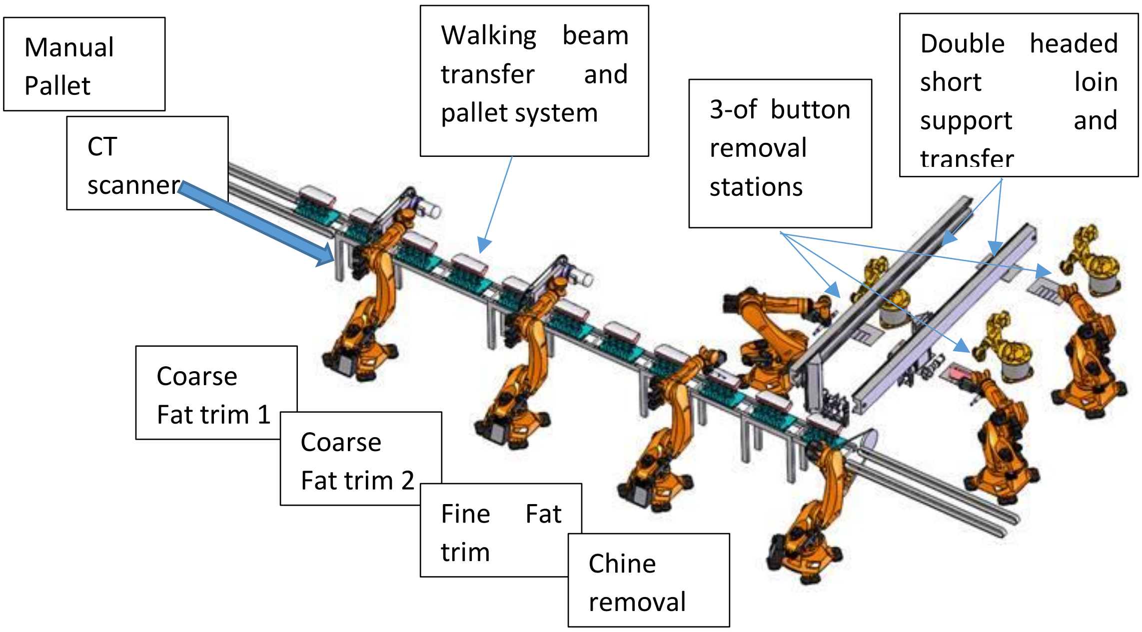

Figure 26: Alpha prototype - validation of beef middle automation processes

The total process consists of:

1. Manual load into pallet
2. Manual transport and processing through an offline CT Scanner
3. Single coarse fat trimming stations – with multiple cuts
4. Offline option to demonstrate fine fat trimming with one of the other process robots.
5. Chine bone removal
6. Button bone removal (just one station)

Where the transfers are:

1. Walking beam transfer of the pallet system. Where the pallet has self-contained spine locking. Only five pallets would be built.

2. Loin support and transfer to button bone removal “nest” with a 6 axis robot (in place of the custom high speed double head transfer device). And the robot replaces two of the gripper servo axis proposed in the custom high speed transfer.
3. Button bone removal station nest infeed device – is not required.

10 second cycle time concept

The total process consists of:

1. Manual load into pallet
2. CT Scanner
3. Multiple coarse fat trimming stations
4. Multiple fine fat trimming stations
5. Chine bone removal
6. Button bone removal

Where the transfers are:

1. Walking beam transfer of pallet system. Where the pallet has self-contained spine locking
2. Double headed loin support and transfer to button bone removal “nest”
3. Button bone removal station nest infeed device

5 . Conclusion

Scott investigated whether CT scanning could be used to provide sensing for beef rack and loin processing, what would be a world first. CT scanning was determined to be feasible for this task and to have significant potential for yield and accuracy improvements.

Following the initial investigation into CT scanning Scott built a “knife and fork” chine removal rig and have demonstrated the ability to apply the CT information to the chine removal of beef racks and loins.

Additionally, two more “knife and fork” cutting rigs were also built; one for the removal of buttons from beef loins, and the other for trimming fat to a defined depth over the length of a beef loin and off rack primal.

A prototype for a combined conveyor system was designed, and proposals for a full production machine were developed.

Following variation agreement #2, the objectives were modified to focus on chine removal and crosscuts for a combined rack and loin product. Alternative paths for this process were investigated. The ability to remove the chine bone from rack and loin products – combined or separated – was demonstrated. Various clamping methods were tested, and a projected cycle time was developed.

With the given objectives achieved this milestone marks the conclusion of this project. All objectives have been successfully achieved and much has been learnt which can be applied to a production machine in future.

5.1 Key findings

Scott has designed and built "knife and fork" prototypes for beef rack and loin:

- Button removal, the most promising candidate of which was the annular knife.
- Fat trimming, the most promising candidate of which was the bandsaw.
- Chine removal, the most promising candidate of which clamped the product prior to CT scanning, and removed the chine of the separated rack and loin.

5.2 Benefits to industry

Implementation of the automated chine removal process developed in this project will have benefits to the beef industry as outlined in the following:

- CT scanning the beef rackloin and robotically chining will result in an increased cut accuracy and increased yield on the final products, which are among the most expensive primal cuts on a beef carcase. Even an increase in accuracy of only 2mm during chine removal will result in an average yield increase of $3.26 per side[1]. Optimising the chine cutting path will reduce the amount of beef eye meat that is left on the chine therefore reducing waste. There is a significant value difference between trim and eye meat which means a significant value gain.
- Health and safety benefits in injury reduction. Amputation is a serious risk when performing some of the processing cuts such as the chine cut. An automated system would remove this risk. Anecdotally it is understood that a plant is likely to experience a significant bandsaw related incident about every 6 months. Implications for this are costs of around $50,000 to $150,000, damage to reputation, loss of skill in the short to long term, and the associated cost of filling the role in terms of recruitment and training. Additionally, manual handling injuries are decreased by reducing the size of the product that is being processed manually.

6 Future research and recommendations

Through this research, various aspects of beef automation have been demonstrated to be achievable using CT data. It was determined that button removal and fat trimming were possible, but due to the significant potential yield improvements chine removal was the most promising candidate for initial automation. Chine removal for a rackloin product was seen as the most useful area to apply this data.

The individual pieces for removal of the chine bone have been demonstrated. The next steps necessary to automate this process are:

- Integration with Rapiscan CT scanner
- Further investigation into manual vs automated clamping
- Finalisation of clamp material and shape

Once these are achieved, a complete solution that integrates a full cycle can be tested.

[1] Based on CT analysis of the chine removal from both the rack and loin portion of the carcase and an average rack/loin price of $15/kg. (Scott, milestone 13)

7 References

Hubble, J. H., & Seltzer, S. M. (2004). *NIST Standard Reference Database 126. Tables of X-Ray Mass Attentuation Coefficients and Mass Enery-Absorption from 1 keV to 20MeV for elements Z=1 to 92 and 48 Additional Substances of Dosimetric interest.* Gaithersburg: NIST.

Khodabandehloo, K. (2016). *Technology evaluation for fat removal for beef striploins leaving uniform thickness behind.* Sydney: AMPC.

Laguna. (2021, 02 25). *Bandsaw Blade Education.* . Retrieved from lagunatools.com: https://lagunatools.com/education/bandsaw-blade-education/

Lin, E., & Alession, A. (2009, 07 30). *What are basic concepts of temporal, contrast, and spatial resolution in cardiac CT?* Retrieved from pubmed.ncbi.nlm.nih.gov: https://pubmed.ncbi.nlm.nih.gov/19717355/

Qi, C. R., Yi, Li, Su, Hao, Guibas, & Leonidas, J. (2017). *PointNet++: Deep Hierarchical Feature Learning on Point Sets in a Metric Space. arXiv preprint arXiv:1706.02413.* Ithaca: Cornell University.

Ronneberger, O. (2015, 05 18). *U-Net: Convolutional Networks for Biomedical Image Segmentation.* Retrieved from arx1v.org: https://arxiv.org/abs/1505.04597

Tan, M., & Le, Q. V. (2019, 05 28). *EfficientNet: Rethinking Model Scaling for Convolutional Neural Networks.* Retrieved from https://arxiv.org/abs/1905.11946

Thompson, W. M., Lionheart, W. R., & Morton, E. J. (2017). High-Speed Dynaming Imaging with a Real Time Tomography System. Rapiscan Systems and The University of Manchester.

7.1 CT types

There are a few well established types of CT Scanners. Axial and Helical Scanners scan slice by slice either in loops or a helical path, and volume-style scanners, where only a single rotation is required. Figure 27 shows a visual demonstration of this difference.

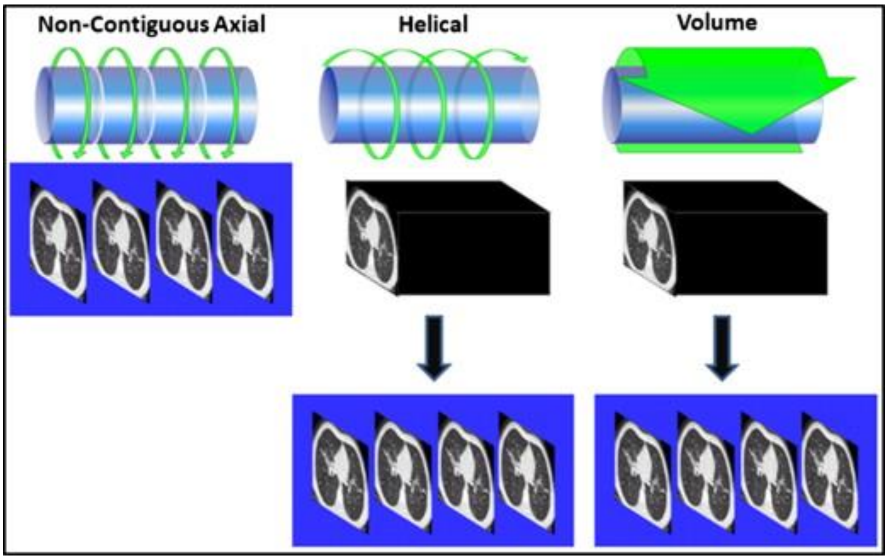

Figure 27 CT variant comparison

A Non-Contiguous Axial scanner rotates once around the target for each slice before starting the subsequent slice. This would not be applicable for beef automation, as this takes a long time.

Helical CT – also known as fan-beam CT (FBCT) – is the dominant form of CT, due to being on the market for longer and low manufacturing costs. In this method, the x-ray tube and detector are rotated around the central axis. The subject of the scan is then fed along this central axis which produces the helical shape of the scan path. These scanners offer significant improvement over the axial models. However speed is still a concern, and many of these models require a cool down period following a scan, making production speeds unlikely.

Cone-beam CT (CBCT) scanners output a cone of x-rays which are incident on a 2D array of detectors. Because a cone beam illuminates a 2D area at a time, it offers much faster scan rates for CT. Depending on the target, a single rotation may be sufficient.

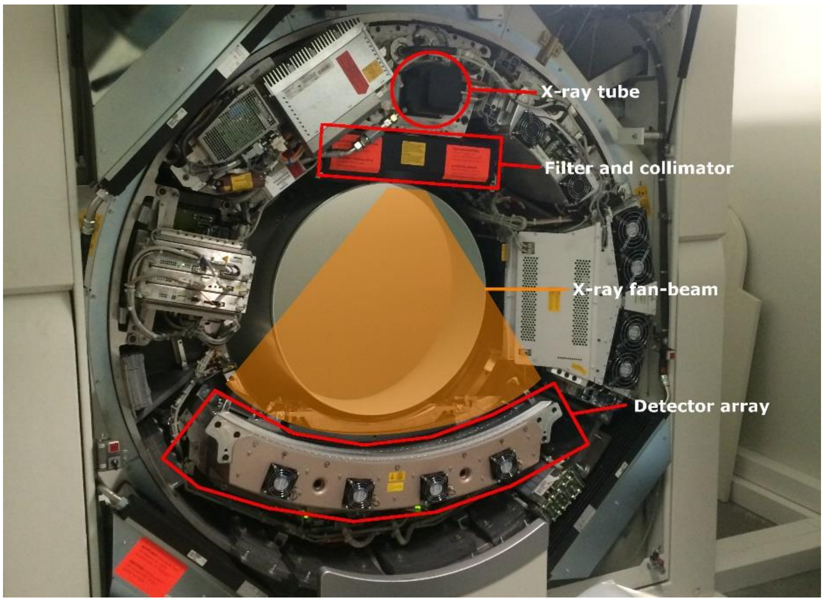

Figure 28: Traditional Fan Beam CT equipment example showing the ‘fan-beam’ from the source to detector.

Cone beam CT has the advantage of needing less rotation and movement than FBCT. For the purposes of beef automation, where meeting production speeds is crucial, this could be an important factor. Cone beam CT has traditionally been seen as less precise than FBCT from complications of the nature of the beam. Multiple scattering of the x-ray beam is more likely to occur in a cone beam than a fan beam.

The majority of CT literature is from a medical context, where minimising radiation dosage is desirable from a radiation safety context, often accuracy is discussed in terms of specific parts of the human anatomy. For the purposes of beef middle automation where the most important distinctions are the bone – lean boundaries and fat – lean distinction. For this, the most important factors are accuracy and precision. Additionally, without the requirement to minimise patient radiation exposure, CT scans of non-living product can be performed with higher levels of radiation to increase the signal to noise ratio.

The advantages of fan beam CT include greater soft tissue definition and greater bone resolution. The advantages of cone beam CT include lower radiation dosage, lower cost, and fewer artefacts from metallic objects.

7.1.1 Fixed Gantry CT

Fixed Gantry CT is a newer variant in which neither the source, detectors, nor the subject rotate. The entire volume is scanned at several angles using several sources distributed around the gantry and a stationary set of detectors. The sources are turned on and off in specific patterns to imitate the effect of rotation. The device generates a fan beam x-ray and may use from ten to thousands of source points.

The absence of motion or blurring results in higher image resolution and fewer artefacts. The stationary multi-beam source delivers a much faster acquisition than conventional systems, corresponding to an increase in throughput. This faster acquisition and reduced wear and tear also reduce amount of maintenance required.

An example of this multisource is the Real Time Tomography (RTT) family of devices produced by Rapiscan Systems. In these devices a ring of sources is activated in a pattern interacting with a separate ring of detectors while stationary (Thompson, Lionheart, & Morton, 2017).

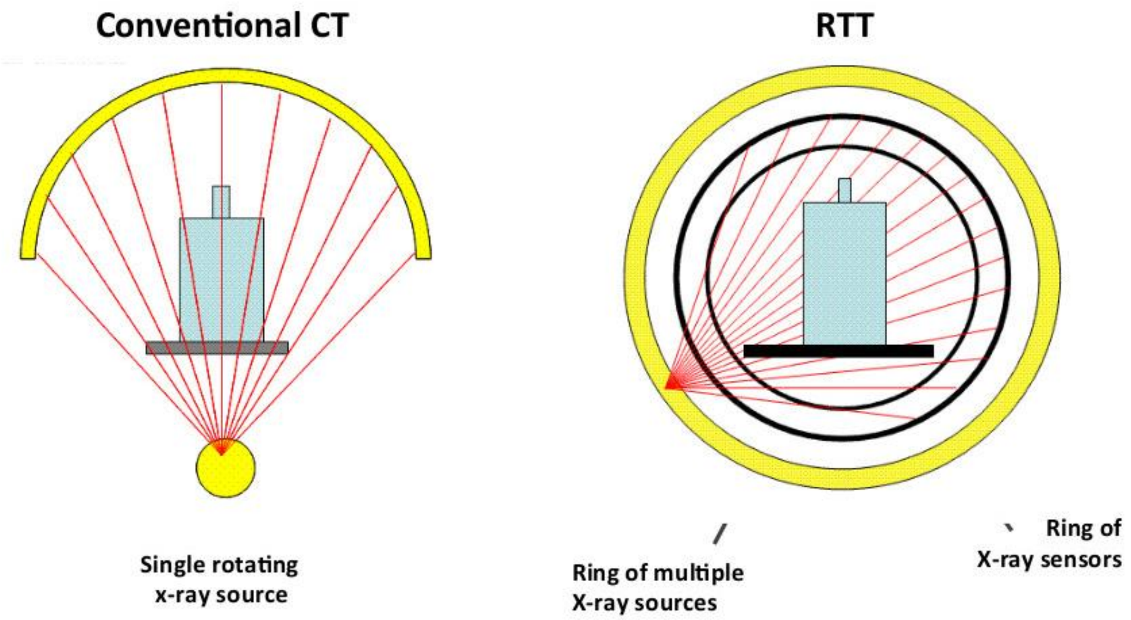

Figure 29: Multi Source RTT compared to a traditional rotating CT system. Image taken from (Thompson, Lionheart, & Morton, 2017)

7.2 Alternate sensing technologies

7.2.1 Ultrasound

Ultrasound uses high energy sounds wave reflections to build up a picture of the inside of the object of interest. A probe, which contains one or more transducers and acts as both a transmitter and receiver of sound, sends pulses of sound into the object. Whenever a sound wave encounters a material with different acoustical impedance, part of the sound wave is reflected which the probe detects as an echo.

The time it takes for the echo to travel back to the probe is measured and used to calculate the depth of the tissue interface causing the echo. The greater the difference between acoustic impedances, the larger the echo is.

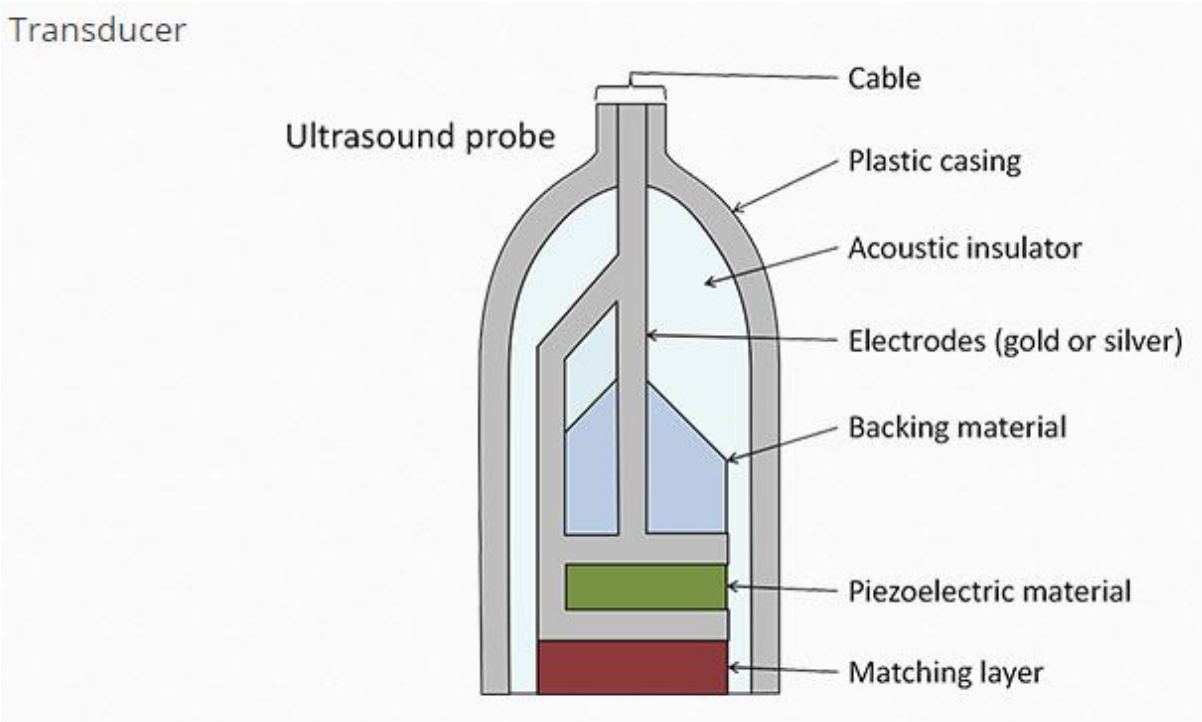

Figure 30: Example ultrasound probe.

An example probe for ultrasound is shown here in Figure 30. Ultrasound technology is cheap and reliable, however the resolution of the images acquired is inferior to CT and x-ray. It also cannot accurately image through bone or provide any external feature detection.

7.2.2 External 3D scanning

3D scanning technologies allow digital reconstruction of the external features of an object. These technologies require an unobstructed view of the object in order to resolve the image correctly.

Typically cheap, fast and reliable, 3D scanning is a strong candidate for supplementing CT technologies, especially for re-datuming objects after they have been moved or the shape changed due to prior processing.

The best example of this for beef middle automation are light / laser scanners. These scanning devices use projected light and a camera system to measure the shape of an object. Projecting a narrow band

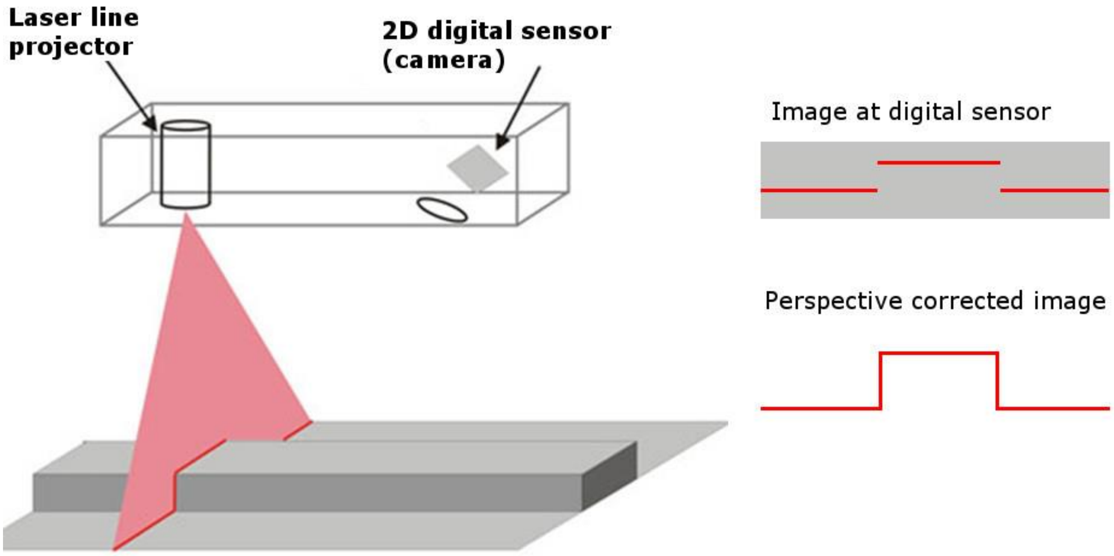

Figure 31: External 3D laser scanning principle diagram.

of light onto a 3D shaped surface produces a line of illumination that appears distorted from other perspectives that that of the projector. This can be used for an exact geometric reconstruction of the surface. The principle of this process is displayed in Figure 31.

There is also the possibility of extending this technology from a single line projection to a more complex structured pattern to allow for the acquisition of multiple samples simultaneously. With cameras recording the resultant pattern at different viewpoints, the geometric distortion of the pattern at those different angles can be decoded to inform about the shape of the object.

7.2.3 2D colour imaging

With standard colour cameras and image processing software, a wide variety of tasks can be performed. In the context of beef middle automation, it is likely that the applications of such a system would be in finding the buttons after the chine removal.

7.2.4 2D x-ray

X-ray absorptiometry of the two-dimensional kind could be seen as a potential low-cost alternative to more complex and expensive CT techniques. Current Scott lamb machines use x-ray beams passing through a product onto a linear detector.