final report

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Objective Primal Measurement (OPM) – Pack-off Primal Pick and Pack: Fundamental Vision and Sensing Evaluation

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Abstract

The primary limitation to automation in the “Pick and Pack” area of an abattoir is appropriate sensing. This project assessed the ability of a number of sensing technologies to perform a number of different tasks. These findings can be used to proceed to commercial prototype design and development.

Hyperspectral imaging was shown to demonstrate differences between uncontaminated meat and fat, and a range of contaminants. Low-cost colour and 3D imaging was shown to be capable of wet beef primal identification. MRI imaging was shown to be able to detect a range of offal contaminants. It was also shown that there is a correlation between MRI data and meat eating quality. As this project was an evaluation study, the next step is to collect more data for these applications capturing a wide variation. From this, more complex algorithms can be built using the findings from this project as a base.

DEXA imaging was not successfully applied to the application of striploin and cube roll processing. It is felt that 3D x-ray imaging (such as cone-beam CT) is required to perform these accurately and reliably.

Executive Summary

The back end of a boning room (beef and sheep) requires a large number of flexible labour units for the area known as ‘Pick and Pack’. With the number of primal and sub-primal specifications customers are demanding, the limitation to automating this area is not robotics but reliable vision and sensing systems. At the conclusion of this project the industry will know what vision systems will and will not work to then drive (and build) automated solutions within the Pick and Pack area.

Hyperspectral imaging (HSI) can be used to obtain spectral and spatial information of an object over the ultraviolet, visible and near-infrared spectral regions (300nm – 2,600nm). This information can then be used to characterise different materials. One particular area of interest is the ability to detect contamination. There are a number of primal defects for which inspection occurs in the pick and pack area. A hyperspectral camera was purchased and installed at SCOTT. A number trials were then performed to provide an initial assessment of which pick and pack defects may be detectable using this technology. It was found that a significant number of the contaminations investigated could be detected by a hyperspectral camera.

Two key processing tasks for striploins and cube rolls include fat trimming and chine removal. Due to the inability of a human to see subsurface features, these operations are difficult to perform manually with accuracy. CT imaging can provide 3D information to perform these tasks but is an expensive technology. This project aimed to investigate the feasibility in using cost-effective dual-energy x-ray absorptiometry (DEXA) to perform these tasks.

Samples of short loin were sourced from an abattoir and DEXA-scanned. A number of methods were investigated using this information to try and reliably identify the subsurface features of interest required to perform these tasks. While some promising progress was achieved, it is felt that a 3D x-ray imaging technology will be required to perform fat trimming and chine removal accurately.

A key requirement for pack-off area automation in this area is the identification of primals. There is a range of sensing technologies available to achieve this, the most cost-effective and simplest being colour imaging and 3D profiling. A high-level evaluation was carried out to assess what performance is achievable with this technology, and what may be required to cover its limitations.

Colour and 3D data were taken for a large number of naked beef primals. Preliminary classification algorithms were written to identify six different primals. These algorithms were then verified with an independent dataset. The initial results were positive, especially considering only a single computer training iteration and that a truly independent verification set was used. More complex classification algorithms would result in further improved performance. It is also important to consider that accuracies will be dependent on the given application.

SCOTT has a business unit which develops high temperature superconductive wires which can be used to construct powerful magnets which don’t require cryogenic cooling and can be used for Nuclear Magnetic Resonance (NMR) / Magnetic Resonance Imaging (MRI) applications. Helium cooling represents a significant cost and maintenance barrier and removing this requirement allows for industrial MRI machines to be manufactured.

Many offal contaminants are sub-surface and therefore not detectable with colour and hyperspectral imaging. Some are also quite similar in density and x-ray absorption to surrounding tissue, making detection using x-ray and CT also challenging. MRI presents an opportunity for

filling this gap. A number of samples of various offal defects for beef and lamb were obtained from an abattoir. These were transported back to the SCOTT facility and scanned with a cryogen-free MRI machine. Most were able to be identified clearly given the right MRI acquisition settings.

Recently, DEXA technology has been shown to allow objective measurement of lean meat yield (LMY). Commercial installations of this technology exist and it is being further rolled out across the country. One important counter-balance to LMY however is eating quality (EQ) – care must be taken not to focus breeding on LMY at the expense of EQ. It has been shown in the literature that there is potential for MRI image features to predict shear force measurements in beef samples. A number of beef samples were scanned with the MRI scanner (24 samples in total). These samples were then tested for shear force and intramuscular fat content. It was shown though that there is potential for MRI data to predict tenderness in beef. It is recommended that more trials be conducted to build upon these findings.

This project has effectively demonstrated where a number of sensing technologies sit in terms of ability to enable pick and pack automation.

Table of Contents

1 Background

The back end of a boning room (beef and sheep) requires a large number of flexible labour units for the area known as 'Pick and Pack'. With the number of primal and sub-primal specifications and ever increasing SKUs that processors' customers are demanding, the limitation to automating this area is not the robotics side of the equation but reliable and fit for purpose vision and sensing systems.

In an analogy to the vision and sensing program the industry undertook with CSIRO/FSA some ten years ago that launched the slaughter and boning automation program, this project proposes to undertake the exact same study and in-field demonstration specifically for the purpose of Pick and Pack.

At the conclusion of this project the industry will know what vision systems will and will not work (and/or are required) to then drive (and build) automated solutions for anywhere within the Pick and Pack area, from raw primal to cryovac primals.

2 Project objectives

2.1 Objective 1:

A 'black box(es)' that can be used prior to any further development of pick and pack automation to ascertain the best (fit for purpose) sensor/vision hardware required.

2.2 Objective 2:

Identified all of the current manual pick and pack activities that can be automated with identified Vision and Sensing. A simple to use matrix that informs future pick and pack automation developments on what vision/sensing system to use for future pick and pack automation tasks.

3 Introduction

Various sensors and applications of sensors were discussed and reviewed with MLA. The outcome of this process is to undertake sensor and vision development within four different platforms:

- Hyperspectral Imaging (HSI)
- DEXA of beef primals – trim to specification and chine bone determination
- Colour and 3D - Wet/Naked primal simple vision and sensing
- Magnetic Resonance Imaging (MRI)

Hyperspectral imaging trials were to focus on end of boning room/pack-off inspection. A range of inspection items were to be assessed to ascertain which can be detected using HSI, and get a high-level understanding of what the requirements of a hypserspectral inspection machine may be.

DEXA trials were to focus on finished beef primals, specifically striploins, for assessment of fat trim specification and chine removal. The key was to determine if DEXA imaging is suitable for this application and how it compares to CT technology, the gold standard for structural feature identification.

The application of wet primal identification was to be assessed with a low-cost colour and 3D sensing setup to assess what is possible with an 'entry level' vision system. From this, an assessment can be made of what further technologies may be required to obtain what level of benefit.

On the other end of the sensing spectrum, magnetic resonance imaging (MRI) can be thought of as the gold standard for soft tissue imaging. As with CT, an intricate, internal 3D structure of a sample is generated from a scan. The mechanism behind MR imaging is different to x-ray. While numerous trials have been conducted with x-ray and CT, little has been done with MRI in the space of red meat sensing. This project aims to start assessing where MRI technology fits within the red meat innovation sensing strategy by performing trials with a high-temperature MRI. That is, an MRI which doesn't require cryogenic cooling (the primary expense of a medical MRI system) and thus, is much more suited to industrial usage.

4 Hyperspectral Imaging Inspection

4.1 Introduction

With recent advancements in computer technology and instrumentation engineering, there have been significant advancements in techniques for food quality and safety. Machine vision and NIR spectroscopy are two of the more extensively applied methods for food safety and food quality assessment.

Machine vision techniques based on red-green-blue (RGB) colour vision systems have been successfully applied to evaluate the external characteristics of foods. Normal machine vision systems are not able to capture broad spectral information which is related to internal characteristics, hence computer vision has limited ability to conduct quantitative analysis of chemical components in food.

Spectroscopy is a popular analytical method for quantification of the chemical components of food. The tight relationship between NIR spectra and food components makes NIR spectroscopy more attractive than other spectroscopy techniques. However these spectral methods were proved inefficient when it comes to heterogeneous materials such as meat, owing to the fact that they are not capable of obtaining any spatial information about objects.

Due to the limitations of regular machine vision and spectroscopy techniques (such as NIR), hyperspectral imaging was developed. Hyperspectral imaging can be used to obtain spectral and spatial information of an object over the ultraviolet, visible and near-infrared spectral regions (300nm – 2,600nm).

There are a number of primal defects for which inspection occurs in the pick and pack area, including presence of: faeces, ingesta, milk, urine, bruising, blood clots, cartilage, bone marrow, bone dust, hair/hair clusters, and pathological lesions. Automating primal inspection would hold significant value to the industry. High-level trials will therefore be conducted to begin understanding which of these defects may be detectable with HSI and what hardware specifications may be required for the task.

4.2 Method

SCOTT acquired a hyperspectral camera and fabricated a scanning structure to enable trialling.

Samples were acquired from a processing facility of a number of primal contaminants. These samples were scanned with the hyperspectral camera. The data were then analysed to obtain a high-level assessment of which contaminants may be detected with HSI, and what hardware may be required to enable this.

4.3 Results and discussion

The mean spectra of all contaminants gathered for this trial was first collated. While it is difficult to differentiate and identify the spectra of each substance individually due to the low sample size, by looking at all the spectra together it becomes possible to identify the similarities in spectral reflectance across all samples. The spectra from each contamination sample was examined to provide a high-level assessment of what may be detectable and what may be challenging. It was found most of the contaminants investigated possessed unique features in their spectra.

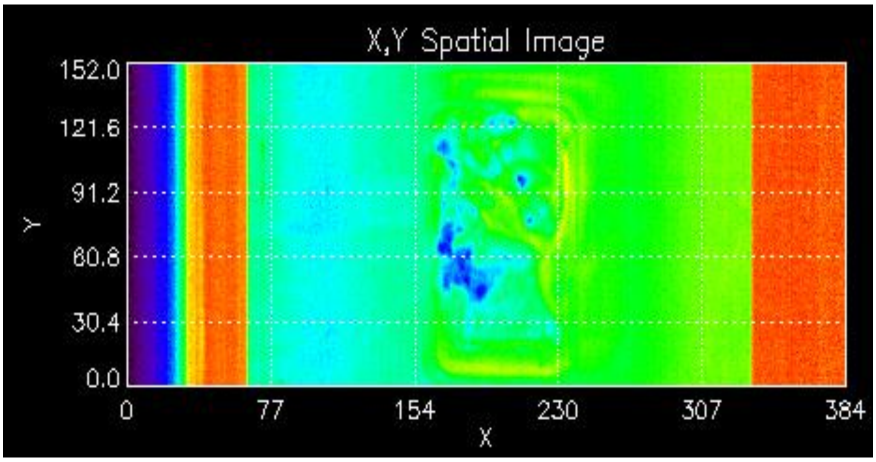


Figure 1 - Pseudo-colour hyperspectral image of contamination sample. The contaminant is indicated by blue.

4.4 Conclusions and recommendations

A significant amount of contamination can be detected by a hyperspectral camera. In lieu of these findings so far, it is recommended that further work be conducted using a larger sample size to build upon the observations made during these trials. Practical considerations for a commercial system design should also be examined.

5 DEXA Beef Primal

5.1 Introduction

Two of the most expensive primal cuts on a Beef side are the cube roll and striploin. These need to be fat trimmed to customer specification. In addition to these two primals, other primals such as rumps also need to be fat trimmed to specification. These primals are prepared from a side of beef by first removing the bone in primal from the beef side (bone-in processing), then removing the primal from the chine bone (boneless processing) and then finally trimming the fat cover to a customer specified depth. This customer specified depth can vary between customers however it is a fixed depth across the entire surface of each unique primal.

As an operator can only see the fat depth at either end of the primal, it is difficult for them to know what the exact fat depth coverage is across the entire primal and to ensure that the entire primal surface is trimmed to a consistent fat depth. For example the trimmer may have been set a target fat depth of 5 mm however realistically the fat depth could range from 5mm to 12 mm throughout the various cross sections of the primal. This would only become apparent once the customer slices the primal down into individual steaks (Figure 2).

Figure 2 - Example of varying primal fat depth from trimming.

CT imaging can be used to provide an accurate, 3D profile of the fat coverage of a primal. The technology however is expensive and requires development to be suitable for Australian abattoir conditions. This project looks to evaluate whether it may be possible to define the required fat trimming profile to sufficient accuracy using DEXA, an x-ray technology which is currently used commercially in the red meat industry.

As aforementioned, another key operation in cube roll and striploin processing is the removal of the chine bone (Figure 3). Again, a CT image could provide an accurate cutting profile by accurately mapping the chine, including the protrusions into the meat (Figure 4). The ideal cut path to be performed is variable, based on a trade-off between maximising yield and further processing of the primal by removing the ‘buttons’ left within the primal (Figure 5). It is envisioned that an automated solution should allow for an adjustable parameter to define this. This project will assess whether it is possible to utilise DEXA to obtain such a profile. This could then be used to drive automated chine bone removal.

The two applications (fat trim and chine removal) could then potentially be combined into one ‘striploin/cube roll processing automation system’.

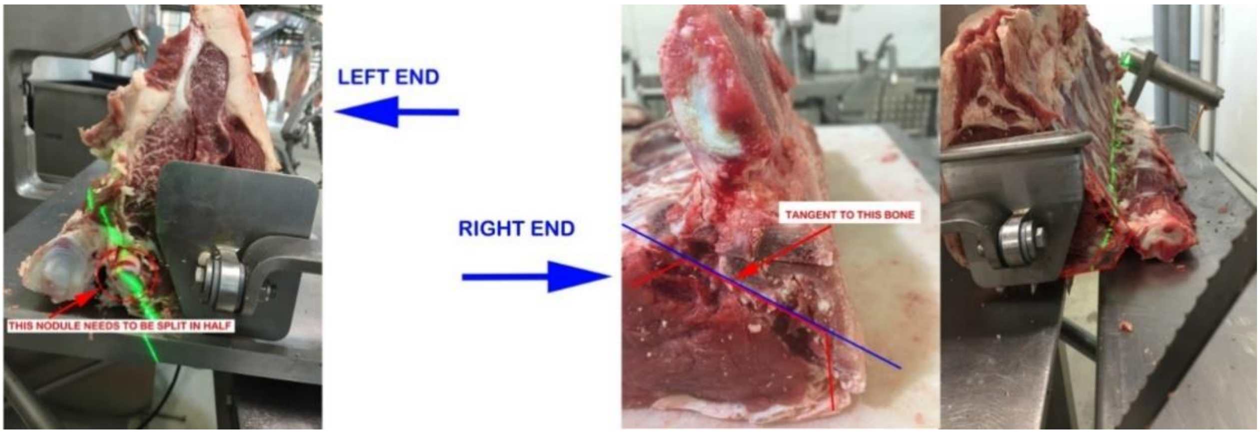


Figure 3 - Chine removal cut location.

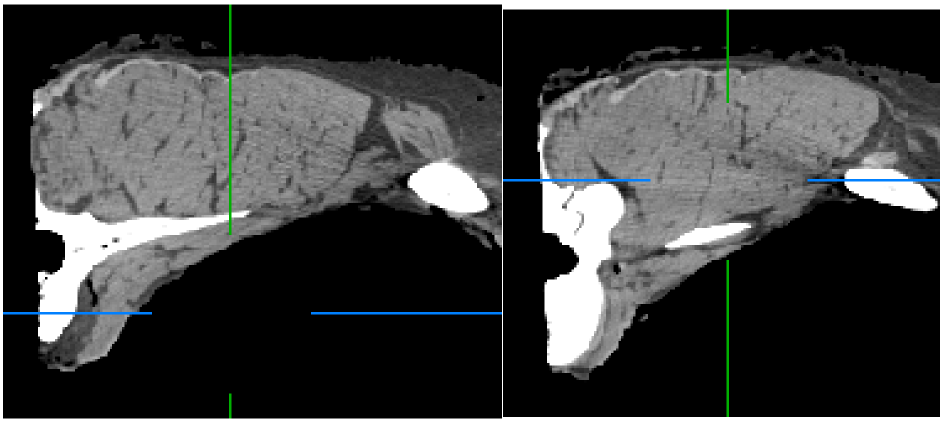


Figure 4 - Protrusions from chine bone into Longissimus Dorsi muscle.

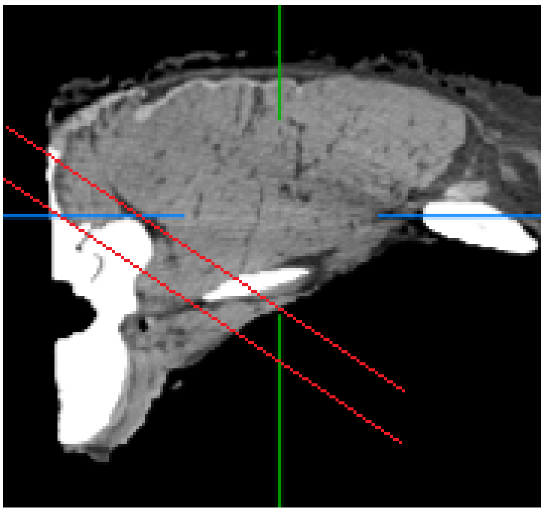


Figure 5 - Variable position of chine cut.

5.2 Method

Four beef short loins were acquired and DEXA scanned. The tenderloins were removed from the samples. Each sample was CT scanned as a reference. A number of approaches were then investigated to identify the cut locations required for fat trimming and chine removal.

5.3 Results and discussion

5.3.1 Chine Removal

Some of the results achieved appeared to show some promise. However, writing vision algorithms which work reliably would be a difficult task.

5.3.2 Fat trim

Similar vision processing methods were investigated to determine the optimal fat trim profile. As with the chine removal, some promising results were achieved, but realistically 3D information is required to reliably inform these cuts.

5.4 Conclusion and recommendations

Beef chine removal is an application which can possibly be achieved by using DEXA. It would however be quite a challenging task and whether the required accuracy could be achieved in an industrial setting at line-speed is yet to be determined. It appears even more challenging to achieve accurate fat trimming using DEXA.

Given the results obtained, it is thought that CT is likely the minimum sensing requirement for these applications. It is therefore recommended that, while that comes with its own risks, developing a primal scanning CT-machine suitable for an abattoir environment should be pursued for this application.

6 Colour and 3D Wet/naked Primal Identification

6.1 Introduction

Some processing facilities can utilise/require circa 40+ operators at the back end of their boning rooms for the purpose of Picking, Sorting, Packing and Quality checking. Operational staff at this end of the facility are required to deal with an increasing range of primal and sub-primal configurations, processing decisions and an increasing range of SKUs.

Automation (or semi-automation) of this area is not limited by hardware (i.e. robots or packing machines) but vision and sensing systems to direct and inform automated hardware. It is not known by any commercial solution provider (with any level of certainty) what vision and sensing hardware is required to enable automation of the Pick and Pack area.

A key requirement for automation in this area is the identification of primals. There are a range of different sensing technologies available to achieve this, but the most cost-effective and simplest to install is colour imaging and 3D profiling. A high-level evaluation will thus be carried out to assess what performance may be achievable with this low-level technology, and what may be required to cover its limitations.

6.2 Method

A cost-effective colour and 3D sensor was taken to a beef processing facility. It was positioned over a conveyor belt carrying beef primals into the packing area. Colour and 3D data were then obtained for a large number of various primals.

The data was first examined and labelled with its correct primal type. Vision algorithms were then created to calculate a number of metrics which characterised the data. These were then used to develop high-level identification algorithms for a handful of selected primals.

6.3 Results and discussion

Data for the following boneless primals was collected and split into a training set (for training the algorithms) and a verification set (for testing their performance). A basic algorithm was then built to classify each of the primals selected using the sensing data. The algorithms were built from the training data set, and then verified using the verification set. A project focussed on the application would involve training more complex algorithms, but this work provides a good high-level picture of what is possible.

The results were analysed in terms of the amount of 'confusion' exhibited – rate of false negatives and false positives and, for the latter, with which other primals. The algorithms exhibited a very high level of performance in the training set. The error rate increased on the verification set, but still with quite a high level of performance.

6.4 Conclusion and recommendations

The results are very promising for a cheap piece of technology, especially for only a single computer training iteration and considering a truly independent verification set was used.

More complex classification algorithms are available and, given a commercial project to fund development, would result in further improved performance. The results obtained suggest promise that the features calculated from the 3D and colour data would serve as suitable algorithm inputs.

In general, the results demonstrate there is promise to the concept of sorting primals with this technology. It is important to keep in mind that the accuracies will be highly dependent on the given application. A lower accuracy rate may be acceptable if it means still being able to remove a significant number of FTEs.

It is envisioned that this work can be leveraged through a number of applications and may drive its own automation and/or act as an enabler for another piece of automation with which it works together.

7 MRI Technology Evaluation

7.1 Introduction

SCOTT has a business unit called HTS-110 which develops high temperature superconductive (HTS) wires. Using these wires, HTS-110 are able to construct powerful magnets which don't require cryogenic cooling and can be used for Nuclear Magnetic Resonance (NMR) / Magnetic Resonance Imaging (MRI) applications. The requirement for liquid helium to cool the large magnets which exist in medical MRI machines presents significant cost and maintenance barriers to implementing such machines in an industrial environment. A 'high-temperature' NMR/MRI machine does not possess this requirement and, is thus, more suited for adaptation into red meat industry applications.

Victoria University Wellington (VUW) have developed an MRI machine using a HTS-110 high-temperature magnet. As part of this project, SCOTT will rent the machine in order to assess the technology in general as well as in the context of a number of red meat industry applications. This machine was thus to be shipped and installed in SCOTT's facility in Tullamarine.

Figure 6 - MRI machine installed at SCOTT.

Two key red meat applications in particular currently present gaps in current sensing capabilities. The first is viscera contamination, many causes of which are sub-surface and thus aren't suitable for surface imaging technologies like hyperspectral imaging. A number of these were investigated using CT, which struggled to clearly present defects with a similar density to the surrounding tissue. Being the gold standard in soft tissue imaging, MRI is expected to be a more suitable technology for offal inspection.

There is a pressing need in industry for a means to objectively measure and characterise product. This is broadly referred to as objective carcase measurement (OCM). Recently, DEXA technology has been shown to allow objective measurement of lean meat yield (LMY). Commercial installations of this technology exist and it is being further rolled out across the country. One important counter-balance to LMY however is eating quality (EQ) – care must be taken not to focus breeding on LMY at the expense of EQ. When referring to EQ, there are four main components assessed in Australia – tenderness, juiciness, flavour and overall liking. These factors are used to calculate a score called the Meat Quality 4 score as per Equation 1 (Bonny, et al., 2017).

Equation 1

$$MQ4 = 0.3 * tenderness + 0.1 * juiciness + 0.3 * flavour\ liking + 0.3 * overall\ liking$$

Tenderness itself is correlated with a number of factors:

- Intramuscular fat content (marbling);
- Amount of connective tissue (i.e. collagen and elastin);
- Stability/quality of connective tissue (i.e. amount of collagen cross-linking);
- Sarcomere length; and
- Proteolysis (as achieved through ageing).

It has been shown in a previous project with MLA that CT technology can be used to predict intramuscular fat content in beef, but this is just one factor informing tenderness. The other factors aren't able to be characterised with x-ray technology. There is some evidence that MRI data can be used to predict tendernes. It was therefore proposed that this project provide an initial, high-level investigation into the potential ability of the aforementioned high-temperature MRI machine to predict tenderness in beef samples.

7.2 Viscera inspection

7.2.1 Method

The MRI machine was shipped to Australia and installed into SCOTT's facility in Tullamarine. The machine came programmed with a few basic pulse sequences installed for data collection. A number of small trials were performed on some viscera samples before a set of parameters were decided upon to produce the most promising data.

A number of samples of various offal defects for beef and lamb were then obtained from an abattoir. These were transported back to the SCOTT facility and scanned.

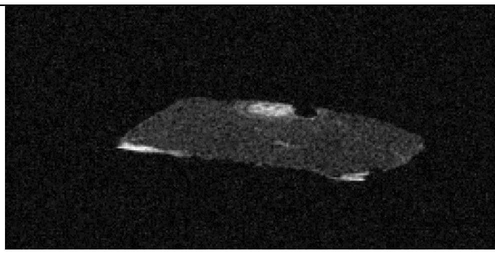
7.2.2 Results and discussion

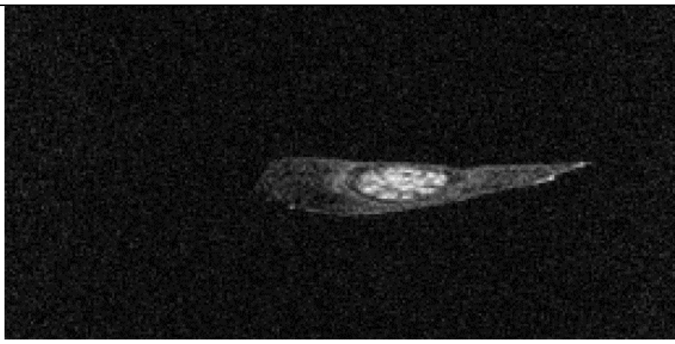
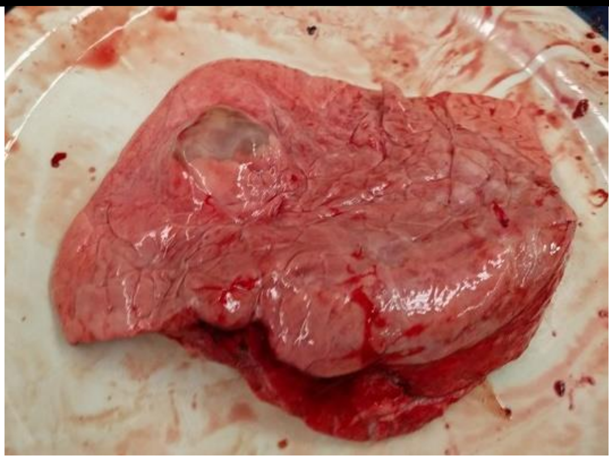
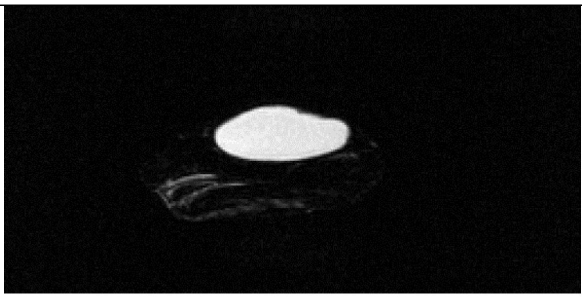
7.2.2.1 ***Hydatids***

Hydatid disease is caused by the hydatid tapeworm which infects dogs, dingoes and foxes. In livestock, infection occurs as a result of swallowing eggs which are present in the faeces of the primary host. These yield embryos which are transported to various tissues where hydatid cysts then develop which carry the next generation of tapeworm heads. (NSW Department of Primary Industries, 2008).

The results for a number of samples are shown in Table 1. The hydatid cyst is clearly visible in one of the MRI images while generally quite difficult to identify in others. It also seems quite distinct to the surrounding healthy liver or lung tissue

Table 1 - Hydatids inspection results

Sample 01 – Beef Liver	
Photos	 
MRI image	
Sample 02 – Beef Liver	
Photos	

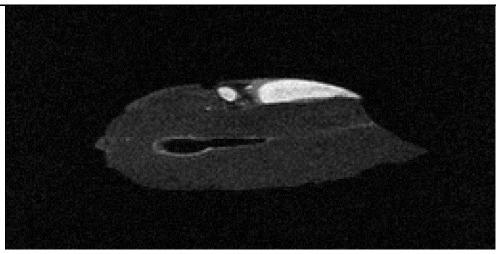
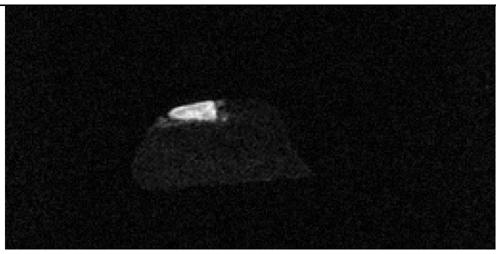
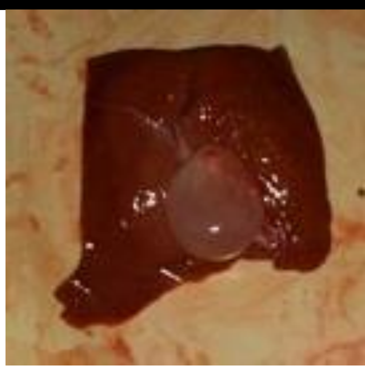
MRI image	
Sample 03 – Beef Lung	
Photos	
MRI image	

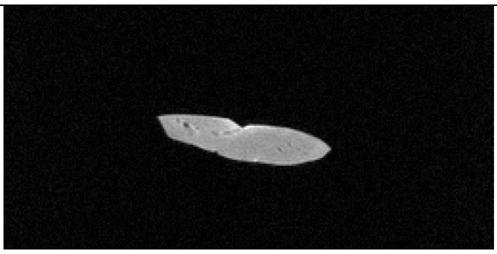
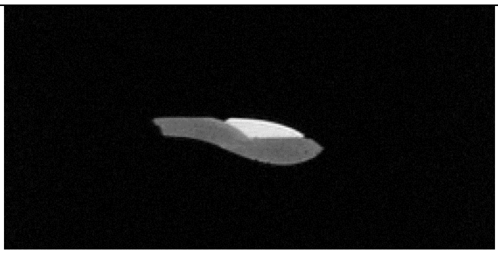
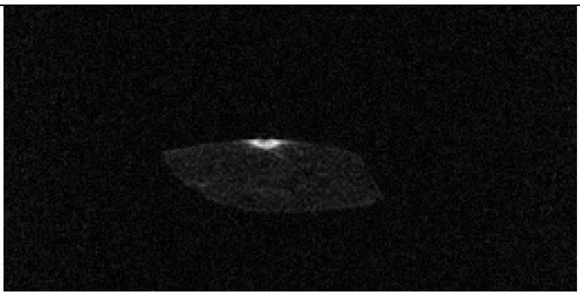
7.2.2.2 *Tenuicollis*

Cysticercus tenuicollis is the larval stage of the dog tapeworm, *Taenia hydatigena,* and is sometimes called 'false hydatid'. As with hydatids, the condition occurs via the ingestion of dog/fox/dingo faeces which is contaminated with tapeworm eggs. It can be indicated post mortem by detecting tracts in the liver (from migrating larvae), fluid filled sacs on the liver or other abdominal organs, and/or white scars on the liver surface. (Victorian Farmers Federation Livestock Biosecurity Network, 2015).

The results from the scans are shown in Table 2. As with the hydatids, the images show tenui clearly against healthy surrounding tissue, which is almost invisible. The defect is also somewhat visible in the PD-weighted images, but not with as much contrast.

Table 2 - Tenuicollis inspection results

Sample 01 – Lamb Liver	
Photos	
MRI image	
Sample 02 – Lamb Liver	
Photos	 
MRI image	
Sample 03 – Lamb Liver	
Photos	

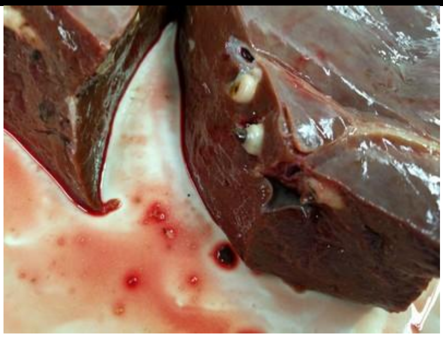
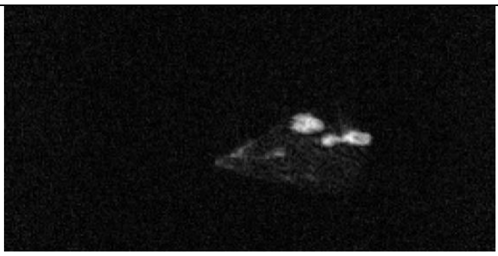
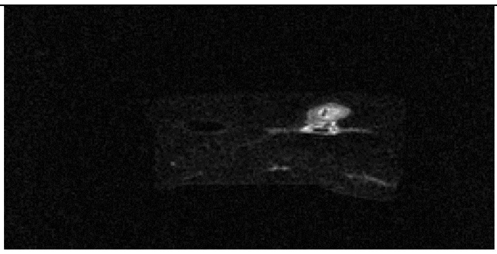
MRI image		
Sample 04 – Lamb Liver		
Photos		
MRI image		

7.2.2.3 ***Fluke***

Liver fluke refers to a group of parasitic flat worms which can infect a range of animals, including sheep and cattle. Once their eggs hatch, they invade snails before further developing and attaching to vegetation as cysts. Once ingested, immature flukes penetrate the intestinal wall into the abdominal cavity. They then penetrate the liver capsule and migrate through the liver tissue until reaching sexual maturity, at which point egg production commences. (NSW Department of Primary Industries, 2017).

The results are shown in Table 3. These results look promising but further investigation is warranted.

Table 3 - Fluke inspection results.

Sample 01 – Beef Liver	
Photos	
MRI image	
Sample 02 – Beef Liver	
Photos	
MRI image	

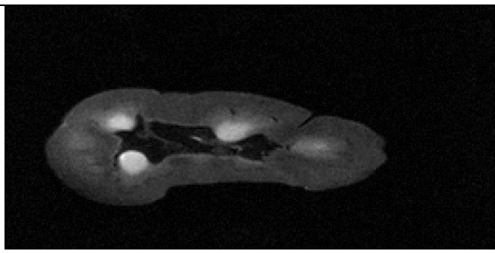
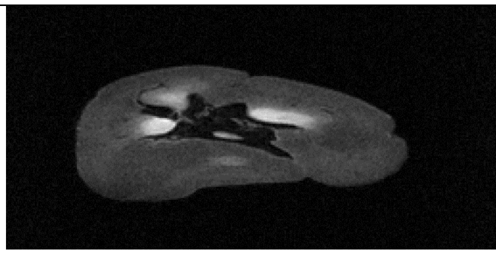
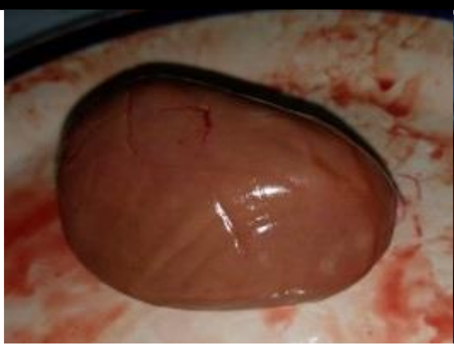
7.2.2.4 ***Nephritis***

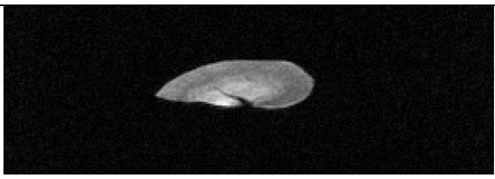
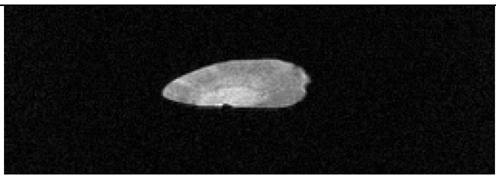
Nephritis is the term used to describe kidneys exhibiting some form of damage – shrunken, scarred, swollen, discolour or spotty, etc. A common presentation is the presence of pale spots. (Matthews, 2016).

Figure 7 - A kidney with nephritis. Note the pale spots. (Matthews, 2016)

Table 4 shows the results from the scans performed. This looks to be quite challenging and requires further investigation.

Table 4 - Nephritis inspection results.

Sample 01 – Beef Kidney	
Photos	
MRI image	 
Sample 02 – Lamb Kidney	
Photos	 

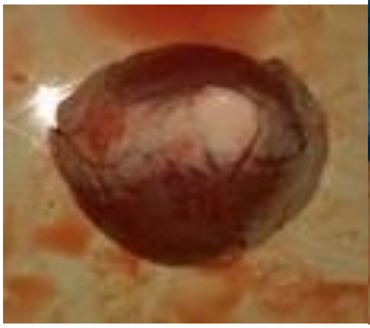
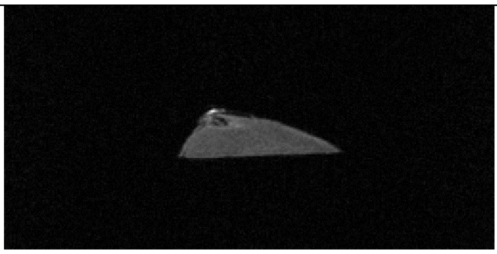
MRI image	 

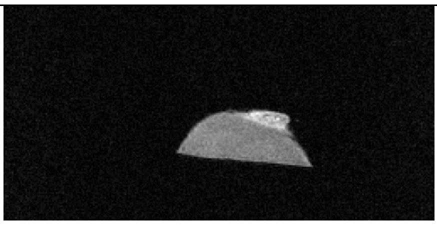
7.2.2.5 *Sheep Measles (Cysticercus ovis / Taenia ovis)*

Sheep measles is caused by a dog tapeworm and results in small cysts in the muscle tissue, including the heart. The cysts are white/cream coloured and may be calcified if present for some time. (Victorian Farmers Federation Livestock Biosecurity Network, 2015).

The results from the scans of the samples are shown in Table 5. This was more challenging than expected, although it is still detectable in the MRI image. Further investigation is required as it is possible using different imaging parameters could yield a better result.

Table 5 - Sheep measles inspection results.

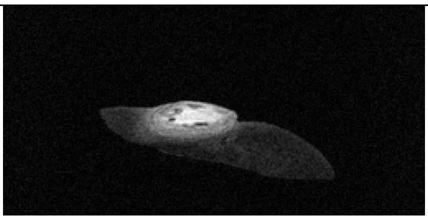
Sample 01 – Lamb Heart	
Photos	 
MRI image	
Sample 02 – Lamb Heart	
Photos	 

MRI image	

7.2.2.6 ***Abscess***

As with many of the defects trialled, it appears as though an MRI image can clearly identify an abscess within liver tissue (Table 6).

Table 6 - Abcess inspection result.

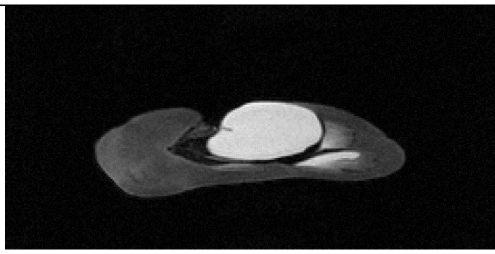
Sample 01 – Beef Liver	
Photos	
MRI image	

7.2.2.7 ***Cyst – Beef Kidney***

The cyst is clearly visible in the MRI image (Table 7).

Table 7 - Cyst inspection result.

Sample 01 – Beef Kidney	
Photos	

MRI image	

7.2.3 Conclusion and recommendations

Many of the defects experienced were able to be identified clearly in the MRI images generated. These defects are known to be challenging, or impossible to detect, using other sensing technologies. Furthermore, they appear to be largely detectable using the same scanning parameters which has positive commercial implications for the technology.

7.3 Meat tenderness

7.3.1 Method

As described above, there are a number of factors which influence meat tenderness. These factors were thus taken into consideration when selecting the meat samples to be scanned. Six beef bodies were selected – three low ossification ox and three high ossification cows. Older cattle tend to have a higher degree of cross-linking and are thus tougher. From each body, the striploin and eye round were isolated. The striploin tends to be a 'tender' cut and is low in connective tissue content compared to the eye round. Each carcase was MSA graded and the MSA grading data was recorded (Table 8).

Intramuscular fat content is another key component of tenderness. It is known however that this can be measured using other technologies, such as CT. Thus, in order to keep the scope of these trials focussed, intramuscular fat content was controlled for as much as possible. A larger-scale trial however should investigate this in the future. The samples were tested for intramuscular fat content however, to ensure any associations which are found aren't just predicting intramuscular fat content rather than tenderness as a whole (or another component of it which isn't currently measureable).

Similarly, sarcomere length also contributes to tenderness. This was outside the scope of these trials, but should be investigated in the future. This may involve obtaining samples (possibly from the other half of a given carcase) which have been Achilles hung versus tenderstretched. Intentionally cold-shortened samples could also be used.

Samples were stored in a fridge until they were scanned by the MRI machine. They were then frozen. Once all the samples had been scanned, they were shipped to UNE in Armidale to be tested for shear force and intramuscular fat content.

Table 8 - MSA grading data for meat samples

SAMPLE	SEX	HSCW	EMA	OSS	MSAMB	MC	FC	RF
01	M	401	73	130	360	2	1	15
02	M	382	70	120	300	2	1	6
03	F	254	40	590	350	4	6	10
04	F	268	42	590	330	3	6	8
05	F	240	38	590	280	3	6	2
06	M	312	68	160	310	2	2	7

7.3.2 Results and discussion

7.3.2.1 *Lab testing results*

The samples were tested for shear force and intramuscular fat content. Shear force values ranged from 2.57kg to 7.15kg while IMF content ranged from 1.66% to 3.28%. It was observed that the younger animals (01, 02, 06) have a significantly lower shear force result (and are thus more tender) then the older animals (03, 04, 05). In the younger animals, the striploin is significantly more tender than the eye-round. The day 10 samples were also more tender than the corresponding day 2 sample, although this was most pronounced with the striploins in the older animals. Intramuscular fat content was fairly consistent between the samples with no clear correlation with cut or animal maturity.

7.3.2.2 *Data analysis*

A number of different data acquisitions were performed on each sample. These data were then analysed first for any univariate correlation with the shear force measurements. A number of multiple linear regression models were then evaluated to model the data. Given the small sample size, the predictive power of any model is likely to be limited. Furthermore, there are more complex statistical methods available which could give better results but which lie outside the scope of this preliminary technology evaluation. The goal of this work is therefore to demonstrate whether or not it is feasible to predict tenderness from MRI data and whether this work should be expanded upon. This will help determine if more trials should be performed to develop and cross-validate robust models.

A number of performance statistics were also calculated for each model. One particular concern given the small sample size is the possibility of overfitting the data. This would yield a model which predicts the training data well, but performs poorly with new observations, and is thus of little use in a practical situation. The goal in assessing the models then was to try and identify those which predicted the data relatively well, weren't overly complex (i.e. the lowest number of features possible), and had good potential to predict new observations well. The following statistics were therefore generated:

- *Adjusted R^2* – A model's R^2 values gives an indicator of how well it predicts the given outputs. One downside is that it will always increase with number of features. Adjusted R^2 compensates for this by penalising models based on the number of features to try and avoid overfitting. Another downside is that R^2 (and adjusted R^2) is quite susceptible to outliers artificially depressing its value.

- *RMSE (root mean square error)* – A measure of the amount of error which exists between the known output values (i.e. measured shear force) and the values generated by the model. 95% of results will lie within ±2*RMSE.
- *Predicted R^2* – One way to protect against overfitting is to perform cross-validation. Since the sample size is so small, it's not feasible to have independent training and validation sets. Leave-one-out-cross-validation (LOOCV) is performed by dropping an observation from the dataset, training the regression model, then verifying how the model performs with the dropped observation. This is repeated for each of the observations in the dataset. An overfit model will produce large errors. Predicted-R^2 is calculated from the result of this process and can be considered as an indicator for how well the model can predict new observations. (NCSS Statistical Software). So adjusted R^2 is an indicator for how well the trained data is predicted, while predicted R^2 is an indicator for how well future data may be predicted.
- *AICc* - A popular statistic used to compare different models is Aikaike's information criterion (AIC). As with the predicted R^2, AIC compensates for number of features. A further correction can be made to further avoid overfitting and to account for smaller sample sizes (AICc). The best model is that which has the lowest value. Relatively speaking, the quality of the other models is gauged by the difference between that model's AICc and the minimum AICc across all models. Models with differences greater than 10 may be discarded, particularly if the R^2 value is low (Burnham & Anderson, 1998) Furthermore, a ΔAIC_C value below 2 suggests strong evidence for the model while values between 3 and 7 indicate a model has significantly less support (Burnham & Anderson, 1998).
- *BIC* – Bayesian information criterion (BIC), another quality metric similar to AIC which aims to penalise complex models to avoid overfitting.

Some of the best models were then selected based on these metrics. The predictive power of the best models was quite high, suggesting that the MRI images can predict shear force. The number of features modelled, while high, is still reasonable suggesting that model complexity was adequately penalised which should indicate a greater ability to predict new values.

One factor which can affect multiple linear regression is collinearity of features (i.e. that one or more of the features are in fact highly correlated) which can negatively impact models and make them appear to perform better than they would when given new observations. It is also ideal to reduce the number of features as much as possible, especially when given a small sample size.

One method of dealing with this is through performing principal component analysis on the input data, to map the 18 inputs into k new dimensions along which the most variation occurs, where k is less than n (the number of samples). These k inputs can then be used to generate linear models. Multicollinearity is not an issue with this approach, as collinear variables should be inherently dealt with when reducing the data into k new dimensions.

Furthermore, a LASSO (least absolute shrinkage and selection operator) regression algorithm was utilised. LASSO is a robust linear regression method. It has an adjustable variable which restricts the model parameters from getting too big as a way of avoiding the possibility of the model favouring certain features too much. Hence it provides a way to reduce model complexity. While this method did not produce better results than the initial modelling attempts and further optimisation is required, moderate to strong correlations are were still present, further reinforcing the hypothesis that MRI image features can predict tenderness. This also gives further confidence that the correlations achieved aren't simply due to overfitting and/or overlapping data.

In order to try and assess the level of multicollinearity which may be present across the features, a pair-wise cross-correlation plot was generated for each dataset. A number of the features were found to be closely correlated. The models only containing unique features were re-evaluated. The precision of the best models dropped slightly which may indicate overfitting of the initial models, or that some of the cross-correlated features contained important information (correlated features don't always need to be reduced). Regardless, the results further reinforced that there is a relationship between the MRI data evaluated and tenderness, as measured by shear force.

For each of the models, the same features were also assessed for the ability to predict intramuscular fat content. It was found that the adjusted-R^2 values indicated no correlation for most of the models generated. This provides confidence that these models are indeed predicting tenderness rather than simply intramuscular fat content.

7.3.3 Conclusion and recommendations

It has been shown that there is potential for MRI images to predict shear force measurements in beef samples. The number of samples was limited (24 when considering all samples) which can lead to overfitting providing misleading model performance statistics. A range of statistical tools were applied in order to reduce the model complexity to avoid the possibility of overfitting the limited data set. These results suggest that a correlation between the MRI image features and the shear force does exist. With more data, a more complex model can be realised which captures the non-linear correlations between the selected features and shear force. Therefore, further work should be considered, which will involve taking more sample data and performing more complex statistical analysis. Furthermore, hardware and software improvements should be investigated in order to reduce cycle time.

8 Conclusions and Recommendations

It is known that the primary barrier to automation in the "Pick and Pack" area is appropriate sensing. This project filled the knowledge gaps in this area by investigating a number of technologies across a number of applications.

A hyperspectral imaging camera was purchased and successfully used to identify a number of contaminants based on high-level analysis of spectral data. The recommended next step is to formalise a scope for a commercial primal contamination detection system, identifying which contaminants on which to place focus. More trials would be performed with the current camera, taking care to cover as much product variation as possible.

DEXA technology is a key enabler for many automation tasks and objective carcase measurement. The ability to use DEXA to drive automation of subcutaneous fat trimming and chine removal of striploins and cube rolls was investigated. The key challenge in both these tasks is locating subsurface features. While some promising progress was made, it is felt that 3D x-ray is required to perform these tasks accurately and reliably. The next step would be to develop a 3D x-ray system (for example cone-beam CT) suitable for on-line processing of primals.

Primal identification is a challenging task due to large amount of product variation and large number of different product specifications. While it would be possible to identify these by augmenting a range of different sensing solutions together (e.g. CT + hyperspectral etc), this project first aimed to establish what is possible with a low-cost sensing solution. Such a solution could then be built upon depending on the application and the customer's specific needs. A cost-effective colour and 3D camera was used to capture data of primals passing down a production line. Initial algorithms were developed for eight primals using simple classification, which were then verified against an independent dataset. From this, a confusion matrix was developed to summarise algorithm performance. The initial results demonstrated that wet primal identification is possible using cost-effective colour and 3D sensing although some degree of confusion was present. The recommended next step is to select a number of specific primals and develop complex classification algorithms to identify these primals with close to 100% success rate and 0% confusion. This could then be used to drive a robotic primal pick and pack system. Furthermore, the algorithms could be incrementally built upon to slowly include more and more primals, thus enabling this automation to expand.

Hyperspectral imaging is a powerful tool for identifying contamination, but is limited to surface detection. 2D and 3D x-ray allow subsurface defects to be identified, but the detection of those with similar density and x-ray absorption characteristics to surrounding tissue still remains a difficult task. MRI provides an opportunity to fill this gap by identifying subsurface defects not detectable with x-rays. A key barrier to MRI technology however is the requirement to cool them with helium which is costly and cumbersome. SCOTT technology possess a business unit called HTS-110 which produce 'high-temperature' superconducting wire. This can be used to produced coils for MRI/NMR machines which don't require cryogenic cooling. Such a machine was sourced for the purposes of trialling in this project.

The MRI machine was shown to be able to detect most of the offal defects examined. The next step would be to perform more trials capturing as much variation as possible to develop algorithms.

There is need in the red-meat industry to implement objective measurement of carcase traits. DEXA scanning is currently commercially available for grading of lean-meat yield. An important counterbalance to this is the objective measurement of eating quality traits as well. This is not something than can be done with DEXA. One of the key eating quality traits is tenderness. While intramuscular fat content can be measured with CT, this is only one component of tenderness. Work has been performed in academia on predicting tenderness using MRI images. A number of samples of meat with varying amounts of tenderness were obtained from an abattoir to perform an initial feasibility evaluation on whether our cryogen-free MRI machine could replicate these results. A range of statistical tools were used to model the data and examine performance, taking care to minimise complexity and avoid overfitting the data. The results achieved suggest that a correlation between the measured MRI data and tenderness exists. It is therefore recommended that a larger scale trial be performed with a larger sample size and more complex statistical analysis.

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