final report

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Carton Fill Profiling DEXA

Final Report

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Abstract

Incorrectly filled cartons are related to significant costs associated with crushing when stacked as well as wastage associated with packaging as well as freight. Scott Automation & Robotics have developed a system which is able to accurately profile the fill within a closed carton and identify it has been filled correctly and safely. This functionality is provided in conjunction with standard inspection tasks. It is recommended that a second stage project now be conducted which builds upon the learnings acquired from this project to produce a DEXA system capable of inspection, carton fill profiling, chemical lean measurement and advanced feedback.

Executive Summary

A number of issues are associated with cartons which are incorrectly or insufficiently filled. When under-filled cartons are stacked in a container they can partially collapse, compromising the entire stack. This can result in product damage and potentially a dangerous situation when a container is opened for unloading at the end of an overseas journey. Both of these negative outcomes result in the processors incurring additional costs for recovery of product or injury to workers. Similarly, continuous underfilling of cartons represents a wastage of both packaging and freight, the costs of which can accumulate significantly.

This project aims to apply Scott DEXA knowledge to determine fill levels of closed cartons through measurement of bone, fat and meat volumes. An existing inspection machine was used as a base platform for the system. Thus, the system would be able to perform inspection tasks as well as carton fill profiling. The machine was upgraded with the necessary hardware and software modifications were applied accordingly.

One of the key bodies of work conducted within this project was the calibration of the x-ray system. A number of different methodologies were trialled to obtain an accurate means of calibrating the response of the x-ray system to the amount of bone and soft tissue that is present. Ultimately this was achieved allowing accurate measurement of these tissues for beef.

Algorithms were then developed which used these x-ray calculations of bone and soft tissue quantities into a fill profile map for the carton. From this, voids above a certain threshold can be identified by the system triggering an alarm. Such voids would be indicative of an incorrectly filled carton and, thus, a potential crush risk. Similarly, the system is also programmed to detect and trigger an alarm if total fill level is insufficient. In either of these cases, an output is also triggered which may be connected to a diverter.

The system was then demonstrated to the customer using a number of different primals configured in a number of different fill orientations within a number of different sized cartons. The accuracy achieved by the system was acceptable for the task at hand, although it could be further improved by adjusting the hardware and the calculation algorithms. The system also demonstrated an ability to accurately calculate chemical lean (CL) and this would also be improved by adjusting the hardware.

One feature which would add further value to the system would be implementation of advanced feedback mechanisms. This could be direct feedback of fill volumes to packers and/or feedback to a database for analysis of trend data.

It is therefore recommended that a second stage project be conducted which builds upon the learnings acquired from this project to produce a DEXA system capable of inspection, carton fill profiling, CL measurement and advanced feedback.

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1 Background

In addition to the use of DEXA technology in measuring the three components of meat, fat and bone in red meat, it can also be used to determine volumetric utilisation in primal meat cartons.

The nature of primal cuts means a range of irregular shapes and sizes, which makes packing of cartons challenging to both achieve a target weight and utilise the carton volume effectively.

With an objective measure of the composition of a carton in terms of meat, fat and bone volume, this information can be used to achieve a true objective measurement of carton fill level in a closed carton.

The value of this development is seen in the reduction in processor product recovery costs. When under-filled cartons are stacked in a container they can partially collapse, compromising the entire stack. This can result in product damage and potentially a dangerous situation when a container is opened for unloading at the end of an overseas journey. Both of these negative outcomes result in the processors incurring additional costs for recovery of product or injury to workers.

Similarly, continuous underfilling of cartons represents a wastage of both packaging and freight, the costs of which can accumulate significantly.

This project aims to apply Scott DEXA knowledge to determine fill levels of closed cartons through measurement of bone, fat and meat volumes.

2 Project Objectives

At the conclusion of this project, Scott will have:

- Developed and demonstrated a system (within the Scott Melbourne factory) that utilises DEXA to measure the meat, fat and bone content of a carton and compare this with the volume of a carton to then ascertain how full each carton is.

3 Methodology

The following workflow was identified for executing the project:

1. Pilot trials and initial system design
2. Purchase of hardware, installation and commissioning
3. Software programming for hardware implementation
4. Calibration of x-rays
5. Algorithm development for carton fill calculation
6. Factory acceptance testing

3.1 Pilot trials and initial system design

A range of product samples were acquired along with test samples of cartons. The cartons were filled with varied amounts of these samples and scanned with an inspection machine. The results were then used to specify what hardware would be required to achieve the application and to formulate an engineering task plan.

3.2 Purchase of hardware; installation and commissioning

Once the hardware was specified, it was to be ordered, installed and commissioned. A standard Scott Automation & Robotics XR3000 inspection system was to serve as the base platform to be modified.

3.3 Software programming for hardware implementation

The software for interfacing with the x-ray hardware was then upgraded and modified as required. The primary goals from this task were to:

- Communicate with, and control, any new pieces of x-ray hardware
- Upgrading of any legacy code to enable the project objectives to be achieved

3.4 Calibration of x-rays

This was the key task for the project. Once the hardware and software modifications were performed, the x-ray system then needed to be appropriately calibrated for the task. This was achieved by:

- Construction of a suitable reference object to calibrate the system
- Creation of calibration algorithms which map x-ray response to projected material thicknesses

These material thicknesses are what enable the system to calculate the fill volume of the closed container.

3.5 Algorithms development for carton fill calculation

Once the x-ray system was calibrated to output projected material thicknesses, algorithms were then developed to calculate fill volume from these values. A number of considerations needed to be accounted for due to the fan-beam geometry and projective nature of the x-rays adding complexity to the task.

3.6 Factory acceptance testing

Upon completion of the system development, its performance was demonstrated to the customer and MLA. The results of this will then drive the next phase of product development for a carton fill profiling DEXA system.

4 Results/Discussion

4.1 Pilot trials and initial system design

Using a Scott Automation & Robotics (SCOTT) DEXA inspection platform, test samples of cartons filled with varied beef product samples were x-ray imaged and weighed. Mechanically deboned meat (MDM) was an excellent material for this application, as pieces could be easily broken into appropriate sizes to approximate levels of carton fill. Sample beef bones were used as an estimate for bone volumes in the cartons along with the MDM material.

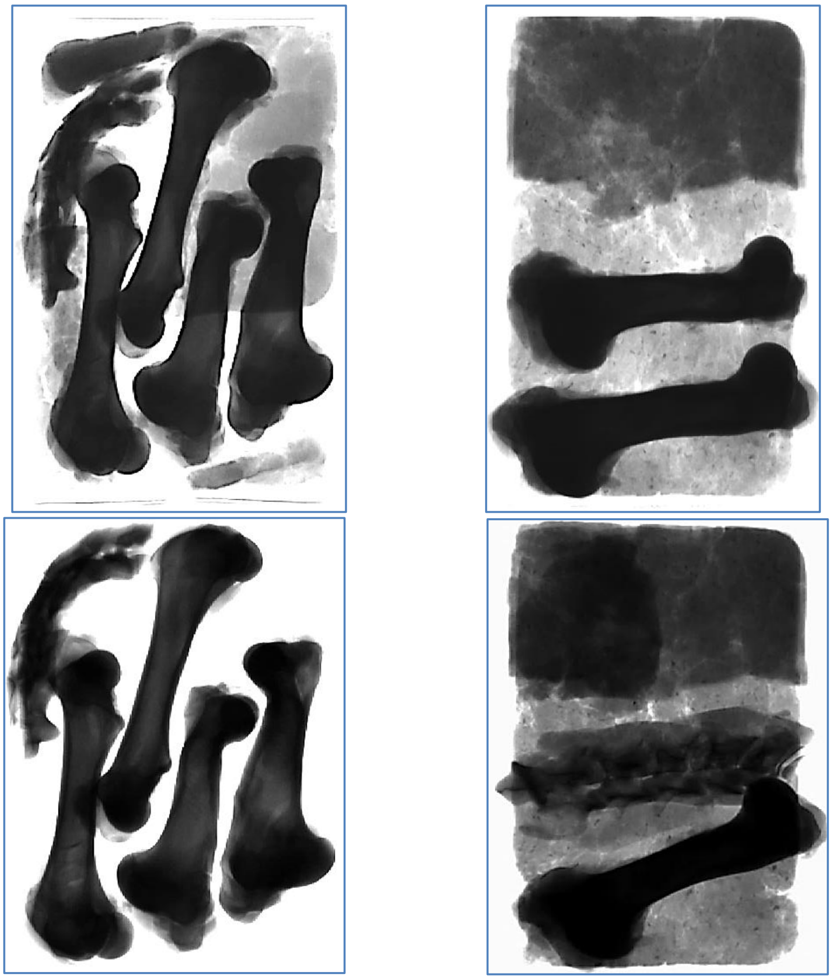

Figure 1: Four images from pilot trials showing different carton fill levels of bone and MDM material, containing meat and fat. The differences in density of the bone compared to the MDM is apparent. Bottom right image shows three levels of MDM, finishing in the top left corner of the carton, and approximates a full carton of meat & fat. Application of the DEXA algorithm to this data is capable of estimating compositions and volumes of bone, meat and fat.

From these trials, it was determined that a sandwich-panel dual energy detector would be utilised for the application. This style of detector involves the low-energy and high-energy detectors to be stacked on top of one another. They are both illuminated by one common x-ray source. This is in contrast to utilising a system with two distinct source-detector pairs for the low-energy and high-energy x-rays. The DEXA detector which would be retrofitted into the inspection machine.

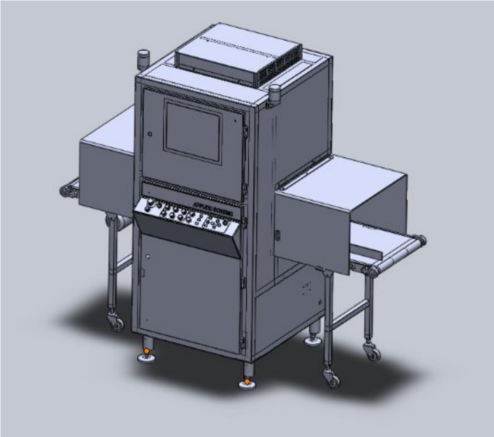

Figure 2: Standard Scott Technology XR3000 inspection platform, but with an upgraded dual energy detector inside. Mechanical changes were required to accommodate the new detector within the cabinet, as well as alterations to the communications interface within software.

4.2 Purchase of hardware; installation and commissioning

The dual energy detector was purchased and installed in the XR3000 inspection machine. While some modification was required, the retrofit was achieved with minimal issues. This suggests that the XR3000 inspection machine can potentially form a suitable base for more complex DEXA tasks, such as carton fill profiling.

Figure 3: Dual energy detector installed in XR3000 inspection machine

4.3 Software programming for hardware implementation

A number of key software changes were implemented:

- Overhaul of some aspects of code to enable more robust operation and compatability for additional functionality;
- Communication and control of the new dual-energy detector;
- Changes to triggering;
- Implementation of calibration files;
- Implementation of DEXA image feedback in the user-interface;
- Upgrade of code from 12-bit to 16-bit resolution to take advantage of the higher resolution data available from the new detector. This was a significant modification but enabled much the higher quality data available to be used to its full potential.

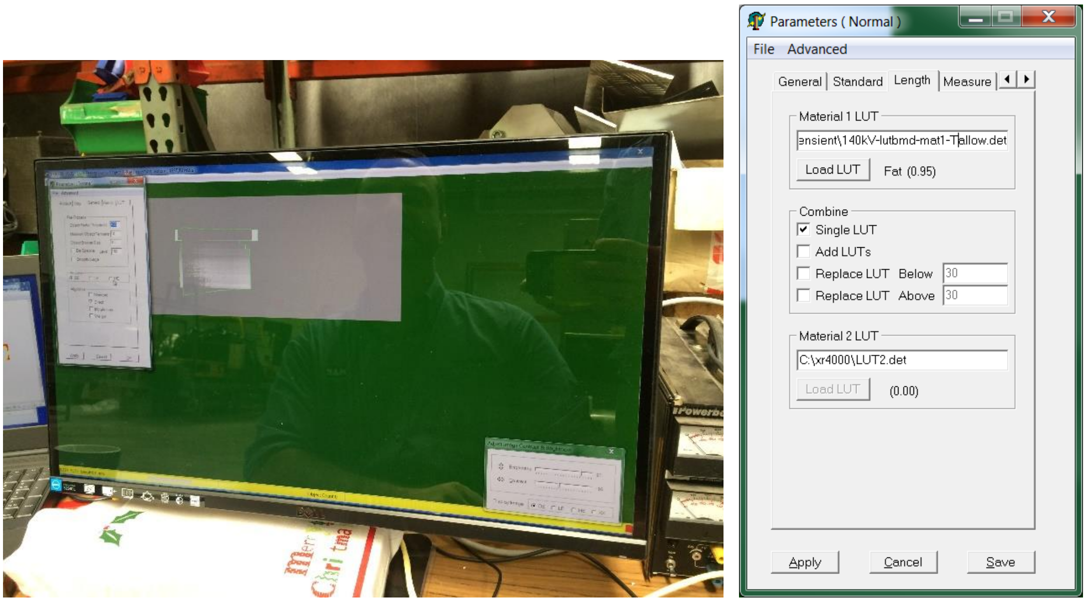

Figure 4: Revised user interface for the x-ray inspection software

4.4 Calibration of x-rays

The key enabler to this project is accurate measurement of bone and soft tissue using DEXA hardware. A significant amount of work was invested in developing a methodology for achieving this and assessing the requirements of the hardware used. The ability to accurately measure these tissues allows the total amount of material within a closed carton to be estimated.

The hardware utilised has a significant effect on the ability of DEXA to be able to differentiate between materials. Ideally, the x-ray sources would be monochromatic – emitting only the energy levels of interest. However, this technology isn't yet commercially feasible. Industrial x-ray tubes emit a spectrum across a range of energies. Figure 5 illustrates the difference between the two. This creates an overlap in the illumination of the two energy levels which must be overcome.

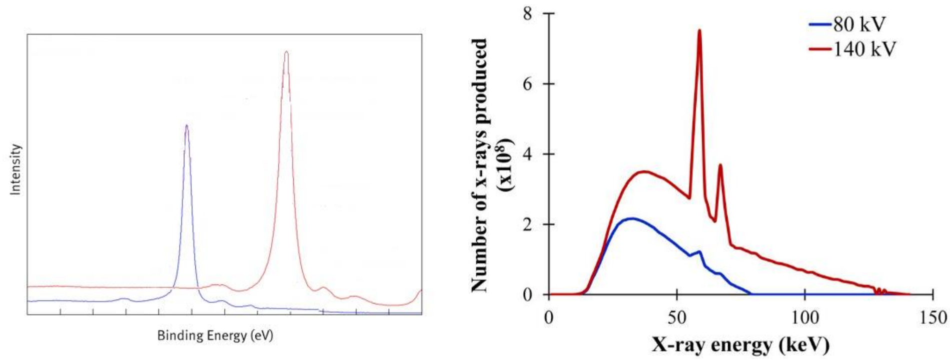

Figure 5 - monochromatic spectrum (left) vs polychromatic spectrum (right) (source: http://www.frontiersin.org/Journal/Abstract.aspx?s=322&name=experimental_pharmacology_and_drug_discovery &ART_DOI=10.3389/fphar.2015.00256)

One measure used to determine the amount of each material in a given part of an x-ray image is the R-value. The use of R-values assumes that there is a constant ratio (R) between the high and low energy signals for a given material regardless of thickness. For monochromatic radiation, this is true. For polychromatic radiation, the ratio can vary hugely with thickness. The actual manner in which this happens is complex and depends upon the illuminating spectrum, the detector and the object. The simplest and most flexible methodology to account for polychromaticity is to utilise a look-up table to allow for accurate discrimination of fat and lean or bone and soft tissue.

A look-up table is essentially a map of how the low energy and high energy signals behave for a given material at different thicknesses. The way in which an x-ray signal attenuates through an object at different thicknesses and energies under polychromatic illumination is a complex process. The look-up table modelling process is therefore quite complex and the result must be cross-checked to ensure, like any model, it behaves as expected across the entire range of expected inputs. If not, the input data must be analysed and model adjusted in an iterative manner, until successful, before then being verified with samples.

Look-up tables (LUTs) are generated by acquiring data to model the response of the low energy and high energy detectors at a range of mixture compositions and thicknesses. As with any model, the more data points used, and the more accurate the input data, the better the model. Due to the complexity of creating accurate and reproducible calibration standards however, compromises may not just lead to an inaccurate model, it may also produce surfaces which are completely unworkable or feasible only in limited ranges. Whilst it is in principle possible to use any two materials as the so called basis materials, it is far better to use the exact materials being identified. Alternative materials can be used if they possess similar densities and atomic compositions.

The development of a calibration methodology to accurately measure beef characteristics using DEXA is therefore a complex task, but one which has far-reaching positive implications throughout all DEXA projects once achieved.

In order to perform the calibration, a number of materials and construction methodologies were trialled as reference objects (also known as phantoms). Eventually a methodology was found which was able to produce good results. These results were then verified using beef tissue samples which had been tested for chemical lean. These samples were constructed with varying thicknesses and with varying compositions of fat:lean. Scanning of these samples verified accurate measurement of soft tissue lengths to enable carton fill calculation.

4.5 Algorithm development for carton fill calculation

The software running on the inspection machine was modified to allow for different processing algorithms to be loaded and run on the machine. Algorithms were then developed to perform the carton fill profiling operation.

When a carton is scanned, an algorithm first identifies the width and length of the box (the height must be entered manually or via a sensor) to calculate the box volume. The data from the low energy and high energy x-ray images is then converted into projected lengths of bone and soft tissue. That is, for every pixel in the x-ray image, a value for the total amount of bone and total amount of soft tissue that the x-ray beam has passed through between the source and the detector at that pixel is given. An example is shown in Figure 6. The information at pixel P_i (shown in green) on the detector is the attenuation of the x-rays originating from the x-ray source and terminating at that pixel (shown in orange). Along this path, the x-ray passes through two different lengths of bone (tb1 and tb2) and two different lengths of meat (tm1 and tm2). The value of pixel P_i for the bone image will therefore be (tb1+tb2)mm. Similarly, for the soft tissue image, this will be (tm1+tm2)mm. Using these values for every pixel in the image, the total amount of material can be estimated and thus, the fill volume of the carton.

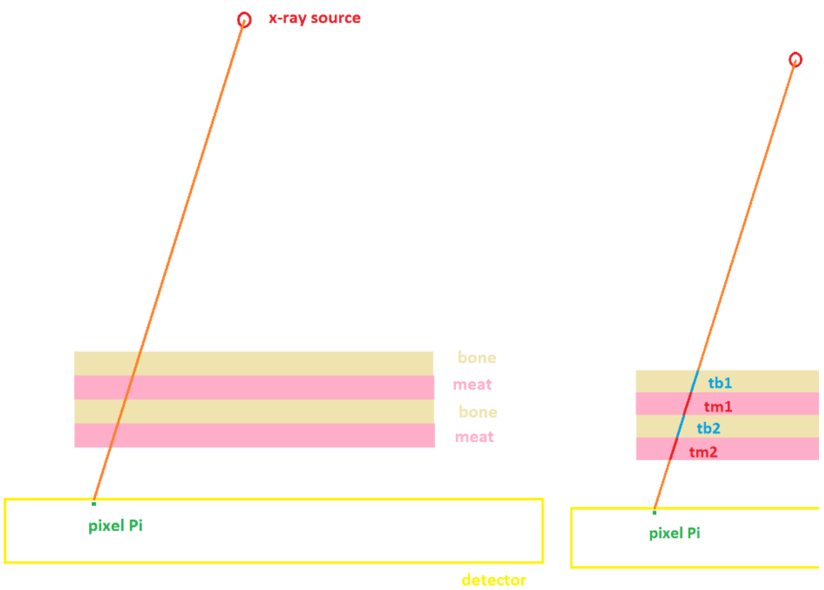

Figure 6: Example ray path calculation

Once these values were calculated for each pixel, another algorithm then analysed these results to identify the presence of any 'voids' in the carton – areas which have been underfilled. Such areas represent a risk for the carton crushing if they are stacked upon. Similarly, the total fill percentage is interrogated. If voids are detected, they are highlighted on the x-ray image, an alarm is sounded and an output fired (which may actuate a diverter). Similarly, if the fill volume is too low, the entire area is highlighted, the alarm sounded and the output fired. The visibility of the highlighting on the image can be toggled by pressing a button on the machine, thus allowing the original x-ray image to be viewed if necessary.

4.6 Factory Acceptance Testing (FAT)

In order to FAT the system, samples were taken in three different sized cartons with various fill orientations. The boxes were filled with a combination of striploins and shortloins which had their volumes estimated using CT scan images. The system was set up to flag voids of a certain size or if total fill percentage was below a threshold. In the former case, the voids are highlighted by a red box on the image. In the latter, a red box overlaps the entire image. In both cases, a flashing light and an audible alarm are sounded after a delay (which would also actuate a diverter downstream in a production environment). The outline of the box is traced in green. The fill volume was also reported on the screen for every scan.

Scan 1 –
Box dimensions (mm) : 545 x 360 x 90
Product: Two striploins
The system reported a fill volume of 86.3%.
The estimated fill volume using the CT data from the striploins is 74%.
PASS – The system would pass this box as being within tolerance.

Figure 7: Scan 1 - Two striploins in 545 x 360 x 90 box

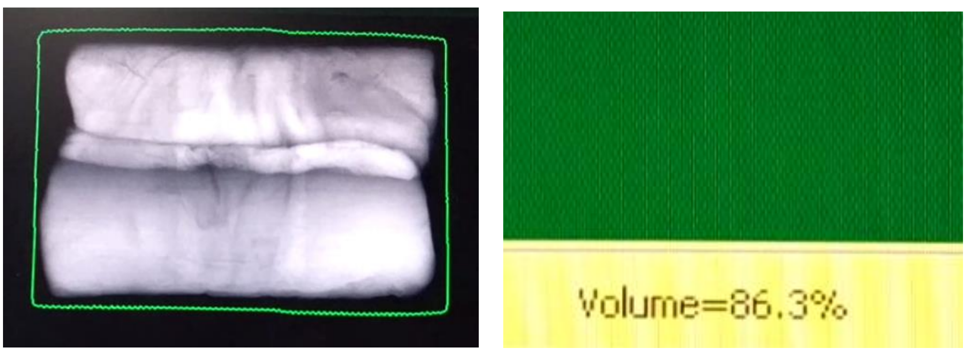

Figure 8: Scan 1 - Scanning Result

Scan 2 –
Box dimensions (mm) : 545 x 360 x 90
Product: One striploin placed along one side.
The system reported a fill volume of 47.3%.
The estimated fill volume using the CT data from the striploin is 40%.
FAIL - The system would fail this box - the void on the side of the box was identified and flagged.

Figure 9: Scan 2 - One striploin in 545 x 360 x 90 box

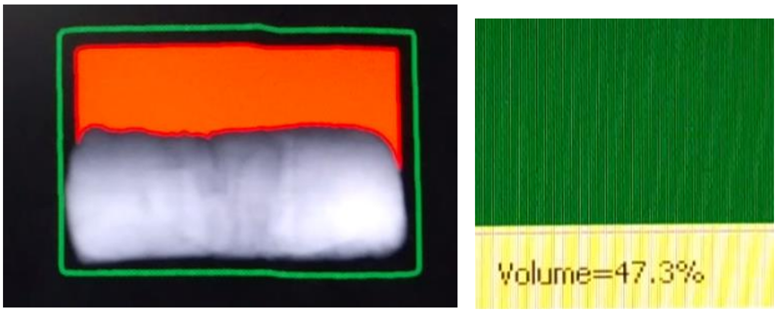

Figure 10: Scan 2 - Scanning Result

Scan 3 –
Box dimensions (mm) : 545 x 360 x 90
Product: One Striploin placed diagonally across the box.
The system reported a fill volume of 48.7%.
The estimated fill volume using the CT data from the striploin is 40%.
FAIL - The system would fail this box - the voids on the corners of the box were identified and flagged.

Figure 11: Scan 3 - One striploin in 545 x 360 x 90 box

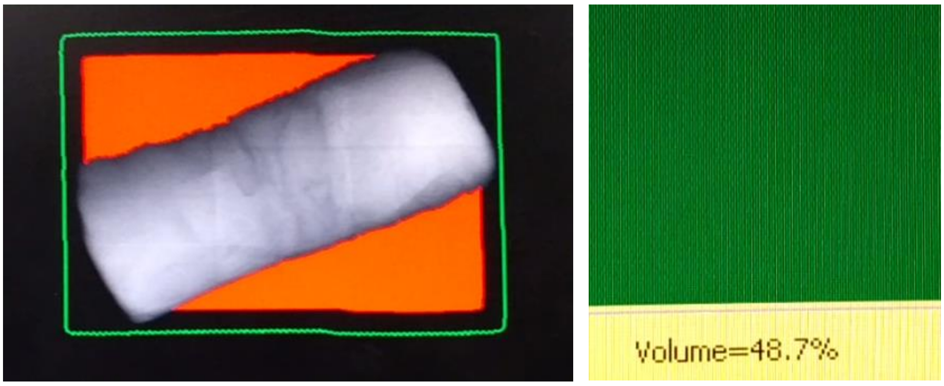

Figure 12: Scan 3 - Scanning Result

Scan 4 –
Box dimensions (mm) : 392 x 303 x 180
Product: Two short loins stacked.
The system reported a fill volume of 66.9%.
The estimated fill volume using the CT data from the striploin is 57%.
PASS - The system would pass this box as being within tolerance.

Figure 13: Scan 4 - Two short loins in 392 x 303 x 180 box

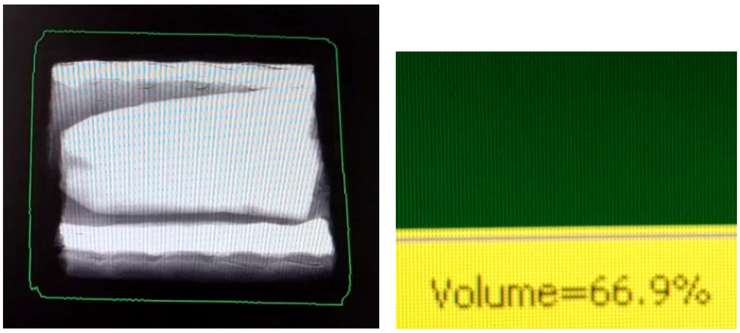

Figure 14: Scan 4 - Scanning Results

Scan 5 –
Box dimensions (mm) : 392 x 303 x 180
Product: One short loin.
The system reported a fill volume of 33.3%.
The estimated fill volume using the CT data from the striploin is 29%.
FAIL – The system would fail this box - the void has been identified and flagged.

Figure 15: Scan 5 - One short loin in 392 x 303 x 180 box

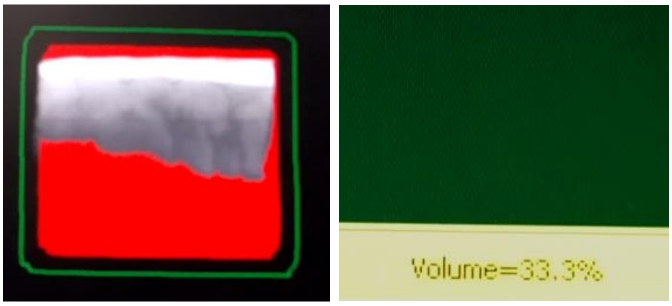

Figure 16: Scan 5 - Scanning results

Scan 6 –
Box dimensions (mm) : 585 x 320 x 170
Product: Two striploins side by side.
The system reported a fill volume of 42.6%.
The estimated fill volume using the CT data from the striploin is 41%.
FAIL – The system would fail this box - the box is underfilled which has been identified and flagged.

Figure 17: Scan 6 - Two striploins in 585 x 320 x 170 box

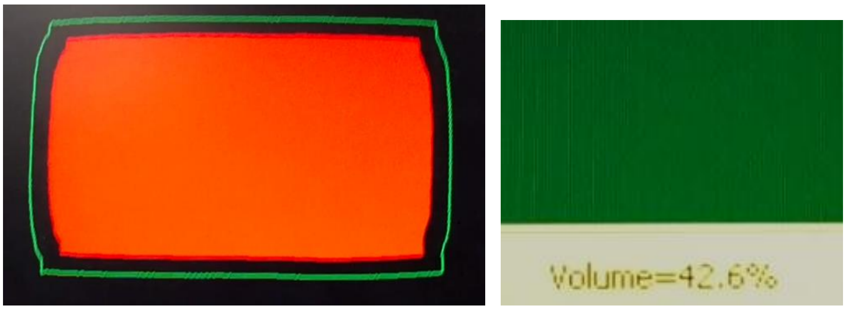

Figure 18: Scan 6 - Scanning Results

Scan 7 –
Box dimensions (mm) : 585 x 320 x 170
Product: Two striploins and a short loin with a void in a corner.
The system reported a fill volume of 42.6%.
The estimated fill volume using the CT data from the striploin is 41%.
FAIL – The system would fail this box - the void has been identified and flagged.

Figure 19: Scan 7 - Two striploins and a short loin in 585 x 320 x 170 box

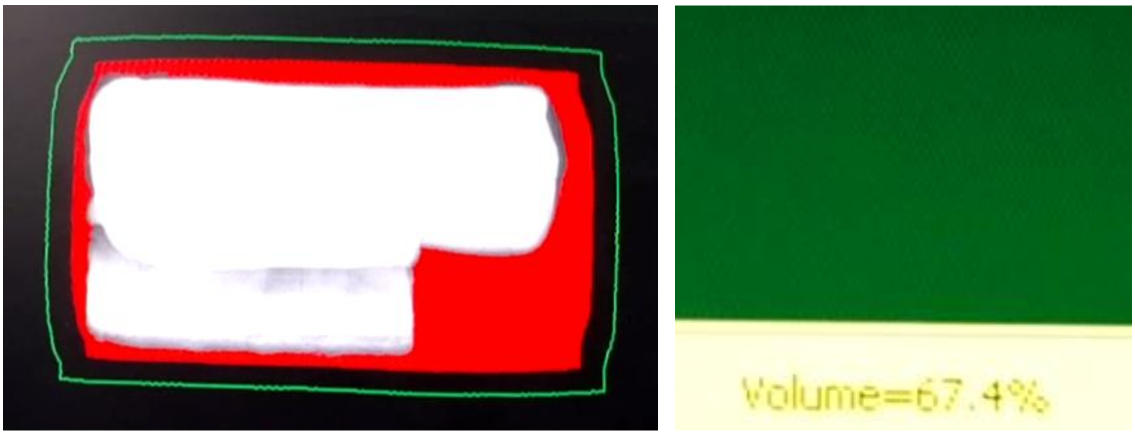

Figure 20: Scan 7 - Scanning Results

A table summarising the results is shown in APPENDIX A – FAT results. Feedback from the customer suggests that the levels of accuracy which have been achieved may already be sufficient for their requirements. However, there are a number of possible measures which can be investigated in order to improve the accuracy of the system.

Firstly, the way in which the volume is calculated can be adjusted. The data obtained through the DEXA system is a cylindrical coordinate system. The tube is the origin and each ray is defined as a distance (*r*) and angle (*φ*) from this point. The conveyor travel provides the third dimension in 3D space (*z*). This is shown in Figure 21, with the fan beam plane shown in Figure 22.

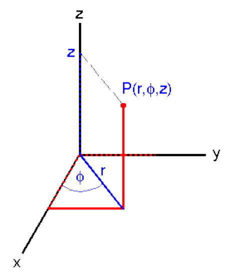

*Figure 21: Cylindrical coordinate system (source: **http://electron9.phys.utk.edu/vectors/3dcoordinates.htm**)*

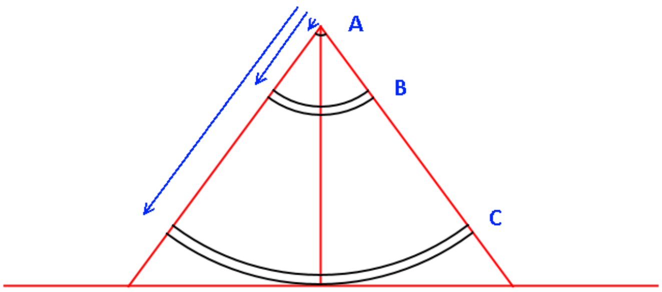

Figure 22: 2D representation of the fan beam geometry

Technically, the volume in a cylindrical co-ordinate system can't be calculated using projected x-ray lengths. The reason is the distance from the origin must be known – the x-ray data only gives the projected lengths through material, not through air. However, a number of reasonable geometric assumptions can be made which alter how the volume is calculated.

Table 1 outlines the result of using two alternative methods to calculate the volumes. These could be built upon to optimise for this application.

Table 1: Effect of different calculation methods

Scan Number	Exp Vol %	Original Vol %	Alternative 1 Vol %	Alternative 2 Vol %
01	73.9%	86.3%	77.8%	87.7%
02	40.0%	47.3%	37.0%	47.8%
03	40.0%	48.7%	38.4%	49.4%
04	57.1%	66.9%	47.2%	67.9%
05	29.2%	33.3%	18.0%	35.2%
06	41.0%	42.6%	22.8%	44.8%
07	60.6%	67.4%	60.6%	67.9%

Secondly, the x-ray hardware can be changed to enable a more accurate calibration to be performed and more accurate measurements to be achieved. An alternative detector could also be investigated. This detector wouldn't have the copper filtration strip between the low energy and high energy modules. It would also have different noise characteristics although this is something that would need to be evaluated through trialling.

One other consideration is the fact that bone is not solid. The outside 'shell' of the bone is known as compact (cortical) bone – this is what the LUTs are calibrating to. Within the bone is a matrix of of spongy (trabecular) bone as well as bone marrow (see Figure 23).

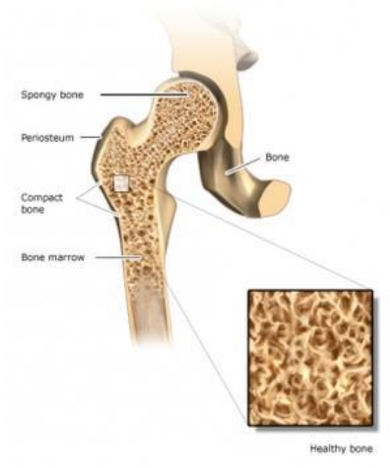

Figure 23: Structure of bone

Figure 24 shows a femur which has been scanned by the system. The point indicated has been measured as being 60mm thick. The x-ray system has identified 18mm of bone and 22mm of soft tissue which is still short of the 60mm measured length. This means that a

DEXA system will under-estimate the length through bone to an extent although implementing the accuracy measures above will minimise this effect.

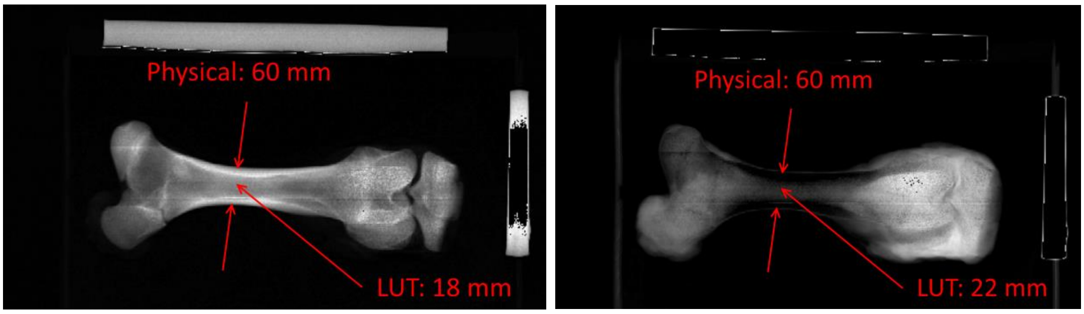

Figure 24: X-ray image of a femur using the bone LUT (left) and soft tissue LUT (right)

One key functionality which can be added to the system is a means to report the systems findings. This can be done immediately by displaying the results on an overhead monitor in a packing area for immediate feedback for staff. Results could also be written to a live database and/or reports generated at a certain interval.

5 Conclusions/Recommendations

A carton fill profiling system utilising DEXA technology has been created by SCOTT and demonstrated. The system was able to accurately identify the fill volume in closed cartons and identify the existence of voids which may indicate a risk of crushing when stacked upon. While the accuracy levels demonstrated meet the customer's need, a number of opportunity areas exist to further improve accuracy based on the learnings acquired throughout the project. This functionality is provided on top of the primary use for the machine, which is contamination detection.

Firstly, utilising slightly different detector hardware and using a higher power x-ray source would improve the quality of the calibration and the results obtained. The algorithms which calculate the fill volume can also be re-evaluated and adjusted.

Two key features which would add significant value to the system would be the implementation of chemical lean (CL) calculation and high quality reporting. By upgrading the hardware, this accuracy can be further improved. Similarly, the addition of customer-specific reporting functionalities can be added to the system based upon their requirements.

It is therefore recommended that a second stage project be conducted which builds upon the learnings acquired from this project to produce a DEXA system capable of inspection, carton fill profiling, CL measurement and advanced feedback.

APPENDIX A – FAT results

Scan	Box Height (mm)	Samples	FAT Video Filename	Comments	Exp Vol %	Reported Vol %	Abs Error Vol	Box Length (mm)	Box Width (mm)
01	*90*	Both Striploins	01-FAT-90mmBox.mp4	Carton Full - **Pass**	73.9%	86.3%	12.4%	545	360
02	*90*	High Marbled Striploin	02-FAT-90mmBox.mp4	One side filled - **Fail**	40.0%	47.3%	7.3%	545	360
03	*90*	High Marbled Striploin	03-FAT-90mmBox.mp4	45 degree fill - **Fail**	40.0%	48.7%	8.7%	545	360
04	*180*	Both Short Loins	04-FAT-180mmBox.mp4	Carton Full - **Pass**	57.1%	66.9%	9.8%	392	303
05	*180*	High Marbled Short Loin	05-FAT-180mmBox.mp4	One side filled - **Fail**	29.2%	33.3%	4.1%	392	303
06	*170*	Both Striploins	06-FAT-170mmBox.mp4	Underfill - **Fail**	41.0%	42.6%	1.6%	585	320
07	*170*	Both Striploins + High marbled short loin	07-FAT-170mmBox.mp4	One corner void - **Fail**	60.6%	67.4%	6.8%	585	320