AMPC

Integrated Robotic Picking and Packing of Primal Cuts

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1.0 EXECUTIVE SUMMARY

The task of picking and packing vacuum packed primal cuts of red meat is a labour intensive task which is currently undertaken as a manual process, resulting in significant labour costs and workplace health and safety risks. Through this project, an automated robotic system capable of replicating the pick and pack operations currently performed in meat processing plants was developed. The system consisted of a six-axis industrial robot, coupled with a vacuum pad foam gripper developed by Strategic Engineering. The gripper was used to physically grip and transport the primal cuts to destinations inside cartons from a moving conveyor. In conjunction, a high resolution three-dimensional computer vision system was developed and utilised in order to identify the primal cut to be packed, and determine the pick and pack parameters for accurate pickup and placement into the carton.

In-house trails were undertaken on a selected subset of ten primal cuts which represent a variety of primal cuts currently being manually processed. The results show that all ten primal cuts could be successfully and efficiently picked, transported, and placed into their corresponding packing configuration at high speeds. The vision recognition system was able to identify the type, mass, and dimensions of the individual primal cut moving along the conveyor, and determine which carton it should be packed into. The robotic system demonstrated a strong ability to pack primal cuts both horizontally and vertically, making it suitable for future plant implementations where different packing arrangements may be required. A cycle time analysis was undertaken and an average cycle time of 7.157 seconds for the round trip pick and pack process was calculated. It was identified that this cycle time could be further reduced if the orientation of the robot and conveyor were altered to reduced robotic travel distance. The developed robotic system has a high potential for efficiently automating the pick and pack procedure in a red meat processing plant without significant design modifications.

2.0 INTRODUCTION

Meat processing plants suffer significant labour costs and workplace health and safety risks associated with the manual picking and packing of primal cuts after processing. Currently, there is no commercially implemented solution within Australia which automates this process using a combined vision and robotic system, and hence there is a necessity for significant research and development to be performed to mitigate the risks associated with the implementation of such a system.

The scope of this project was to design a system capable of picking and packing individual primal cuts via a six-axis robot, using an improved vision system developed from AMPC 2014-1007 “Development of Primal Cut Recognition and Localisation Software for use in Robotic Pick and Pack Systems”. Primal cuts were picked from an in-feed conveyor and then packed efficiently into cartons. This task integrates the previously developed intelligent sensor network which captures and processes the 3d scene of the packing environment in real time to identify information such as primal cut type, position, and orientation.

While previous research and development on a vacuum gripper suitable for the pick and pack of primal cuts through AMPC 2014-1010 “Pick and Pack - End Effector Gripper Development”, was undertaken, significant issues regarding the premature release of the gripped primal cut during transportation and unwanted stretching of the vacuum bag were observed. Hence, this system will use an off-the-shelf gripper which securely holds the primal cut and maintains vacuum bag integrity. Additionally, this project has been directed at a particular subset of primal cuts which have been identified to be most suitable for robotic picking. The output of this project was an autonomous robotic cell capable of efficiently picking and packing primal cuts without the need for manual intervention.

This project was limited by the number of primal cut samples that could be used for in-house trails. Additionally, environmental conditions typical of meat processing plants were not able to be replicated during the in-house trials, this did reduce the rigidity of the primal cuts and cause the vacuum sealed bags to stretch easily. As a result, it may be more difficult for the developed gripper to successfully pick and pack the individual primal cuts.

3.0 PROJECT OBJECTIVES

Objectives for the Integrated Robotic Picking and Packing of Primal Cuts project are outlined below:

- Determine a subset of primal cuts that can be robotically packed with commercially available off the shelf robotic grippers and previously developed vision sensing software from the AMPC 2014-1007 project.
- Develop a robotic picking and packing system that efficiently packs vacuum sealed primal cuts into cartons.
- Trial system at Strategic Engineering's workshop and report on its efficacy and suitability for later implementation in a plant environment.

4.0 METHODOLOGY

4.1 Primal Cut Selection

Carrying on from the research conducted during the previous R&D project "MLA/AMPC "A.TEC.0108 Pick and Pack Materials Handling". Primal cuts were selected in order to both maximise the potential labour savings achieved through an automatic pick and pack system, as well as to determine the versatility of the developed system. A total of ten primal cuts were selected, with primal cuts sourced and supplied by Oakey Beef Exports and the Bindaree Beef Group. The typical carton sizes, capacities, weights, and sizes of the selected primal cuts are shown in Table 1. Both sideways and flat packed primal cuts were selected for this project in order to reflect the packing system currently implemented by project participants.

Table 1: Primal cut selection

SKU	Product Name	Carton Size	Capacity	Approximate Max Weight of Cut (kg)	Approximate Min Weight of Cut (kg)	Approximate Size L x W x H (mm)
1	Topside	Medium	4	12	9.95	400 x 400 x 200
2	Chuck Roll	Medium	2	12	8.5	600 x 300 x 200
3	Clod	Medium	2	14	9.5	600 x 420 x 150
4	Bolar Blade	Medium	2	9.3	6.7	600 x 200 x 150
5	Point End	Medium	2	9.3	6.7	500 x 400 x 150
6	Striploin	Medium	6	9	7.33	650 x 300 x 150
7	Rump	Medium	4	8.67	6.33	400 x 300 x 170
8	Knuckle	Medium	4	7.5	5.75	350 x 250 x 250
9	Tenderloin	Small	6	3.3	2.3	650 x 150 x 100
10	Short Ribs	Medium	10	2.3	1.75	330 x 170 x 50

Top sectional profiles of the selected primal cuts were collected using a profiling jig to calculate the conformability requirements of the developed robotic gripper. It was determined that a high conformability was required, due to the high surface contouring of the majority of the primal cuts as shown in Figure 1. Additionally, a variation in the rigidity of the primal cuts was observed; those with bone or thick fat caps were significantly more rigid than those without.

Figure 1: Primal cut profiles, from top-left clockwise: Tenderloin, Striploin, Topside, Point End. High surface contouring can be seen in Topside and Point End.

4.2 Gripper Design and Manufacturing

4.2.1 Gripper Selection Criteria

Selection criteria for the gripper includes the variability of the primal cuts, surface contouring, interaction with various packing medium, and finally suitability and dexterity to allow the primal cut to be placed in an optimised location within the carton. Both mechanical and vacuum grippers were analysed as part of this process. Mechanical grippers, such as those shown in Figure 2, while allowing for a secure hold of the product, have inherent limitations regarding the placement dexterity of the primal cut into the carton, due to their size and mechanism. To pack primal cuts using mechanical grippers requires dropping the cut from a height into the carton. This is to allows for clearance between the carton and the fingers of the mechanical gripper. Additionally, a single gripper lacks the ability to accommodate a large volumetric range of primal cuts. Whilst in most cases product damage would be negligible, vacuum bag integrity may be compromised by the gripper attachment points.

Vacuum grippers allow for a potentially sleeker gripper footprint and greater dimensional variability, allowing the accommodation to the full range of primal cuts. Without having a mechanical interference during release, allows cartons to be packed more efficiently and at a variety of placement angles. Hence it was determined that a vacuum gripper would be the best possible gripping mechanism to pick and pack primal cuts.

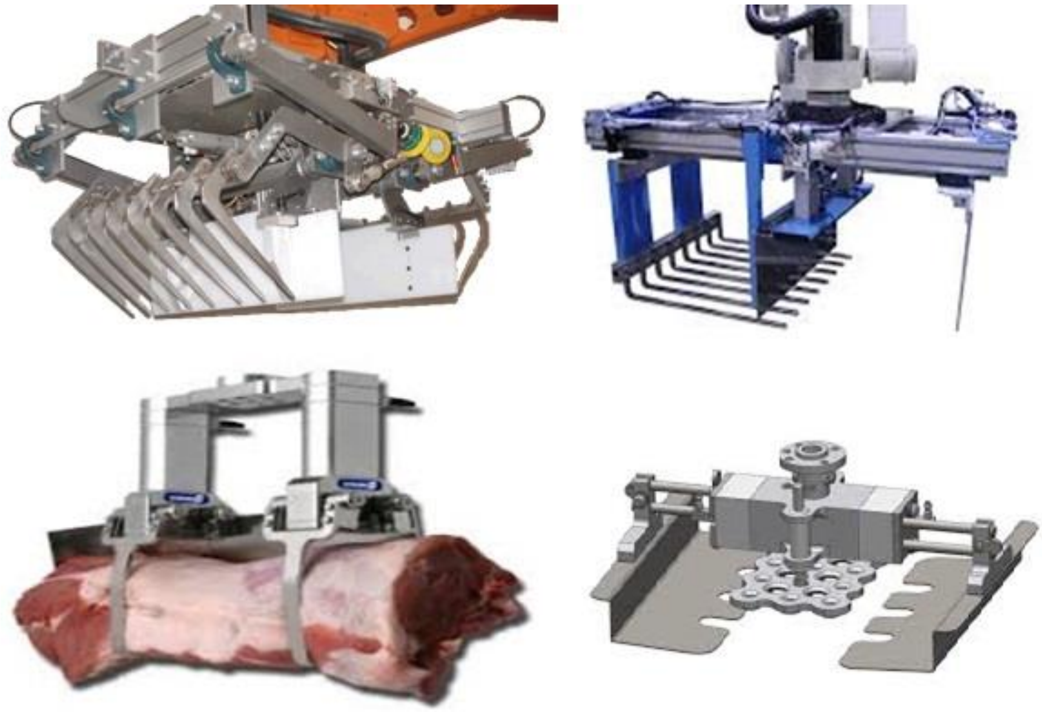

Figure 2: Various mechanical grippers. Their large size and inherent limited placement dexterity can be seen.

4.2.2 Vacuum Gripper Selection

Specific selection of the vacuum gripper was undertaken through the comparison of three main vacuum gripper “off the shelf” variants; Multi-Cup Vacuum Gripper, Oval Vacuum Gripper, and Vacuum Pad Gripper, as shown in Figure 3.

Figure 3: Examples of the three vacuum grippers variants. Left to Right: Multi-Cup, Oval, Vacuum Pad.

Multi-Cup Vacuum Gripper

The multi-cup vacuum gripper is beneficial over a single or multi-large cup style gripper as the reduced cup area minimised bag distortion as identified in AMPC 2014-1010 “Pick and Pack - End Effector Gripper Development”. By using multiple small cups, there is minimal stress on any one portion of the vacuum bag, while offering an opportunity for cup redundancy and product contour capability. Additionally, there is an opportunity for individual cup vacuum control if a decentralised vacuum generation system was used. However, the use of bellow cups alone offers minimal support for inertias developed during transportation, resulting in slower maximum transport speeds. It was also observed that minimal grip was obtained on the bag if it was damp or wet. Suitable friction between the gripper cup lip and the bag could not be maintained and the vacuum seal was lost.

Oval Vacuum Gripper

The oval vacuum gripper is able to lift a significant weight and size of product. It was observed that smaller products which do not completely encapsulate the foam ring are not able to be picked up, and hence the variety of cut sizes a single oval gripper is able to pick and pack is limited. This style of gripper can be combined with a side channel blower to handle reasonable vacuum losses which may occur due to the crinkling of the vacuum bag. However, as identified in AMPC 2014-1010 “Pick and Pack - End Effector Gripper Development”, there is a tendency to pucker and stretch the vacuum bag due to the unsupported hollow central section. This increases the stress on the vacuum bag seams, increasing the risk of vacuum bag seal integrity failure, as well as distorting the meat inside the bag considerably. This style of gripper is not easily able to conform to the meat profile contours due to the requirements for a seal between the vacuum bag primal cut and the gripper to be maintained around the proximity of the foam sealing rim.

Vacuum Pad Gripper

Similar to the oval vacuum gripper, a vacuum pad gripper is able to lift a significant range and size of primal cuts. Additionally, the foam pad is able to provide support for inertias developed during transportation from the pick to the pack position by the robot, allowing an increased maximum transport speed than that of an unsupported load. While the off-the-shelf vacuum pad gripper initially considered was able to lift horizontally, vacuum seal reduced significantly when turned vertically due to the ‘ball-valves’ inside the ports behind the foam pad, which rely on gravity to operate effectively. Due to a large number of vacuum suction points, there was significantly reduced stretch on any one point of the bag, and the pucker effect observed in the oval vacuum gripper was negligible. Conformance of the vacuum pad gripper to the various meat profiles was directly correlated to the foam pad thickness. Vacuum flow control could be obtained easily if a decentralised vacuum generation system was used. Finally, there was no observed vacuum loss between the primal cut and the gripper pad due to any dampness on the outer surface of the primal cut baggage.

From the observations described above, it is evident that a vacuum pad gripper variant would be most suitable for this project. Additionally, the following variables were identified as significant contributors to maximising the gripper’s ability to securely and efficiently pick and place the vacuum bagged primal cut:

- **Gripper Profile:**
  It was identified that the gripper profile should be as thin as possible to meet the required packing configurations whilst maintaining structural integrity. A thin gripper profile is able to move vertically within the confinements of the carton whilst packing, allowing a sideways packing configuration to be possible.

- **Foam Thickness:**
  Through various trials, a correlation between foam thickness and contouring ability was observed. A thicker foam pad allowed for a wider range of primal cuts to be picked as a larger surface area of the bagged primal cut was exposed to the vacuum pad gripper surface.

However, it was found that extreme foam thicknesses increased the evacuation time, and potentially blocked the vacuum flow holes through the collapse of the foam into itself. Thus, a suitable intermediary range was identified which allowed high contouring whilst maintaining low evacuation times.

- **Coverage Ratio:**
  Ideally, the same gripper must be able to pick and pack the full range of primal cuts in this project. Thus, each primal cut should be completely covered by the foam pad in order prevent the vacuum bagged primal cut from 'peeling off' the gripper due to an unsupported section. This was especially important for primal cuts without bone or fat caps where there was a lack internal rigidity.

- **Vacuum Flow Control:**
  Due to the wide volumetric range of primal cuts selected, it was crucial to control the vacuum flow to the gripper. For example, if a small primal cut was picked which did not cover the entirety of the vacuum pad, it was important to maintain vacuum on the primal, whilst limiting the vacuum flow to the uncovered surfaces. If this did not occur, a vacuum would not be maintained and the primal cut would simply fall. In addition, this style of flow control must be undertaken irrespective of the orientation of the gripper at any point in time. The vacuum flow must also be stopped in order to release the primal cut when positioned for packing.

4.2.3 Gripper Design

In order to meet the requirements of the different pick and packing configurations as outlined in Section 4.1, an off the shelf gripper was required. Due to the lack of suitable options from alternative vacuum pad gripper suppliers, Strategic Engineering conducted an internal research and development project to develop their own vacuum pad gripper suitable for the red meat industry. As a result of this internal research, rapid prototyping of the gripper was undertaken to maximise its potential with respect to the pick and pack of vacuum bagged primal cuts. As such, the prototype gripper was designed to meet the identified parameters discussed in Section 4.2.2. A rendered diagram showing isometric and exploded views of the internally developed vacuum pad gripper is shown below in Figure 4.

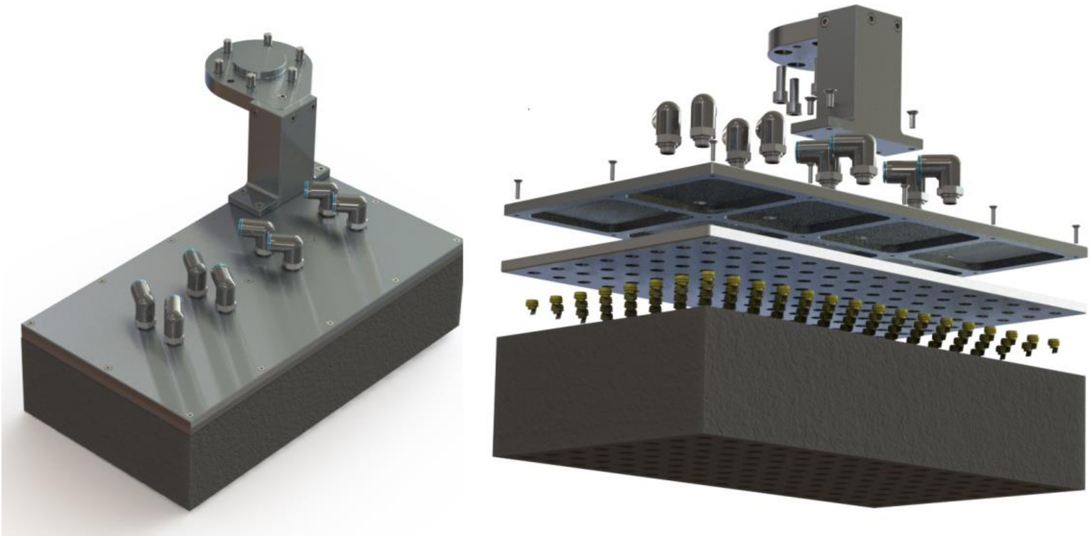

Figure 4: Rendering of the gripper design; isometric and exploded views.

Given the constraints of the carton dimensions, the developed gripper has a footprint of 250mm x 460mm. The two plates are each 10 mm thick, and either a 100mm or 120 mm thick semi-closed cell foam pad was used, depending on the primal cut that was packaged. The foam pad has through holes which are lined up with the holes in the plate to allow for vacuum flow. In addition, the gripper was developed with the following notable features:

- **Thin plate profile, thick foam pad:**
  The thin plate allowed for tight packing into the cartons whilst maintaining rigidity, while the foam pad allowed for conformability to the various primal cuts.

- **Modular vacuum control:**
  The gripper was divided into eight modules, each of which could be separately controlled by the robotic system depending on the primal cut to be picked. In addition, an array of flap valves was used instead of typical ball valves. This allowed primal cuts which do not fully cover the gripper pad to be picked and rotated to any orientation (such as vertically) with minimal vacuum loss.

- **Offset robot attachment position:**
  The attachment between the robot's roll face and the gripper was offset from the centroid of the gripper. This allowed the gripper pad to be inserted into a carton without interference between the carton and the robot arm.

4.2.4 Gripper Fabrication

The developed gripper was fabricated in-house and can be seen in Figure 5. Vacuum pressure was fed individually to each of the eight module chambers via the eight push on fittings. Angle fittings were used to minimise the thickness of the completed gripper. The offset mounting extension enabled the gripper to reach into the cartons, allowing for efficient packing.

Figure 5: Fully assembled vacuum pad gripper with 120mm thick foam.

4.2.5 Integration with Six-Axis Robot

A suitable pneumatic valve control system was required in order to control the vacuum flow to the gripper for efficient pick and pack. A decentralised vacuum control system was developed, allowing each module in the gripper to be controlled independently. This system increased the efficiency of the compressed air used as only the modules required to pick up the primal cut were activated. To provide vacuum to the gripper, high flow rate inline vacuum ejectors were used. Their high flow rate was able to compensate for potential vacuum loss as a result of a suboptimal seal between the foam vacuum pad and the bagged primal cut. A diagrammatical overview of the integrated robot vacuum system, highlighting the compressed air routing and pneumatic assembly components is seen in Figure 6. The completely integrated robotic and pneumatic system is shown in Figure 7.

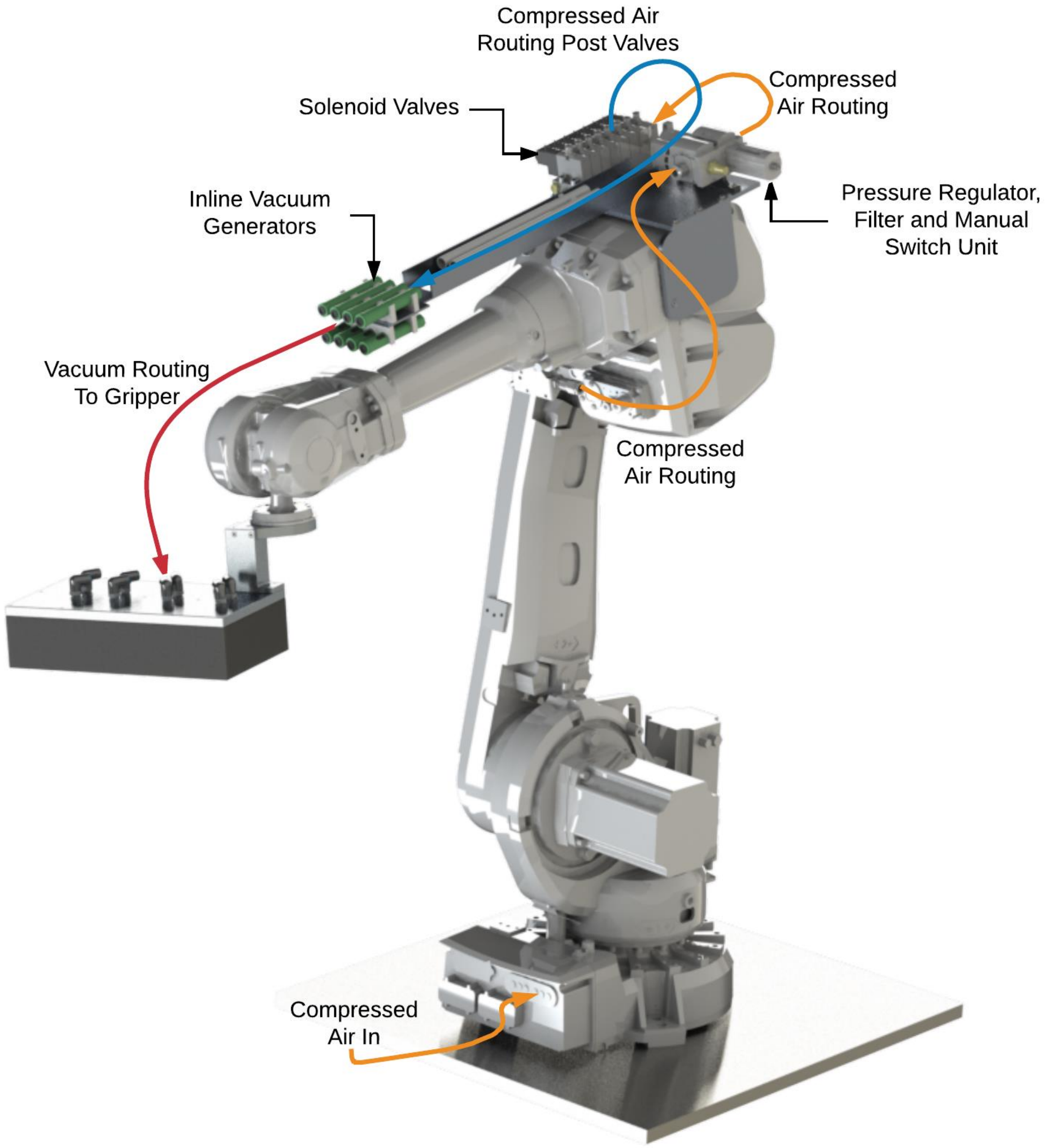

Figure 6: Rendering and diagrammatic overview of robot pneumatic system. The routing tubes, pressure regulator, solenoid valves, and inline vacuum generators are highlighted.

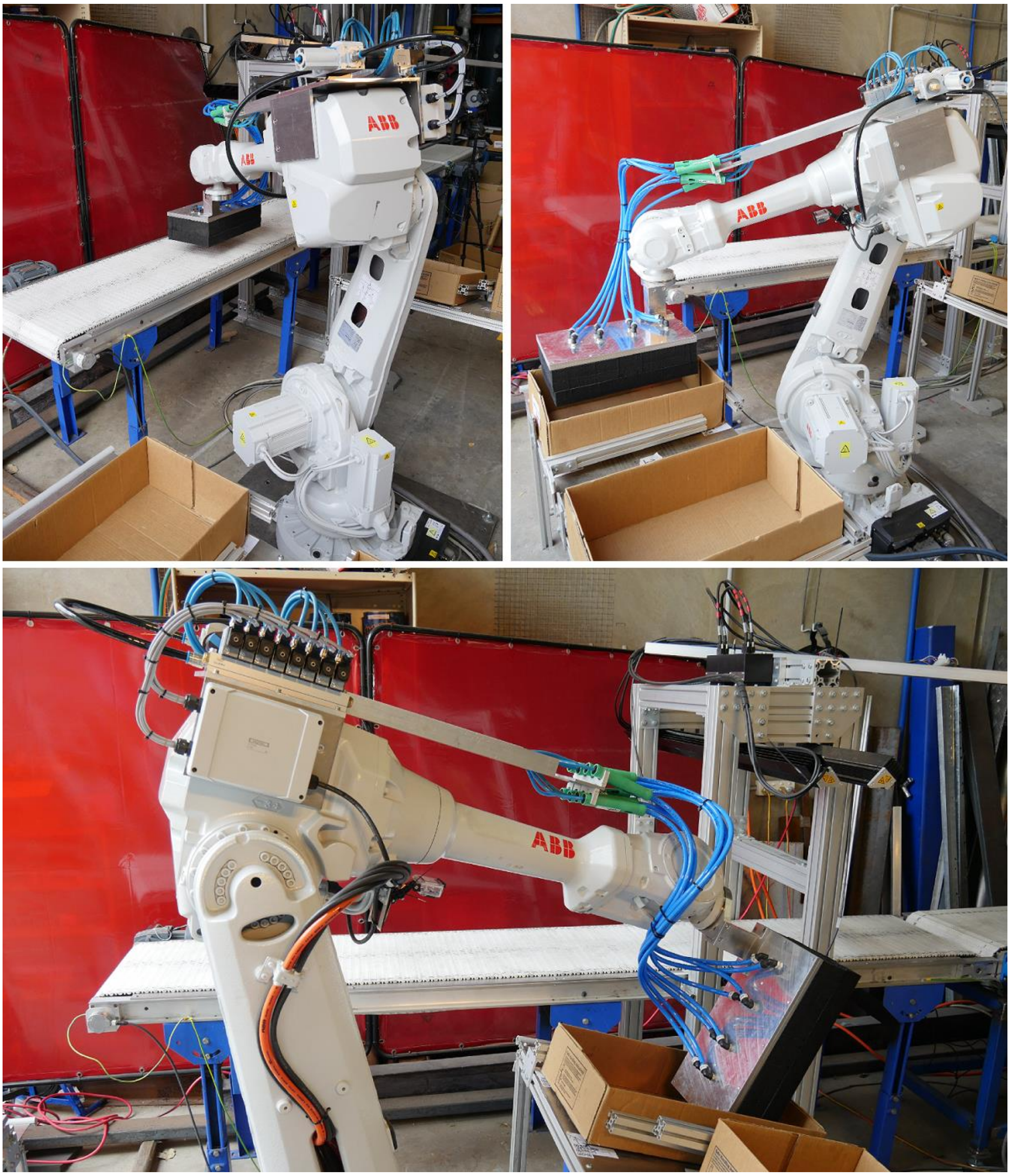

Figure 7: Fully integration pneumatic vacuum gripper system with the ABB IRB 4600 six-axis robot. Pick off and pack positions are shown.

4.3 Hardware Procurement and Setup

In order to automate the pick and pack of vacuum bagged primal cuts, the industrial robot and gripping system was integrated with a vision and conveyor system. The conveyor system emulated transportation conditions similar to that of those found in a typical red meat processing plant.

4.3.1 Vision System

The vision system was used to identify the type of primal cut and its various properties as it moves along the conveyor. A high resolution 3D vision system consisting of image capturing hardware and a processing computer was developed in order to analyse the primal cut images in real time. The hardware componentry used for image capturing includes:

- **Chromasens allPIXAPro4096 3D Vision Sensor –** Stereoscopic line scan required to produce highly detailed images at a resolution of 4096 pixels across the conveyor with a combined height map.
- **Chromasens Corona II LED Lights –** Two 1.2m long lights required for illumination and to remove shadowing for the high-speed line scan camera capture.
- **Frame grabber –** A dual Camera Link interface to the PC.
- **Encoder –** Programmable 10000-line incremental count quadrature needed for timing line capturing of the stereoscopic camera.

Due to the tight space constraints within typical plant boning rooms, the vision system was mounted above the conveyor as seen in Figure 8. Figure 8 also highlights the 3D vision sensor and LED lights which were used to image the primal cuts. As the height deviation between the primal cuts is large, two LED lights were implemented to obtain a 200 mm depth of field image. This allowed the primal cuts to be correctly illuminated along their entire top surface contour.

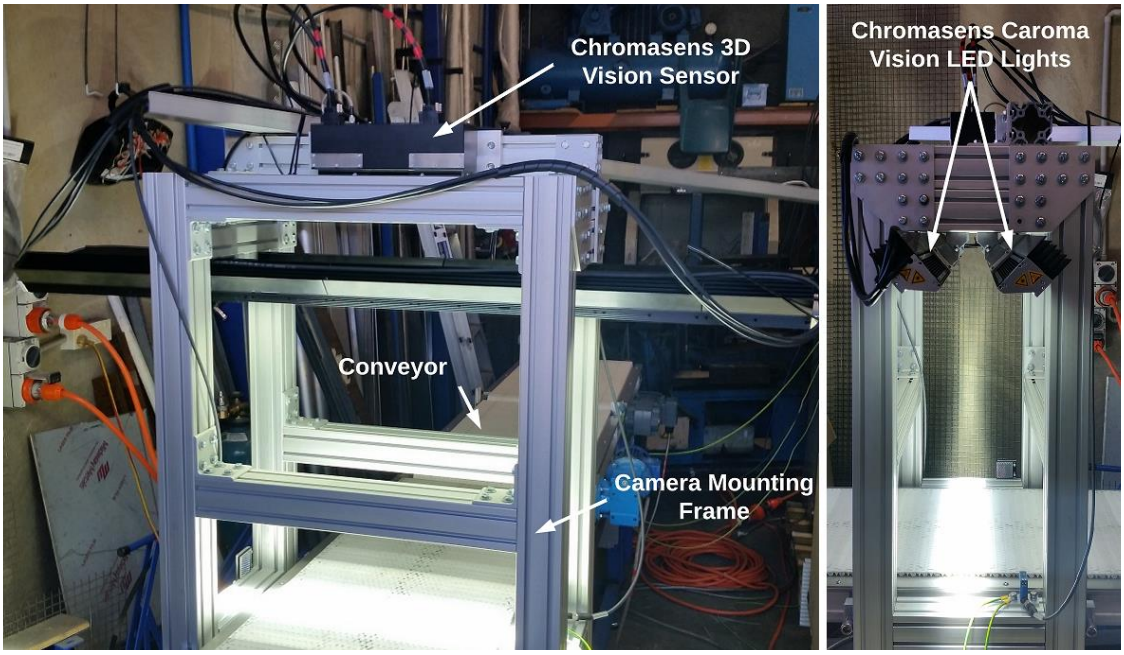

Figure 8: The completely integrated vision system, consisting of the vision sensor, lights, and mounting frame.

Integral to the vision system was the associated computing and electronic components used to process the images. The component used as part of this system is detailed in Appendix 8.1, Table 4.

4.3.2 Conveyor System

An extended three stage conveyor system was developed as part of this project, as shown in Figure 9. The first stage was used for the initial loading of the primal cut onto the conveyor system. The second stage was an in-house developed check weigh which utilises four load cells to record the weight of the primal cut. The third stage was used to transport the primal cut under the vision system and into the pick region of the robot. The sensory and transportation hardware required for the three-stage conveyor system is detailed in Appendix 8.1, Table 5.

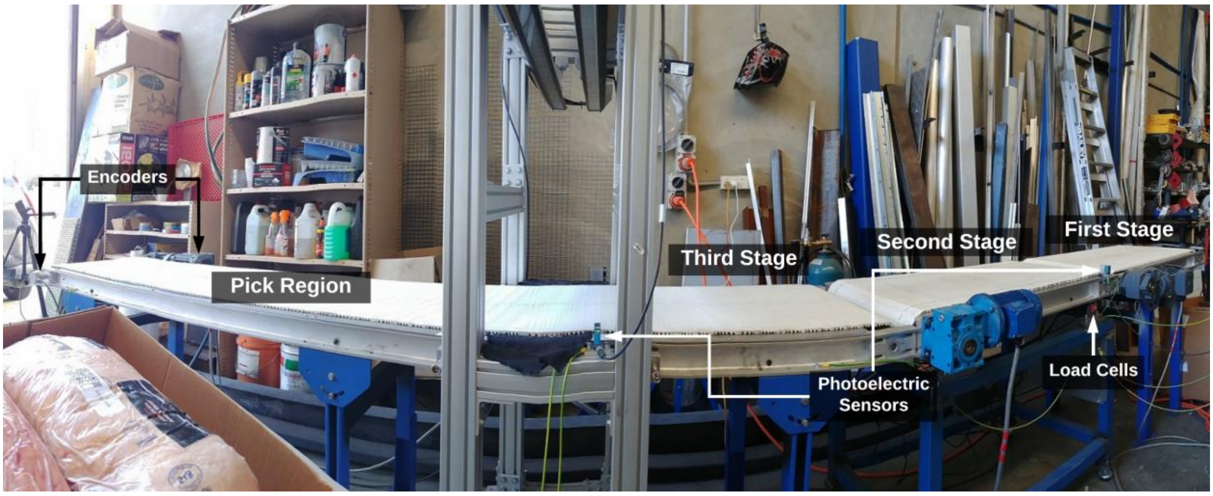

Figure 9: Annotated view of the developed three stage conveyor system.

4.3.3 Robotic System

To physical perform the pick and pack movement, an ABB IRB4600 six-axis industrial robot was used. This robot has a 60kg payload capacity, allowing it to perform the pick and pack functions effectively for the variety of primal cuts analysed within the scope of this project.

Additionally, the ABB IRB4600 was equipped with conveyor tracking and multitasking modules. The conveyor tracking module allowed for interfacing with an encoder on the conveyor which was used to accurately track the position of the primal cuts on the conveyor. Multitasking functions were used to receive data from the vision system to dynamically guide the robot during picking of the various primal cuts. This data told the robot which carton to go to, how to pick up the cut, how fast the robot should move, how to pack the cuts, and if there were to be an error, to ignore the next primal cut.

4.3.4 Control Cabinet

All the system controllers and electrical components were wired inside the main control cabinet. The main components are listed below and detailed in Figure 10 and Figure 11:

- 3 x 24V DC Power Supply Units (PSU)
- 5 x XCL4 LED Controllers
- 3 x Variable Frequency Drives
- Framegrabber IO Board
- Vision PC

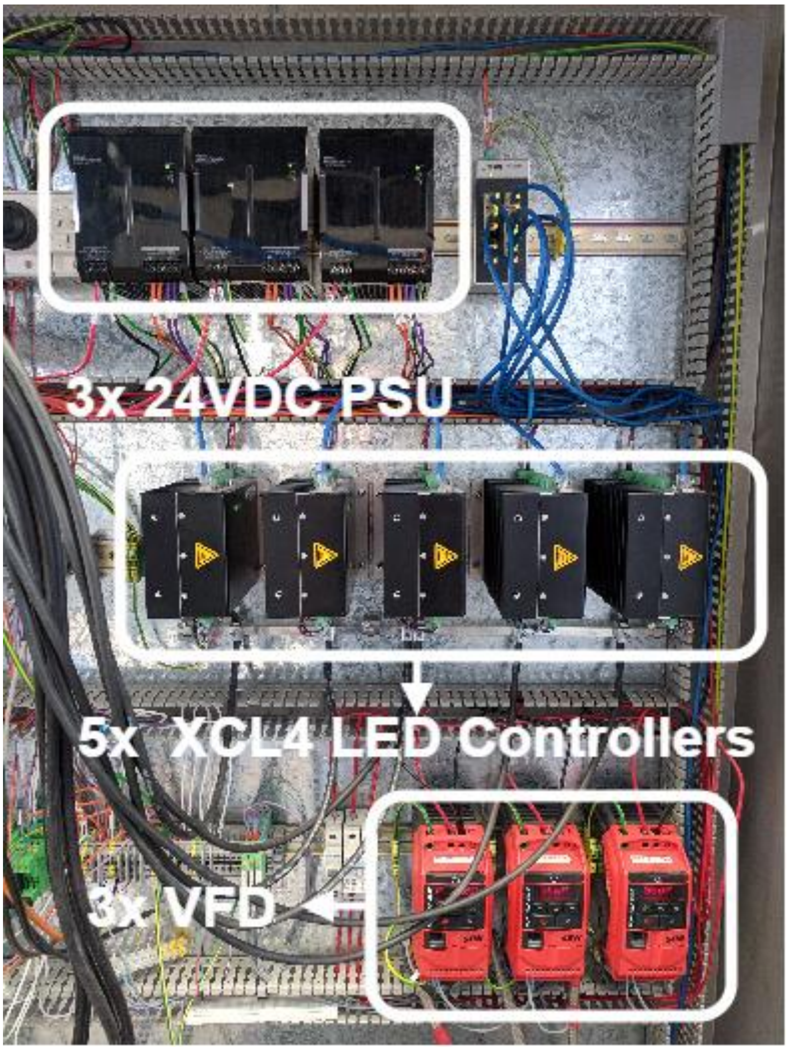

Figure 10 - Control Cabinet: PSU's, LED Controllers and VFD's

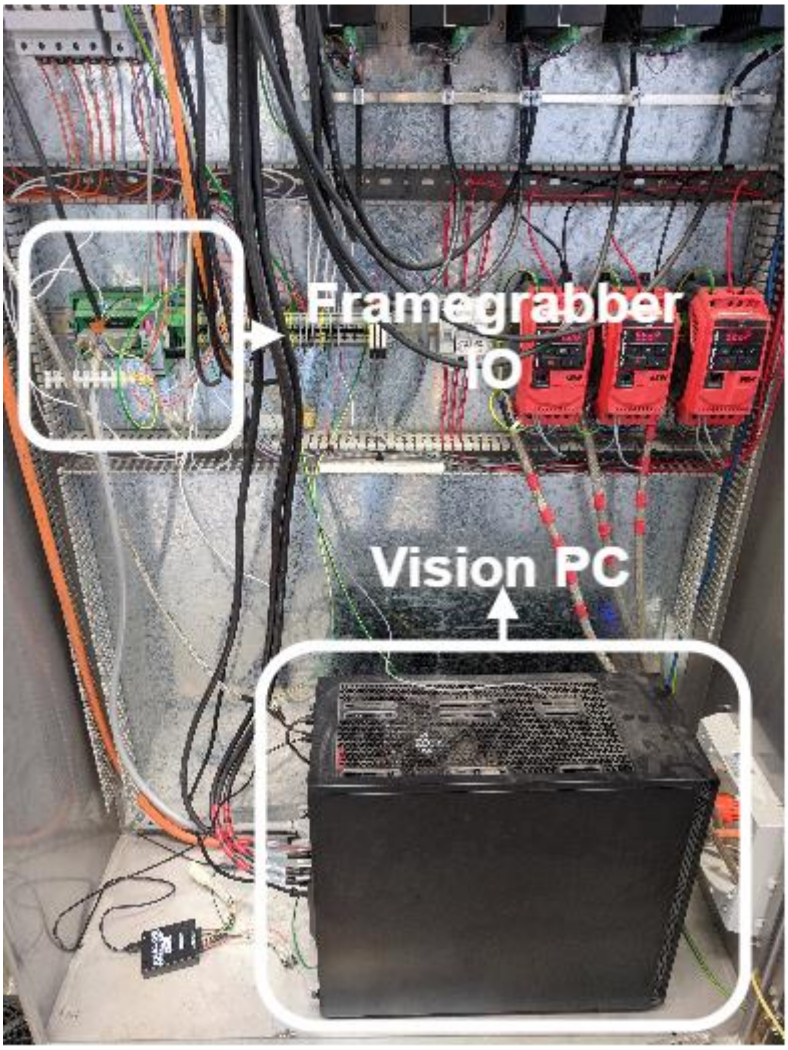

Figure 11 - Control Cabinet: Framegrabber IO and Vision PC

4.4 Vision System

The vision system was used to capture images of the primal cuts which passed along the conveyor underneath the camera. Images were captured by the stereoscopic line scan camera and then processed in the vision PC to calculate picking and packing parameters which were used to guide the robot during the picking procedure.

4.4.1 Vision Application

HALCON is a vision system development environment which was utilised in this project to develop the Vision Application. HALCON was used as it facilitates rapid development of vision system applications. HALCON contains a suite of advanced image processing libraries. The Vision Application has been developed in several modules, these are:

Image Capture

The HALCON development environment was used to create a module for the acquisition of images using inbuilt frame grabber functions. The images are transferred into the vision PC Application via the BitFlow frame grabber card. This frame grabber connects to the allPIXA stereoscopic camera and to the photoelectric sensor as an external camera trigger. When the external trigger was engaged by a primal cut passing under the camera along the conveyor, the frame grabber triggers the camera to start capturing rows of images for a fixed distance of travel. These lines are combined into an image that the frame grabber makes accessible to the image acquisition module. As the camera is stereoscopic, both cameras captured an image simultaneously and each image is sent to the frame grabber. These images are known as the Master and Slave images and are shown below in Figure 12

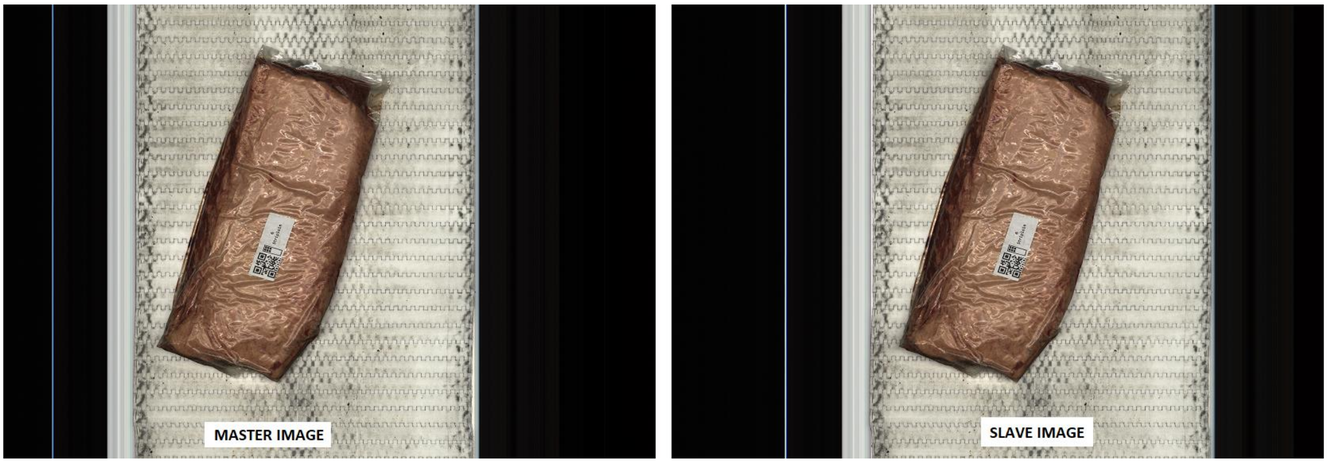

Figure 12 – Master and Slave Images

Generation of Height map and Rectified Image

A HALCON module was created to process the raw master and slave images into a rectified image and a 3D height map. The Chromasens CS3D API was used for the generation of this data. This module takes the raw master and slave image data from the image acquisition module and sends the images along with configuration settings to the CS3D API for processing. The CS3D API generates and returns a rectified image and a three-dimensional height map. The height map is generated by correlating pixels between the master and slave images. A window size of 10x10 pixels was set in the configuration data. This window size defines the area (or patch) of neighbouring pixels that are used to determine the pixels that corresponded between the master to the slave image. The heights of corresponding patches of pixels are then determined through triangulation and trigonometric calculations. The CS3D API makes use of dual graphics cards inside the PC to achieve a fast processing time of less than four hundred milliseconds to generate the height map. A rectified image is the result of merging the master and slave colour images into one centred two-dimensional 24-bit colour image. The height map is a single channel grayscale image where each grey value pixel represents the vertical distance from the camera lenses to the height at that point of the image. Figure 13 shows the rectified image and Figure 14 shows a height map image generated from the master and slave images. Figure 15 shows a 3D view generated from overlaying the rectified image onto the 3D height map.

Figure 13 - Rectified Image

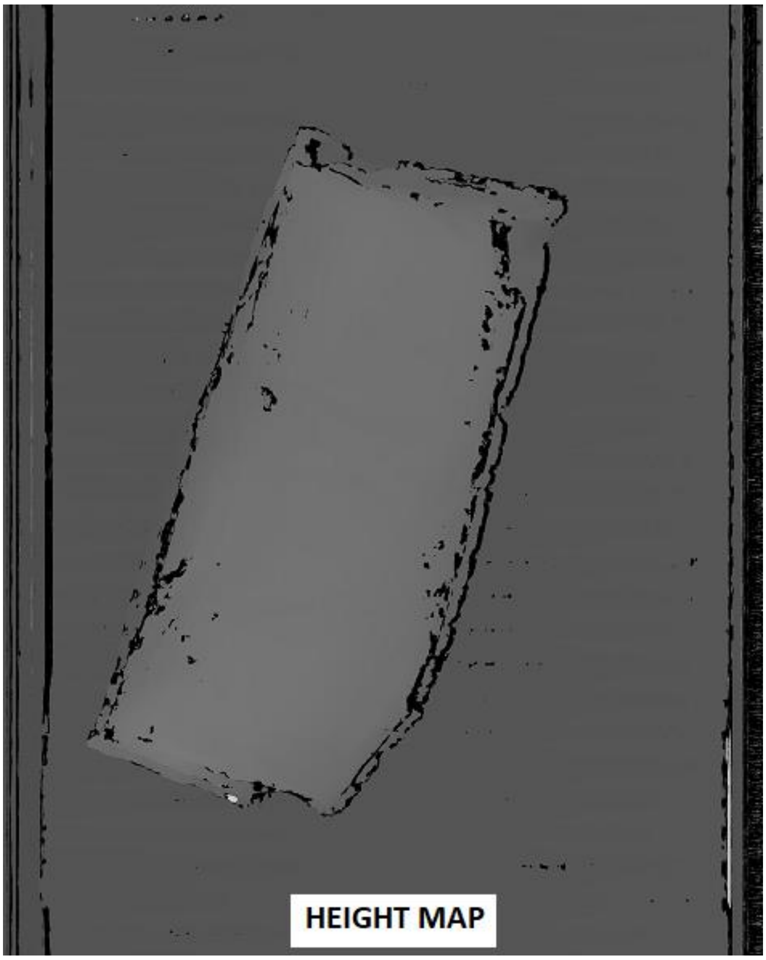

Figure 14 - Height Map

Figure 15 - 3D View of Primal Cut

Image Analysis and Processing

To determine the position of the primal cut, first the area of the image containing the primal cut must be extracted away from the conveyor belt. This process is completed using colour image analysis along with extracting height map data for areas over a certain height. After filtering the results of the analysis the region of the primal cut is determined. Figure 16 below shows the rectified image along with the region of the primal cut found inside the HALCON Development environment.

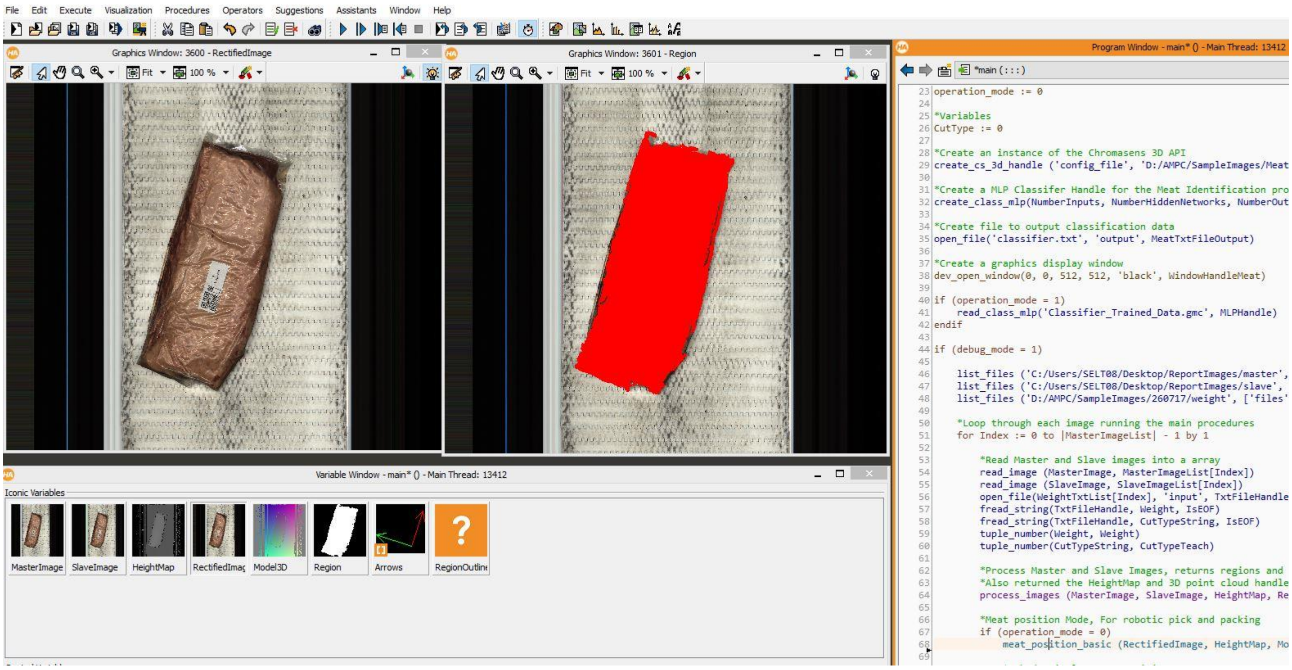

Figure 16 - Region Image in HALCON

With a region of interest found, HALCON functions were used to determine measurements of the primal cut and its position on the conveyor belt. A method known as bounding box is used to determine the Length, Width, Centre Position and Yaw (Angle of rotation) of the primal cut. A bounding box works by surrounding the region of interest with a virtual box with the smallest possible lengths for each side of the box. Length and Width dimensions can be taken straight from the length and width of the bounding box; these are used for determining the pack location in the cartons. Yaw, the angle of rotation of the meat on the conveyor can be found by measuring the angle of the box against the travel direction of the conveyor. The centre point of the bounding box and the yaw is used to provide the pickup position and rotation to the robot. Figure 17 below shows the primal cut within its bounding box along with its pick position and rotation.

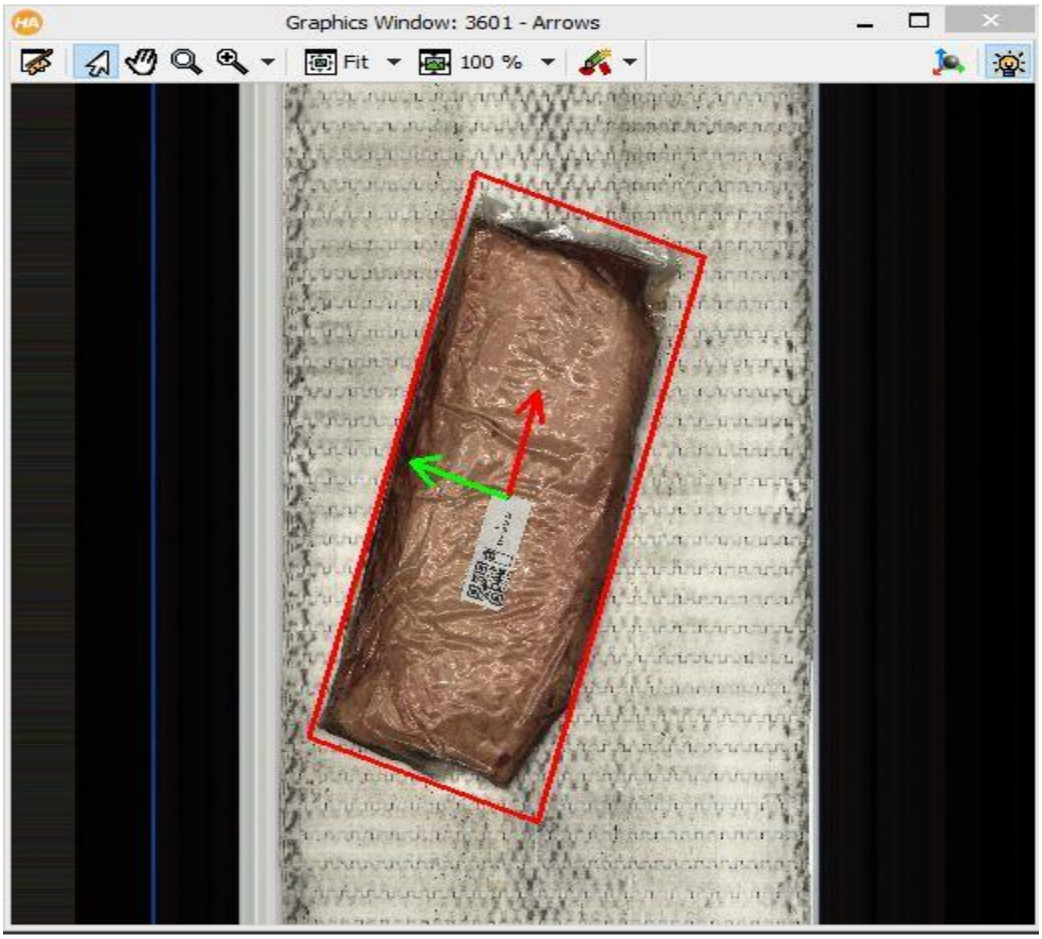

Figure 17 - Bounding Box and Pick Point

The height of the primal cut is also required for reliable picking. The height measurement required by the robot is the highest point on the primal cut. To determine this point, the height map is scanned within the region of interest for the highest pixel position. Any outlier values caused from noise in the height map are ignored as these values would be stray high point not consistent with their surrounding heights. The values of the heights within a thirty-pixel radius from the highest point are averaged and this is used as the height for pickup. This is shown in Figure 18 below with the thirty-pixel radius circle outlined.

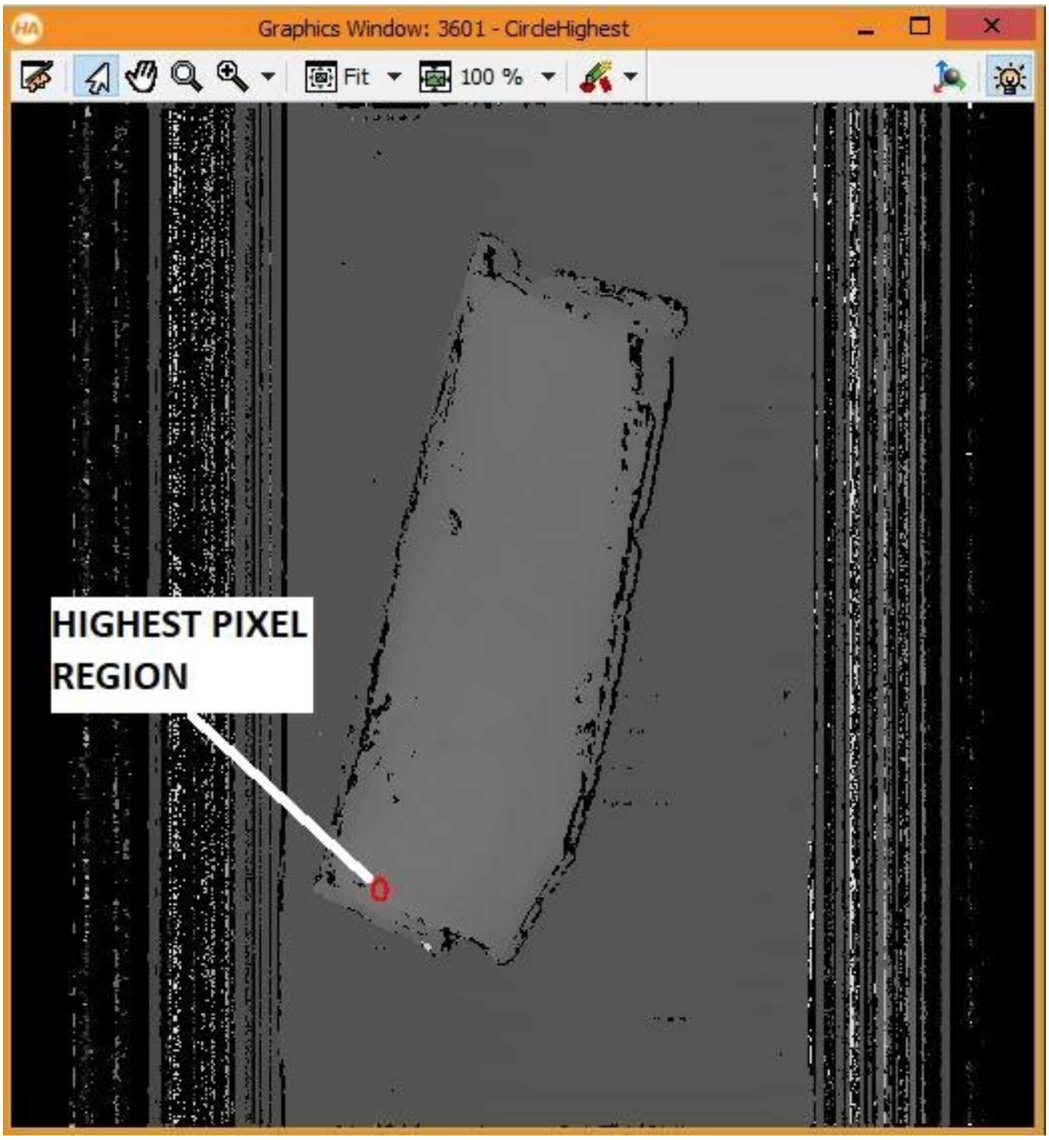

Figure 18 - Height Map Highest Position

Label Recognition

Labels were developed in-house for the system to be able to identify what primal cut was being picked and to determine what it was to be packed into. QR codes were used as a 2D barcode system for the labels. HALCON has built in functionality for reading QR code values. The QR function scans the captured image and decodes the QR to a number value which represents a primal cut type. Figure 19 below shows an example of the labels developed for identification. These labels also featured a number, text and a simple dot code for convenience.

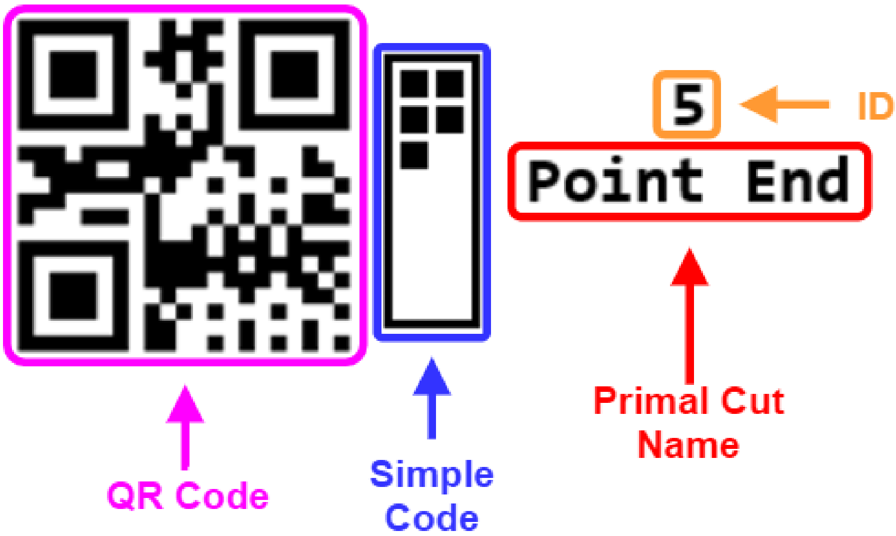

Figure 19 - QR Code Label

4.4.2 Application Structure

The vision application was composed of four distinct components which can be seen in Figure 20:

- **Vision Recognition**
  Handled the image capture from the frame grabber, generation of the height map and rectified image, and image analysis and processing using the HALCON scripts.

- **Communication**
  TCP/IP Sockets were required to control the five Corona II XLC4 lighting controller states during camera operation. The XLC4's were responsible for supplying power to the Corona II line scan LED lights for illumination of the moving stage.

- **Check Weigh**
  Interfaces to load cells to capture the weight of the triggering primal cut which moved over the check weigh conveyor.

- **User Interface**
  Displayed the results and allows user input to change system parameters used during the operation of the application.

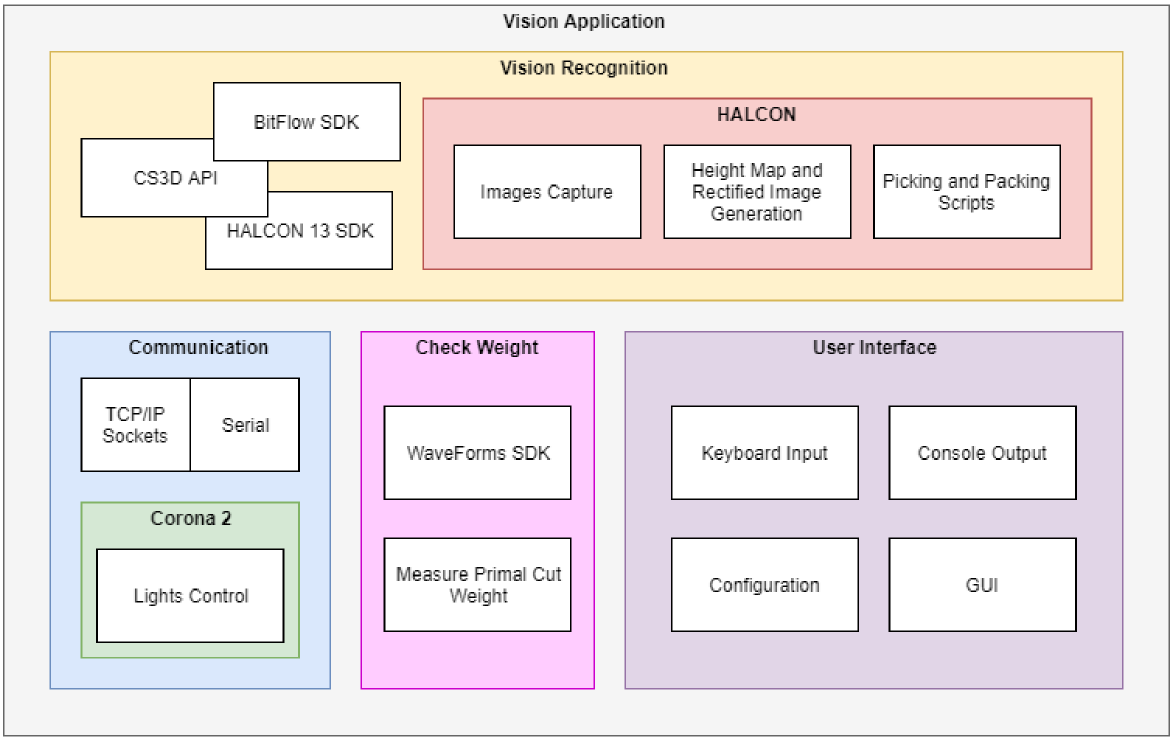

Figure 20: Vision application architectural diagram

Application Program Flow

The application controlled the flow of data using three threads; one for image capture, one for loading into the CS3D API, and lastly one for unloading from the CS3D API, performing the high level image processing, displaying results and dissemination of data and relevant commands to robot. The details of the developed application program flow are shown in Figure 21. This multithreaded design of the application was required by Chromasens for their CS3D API solution and allowed for a higher throughput of data as the primary tasks could occur in parallel.

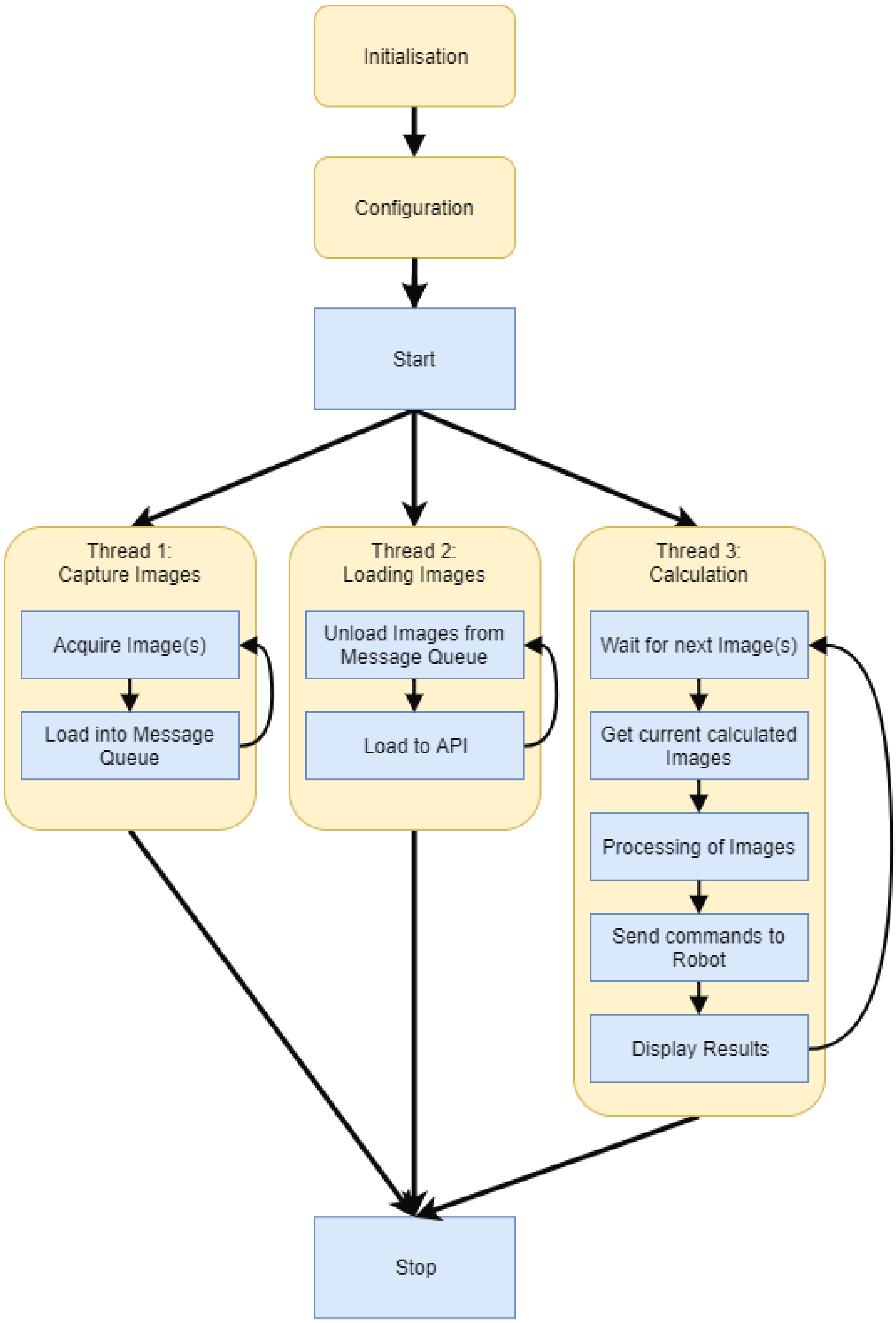

Figure 21: Diagram of application program flow

4.4.3 Process Overview

During the application runtime, the following stages of operation were executed:

1. **Initialise application functions**
    a. HALCON 13
        i. Start HDevEngine
        ii. Load Procedures
    b. CS3D API (via HALCON Extension)
        i. Set CS3D start parameters
        ii. Begin CS3D image handling
    c. Framegrabber (via HALCON Extension)
        i. Set capture frame size (length, width)
        ii. Set capture mode (continuous grabbing with trigger)
    d. LED Control
        i. Open socket connection
        ii. Set to on state
    e. ABB Robot
        i. Open serial connection to robot
    f. Check Weight
        i. Connect to check weigh device
        ii. Zero weight

2. **Frame capturing**
    a. Capture master and slave images

3. **Load master and slave images into CS3D API**

4. **Retrieve CS3D API output images (height map, rectified image)**

5. **Process images to determine primal cut and its dimensions**
    a. Region image of the meat from the conveyor
    b. Identify QR code and decode
    c. Calculate dimensions and origins

6. **Calculate picking and packing data for the primal cut and carton**

7. **Send picking and packing data to robot**

8. **Display results on screen**
    a. Rectified and heightmap images
    b. Picking coordinates
    c. Packing carton

4.5 Pick and Pack Algorithms

4.5.1 Picking Algorithms

A modular picking algorithm was developed to accommodate the various orientations and separations between the individual primal cuts as they moved along the conveyor. As outlined in Section 4.4, the vision system could determine the size, mass (as the check weigh output), and volumetric profile of the primal cut, as well as its position and orientation with respect to the conveyor. A photoelectric sensor was used to initiate the image capturing process when triggered by the leading edge of the primal cut. Additionally, this trigger was utilised to add the primal cut object to the robot's conveyor tracking module queue where an encoder was used to accurately track the movement of the primal cut along the conveyor. Once scanned by the vision system, the primal cut type was identified using an attached QR code, and the desired pick coordinates and yaw rotation were sent to the robotic system via serial communications. Figure 22 shows a rotated primal cut and the corresponding rotated pick position of the gripper as determined by the vision system.

Figure 22: Rotation when picking primal cut on angle

In order to determine the pick position for the robotic gripper, three pick offsets were calculated from datums located on the conveyor:

- Distance from the edge of the conveyor to the centre pick point,
- Distance from the leading edge of the primal cut to the centre pick point,
- The maximum height of the primal cut above the top of the conveyor belt.

An example output of the three pick offset, as well as the yaw rotation that was sent to the robot system after the correct identification of the primal cut from the QR code, is detailed in Figure 23. In addition to this, the modules of the gripper to be activated for vacuum suction as well as the current number of primal cuts occupying the carton to be placed into are shown.

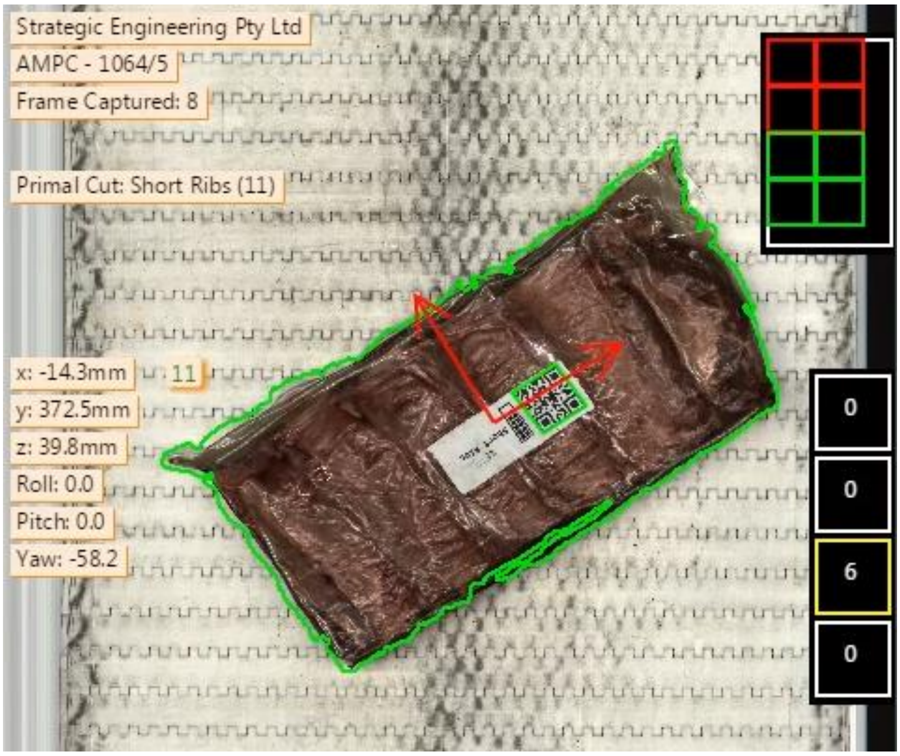

Figure 23: Snapshot of Vision System output detailing pick coordinates and yaw rotation (left), gripper modules to activate (top right), and destination carton and current number of primal cuts in carton (bottom right).

As outlined in Table 2, the primal cuts were classified into groups which represent the selected carton and orientation which they were to be packed into (i.e. similar sized primal cuts are packed with the same packing arrangements). Additionally, each type of primal cut was given a picking style so that it could be efficiently placed into cartons.

Table 2: Primal cut picking and packing styles

Primal Cut	Packing Orientation	Group	Picking Style
Topside	Flat Packed - Shingled	B	Offset – Top and Bottom, Medium speed
Chuck Roll	Flat Packed - Shingled	B	Centre picked, Fast speed
Clod	Flat Packed	A	Centre picked, Slow speed
Bolar Blade	Flat Packed	A	Centre picked, Fast speed
Point End	Flat Packed	A	Centre picked, Fast speed
Striploin	Side Packed - Short	D	Offset – Left Side of gripper, Fast Speed
Rump	Flat Packed - Shingled	B	Offset – Top and Bottom, Medium speed
Knuckle	Flat Packed - Shingled	B	Offset – Top and Bottom, Medium speed
Tenderloin	Flat Packed – Head to Tail	B	Offset – Left and Right, Fast speed
Short Ribs	Side Packed - Tall	C	Offset – Top tip, Fast Speed

As each primal cut required different packing conditions, the picking algorithm calculated different pick positions for the gripper depending on its group, picking style, and the number of primal cuts already inside the carton. This allowed the gripper to pack the carton to full capacity whilst allowing the primal cut to be placed and not dropped. This is illustrated in Figure 24, where a large pick offset was used to allow the tenderloin primal cut to be packed against the left side of the carton.

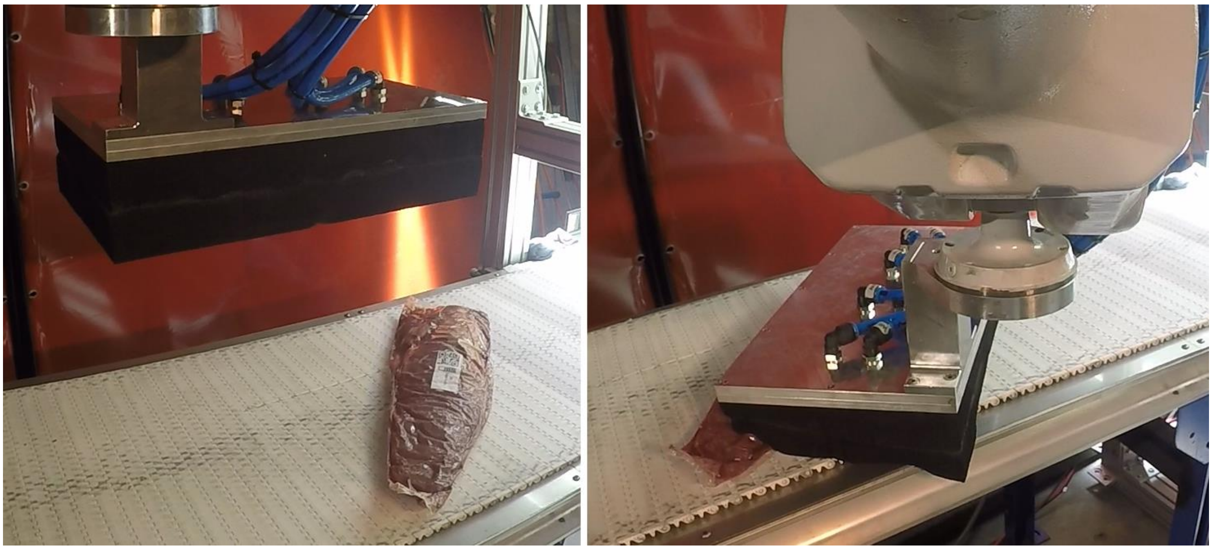

Figure 24: Tenderloin head first and offset on pick up

4.5.2 Packing Algorithms

To replicate packing configurations used in commercial processing plants, flat packing, shingled packing, and two styles of sideways packing were developed. As highlighted in Table 2, large primal cuts (group A) were flat packed in low quantities into cartons, while small primal cuts (group B, C, and D) were either shingled or packed sideways to maximise packing density.

Flat and Shingled Packing

Primal cuts which were flat packed were picked from the centre and placed into the centre of the carton, stacking the cuts until the carton was full. The shingle packed primal cuts (Group B) were packed alternating against either one of the short sides of the carton, with the primal cut edges overlapping (shingled) on one side. Both the flat pack and shingled packing configurations are shown in Figure 25.

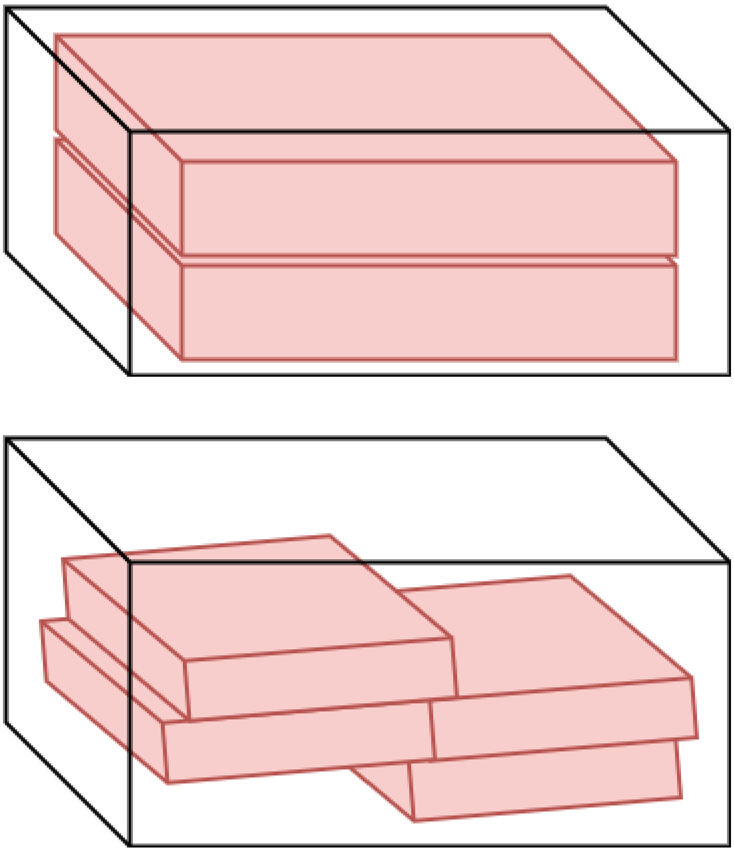

Figure 25: Flat (Top) and shingled (Bottom) packing diagram

Side Packed - Long

Group D primal cuts required packing against the long side of the carton, as shown in Figure 26. A combination of the six-axis potential of the robot and the offset attachment between the roll face of the robot and the gripper as shown in Figure 4, made it possible to orientate the gripper to be able to side pack primal cuts in the carton. In addition, the carton was orientated on a fixed angle with respect to the horizontal as seen in Figure 27. This allowed the robot to place easily into the carton while assisting the primal cuts to stay stacked against the side of the carton once placed. While the gripper was required to be inserted completely inside the carton to pack the primal cuts against one another as seen in Figure 30, due to its thickness, it could not insert the last primal cut in a similar manner. Hence, the gripper would pick the primal cut at an offset and utilise the gap between the last primal cut and the opposite carton side to slide the final primal cut into position as seen in Figure 27.

Figure 26: Side packed (long) diagram

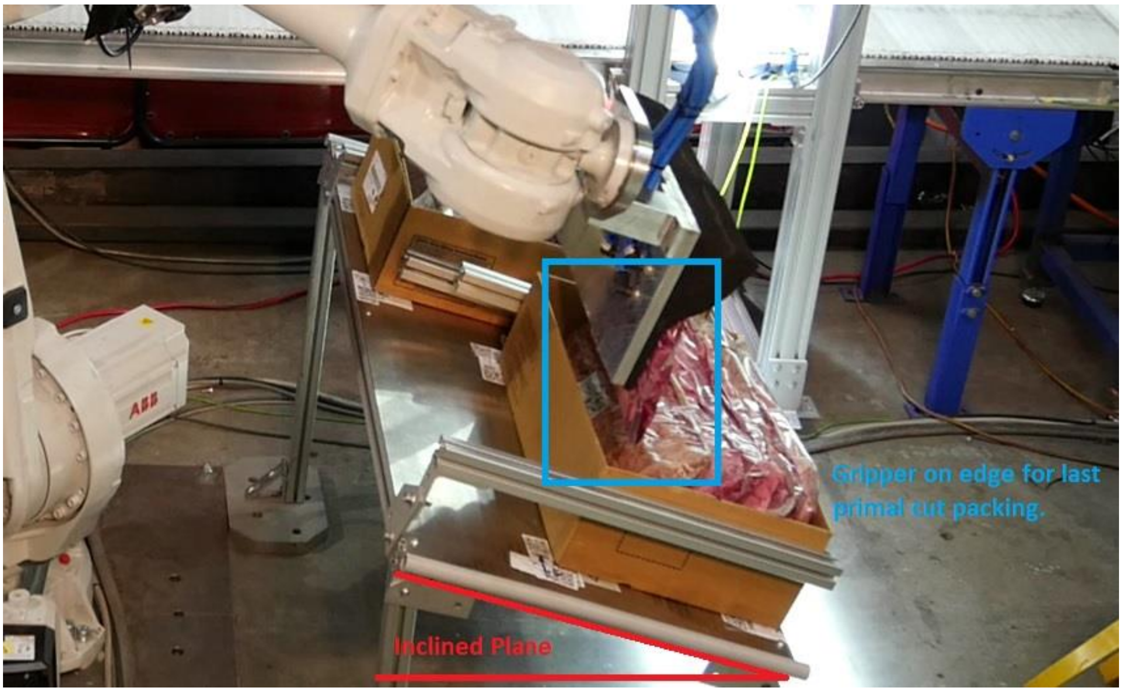

Figure 27: Side packed (long) inclined plane, gripper on edge of cut for last striploin.

Side Packed – Short

Group C primal cuts were packed on their side along the short side of the carton, as shown in Figure 29. To perform this operation, the robot picked the primal cut with the top section of the gripper and rotated the gripper to allow its short side to be positioned inside the carton as seen in Figure 30. Similar to the side-long packing carton, this carton was placed at a 15-degree angle (Figure 28) to assist the primal cuts to stay stacked against the side of the carton once placed. Additionally, a similar slotting method to the side-long packing was used when packing the last two primal cuts into the carton.

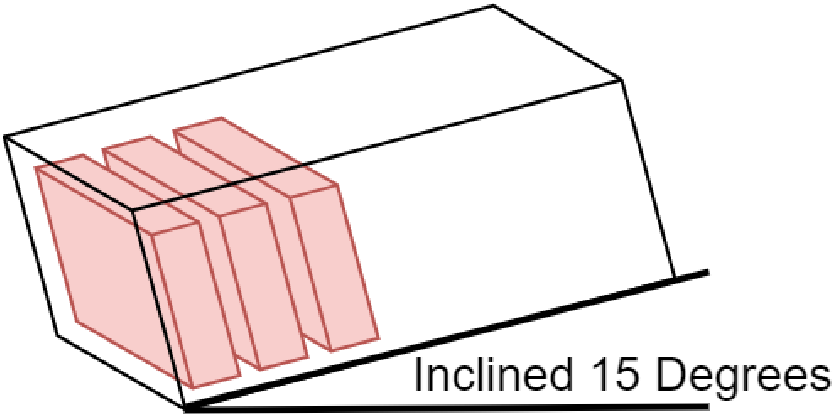

Figure 28: Side packed (short) inclined

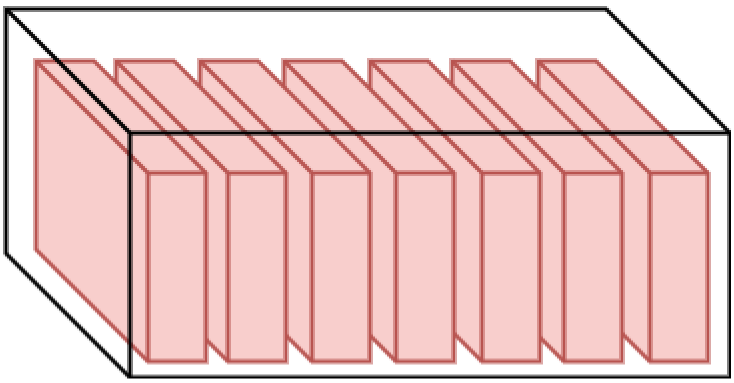

Figure 29: Side packed (short) diagram

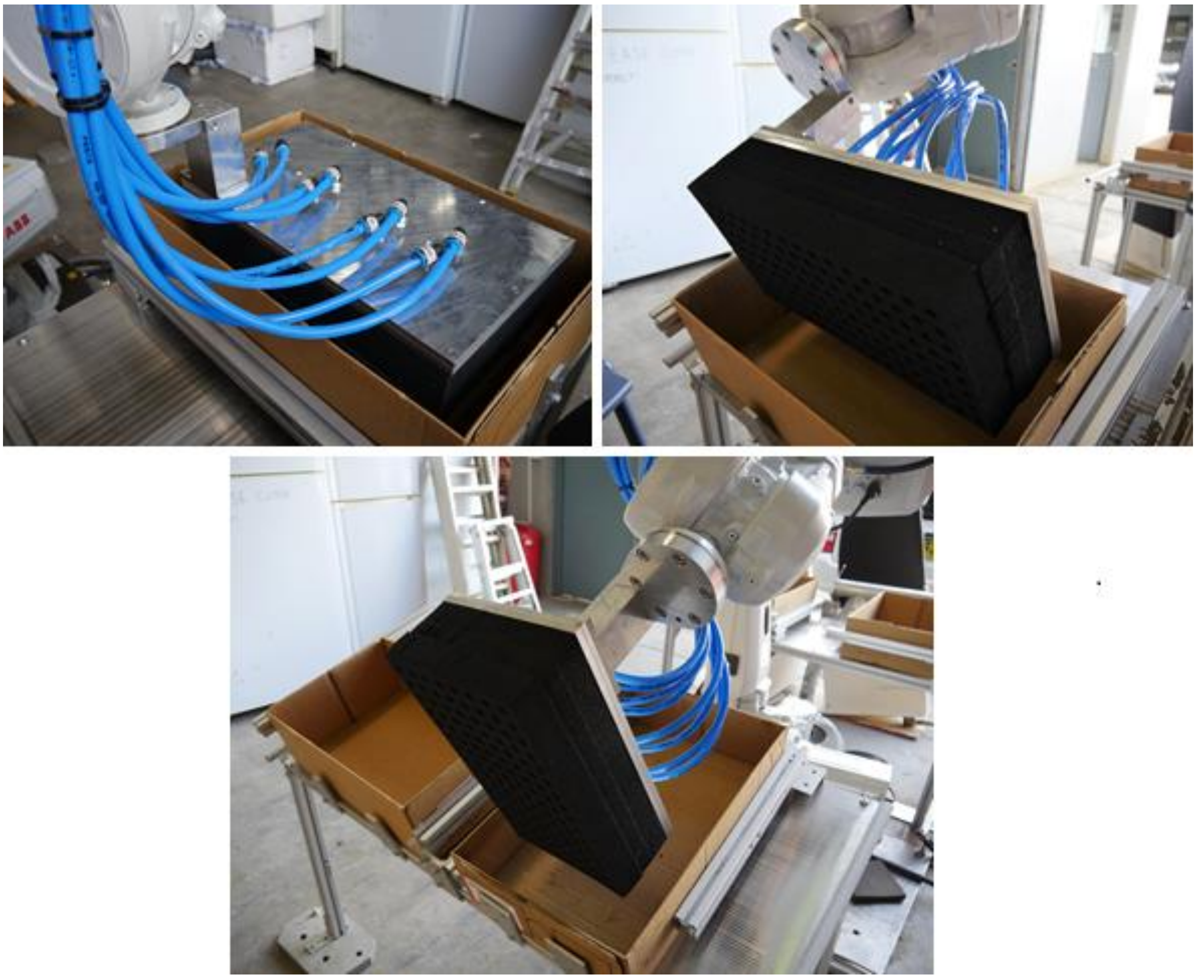

Figure 30: Flat packing arrangement (Top Left) side-long packing (Top Right) side-short packing (Bottom) robot gripper orientations without primal cuts.

4.5.3 Cycle Time Optimisation

In order to increase the throughput potential of the robotic system, a cycle time optimisation strategy was implemented. Since the grip strength of the vacuum pad gripper on each primal cut was highly dependent on its weight and topography, the maximum robot movement velocities and accelerations should reflect this grip strength. A system was implemented which aimed to maximise the movement speed of the robot while maintaining a secure grip between the vacuum pad and the primal cut.

A different program cycle for each of the primal cuts was developed to reflect this change in grip strength across the primal cuts and their respective packing configurations. While the majority of primal cuts were gripped adequately for the nominal robotic cycle time, the robot speed settings for movement of some primal cuts required alteration. The Topside, Knuckle, Rump and Clod were identified as requiring longer vacuum suction times during picking, and slower transportation speeds to minimise inertial effects during transportation.

5.0 PROJECT OUTCOMES

5.1 Packing Trials

Successful in-house trails of the developed pick and pack system were performed. Packing was undertaken on a total of ten different primal cuts in order to rigorously test the limitations of the system. As previously detailed in Table 2, primal cuts were either packed horizontally flat or vertically stacked in order to maximise the number of products per carton, as well as to correctly emulate current in-plant packing configurations. Additionally, all trials were run at high speed to showcase the systems ability to operate near commercial in-plant speed requirements without any major modifications. A total of four cartons were used, two either side of the robot, to highlight the working range of the robot. The two cartons used for the flat packing where horizontal, while the two cartons used for the sideways packing were inclined at a 15-degree angle to assist in the stacking of the packed primal cuts so they would not topple (fall out of position) after being placed in position. During the trials, two different gripper foam thicknesses were used; 70 and 120 mm. The 70 mm foam pad was used for the Bolar Blade, Point End, Tenderloin and Short Ribs, while the 120 mm foam pad was used for the Topside, Chuck Roll, Clod, Striploin, Rump and Knuckle. The thicker foam was used as it could conform to the high surface contouring of these primal cuts more readily.

5.1.1 Flat and Shingled Packing

Flat and shingled packing trails were undertaken on the Topside, Chuck Roll, Clod, Bolar Blade, Point End, Rump, Knuckle and Tenderloin primal cuts. These primal cuts were successfully picked and packed efficiently into their respective cartons. The system was able to account for any primal cut orientation with respect to the conveyor by orientating the gripper during the pick sequence so it would align with the gripper ready to be correctly packed into cartons. Due to the gripper design, placement of the primal cut into the carton was smooth, without any significant delay in the release once the vacuum pressure was removed. Figure 31 highlights the pick, intermediary, and pack position of the robot for the horizontal packing. Additionally, Figure 32 to Figure 39 showcase the packing sequence of the various horizontally packed primal cuts.

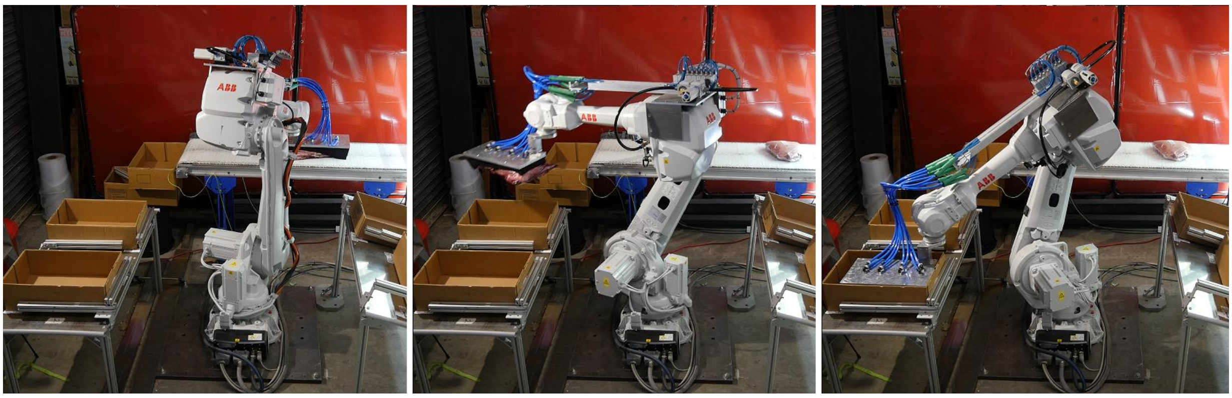

Figure 31: In-house trial system overview highlighting the pick, intermediary, and pack positions for flat and shingled packing.

Figure 32: Shingled packing of Topside

Figure 33: Shingled packing of Chuck Roll

Figure 34: Flat packing of Clod

Figure 35: Flat packing of Bolar Blade

Figure 36: Flat packing of Point End

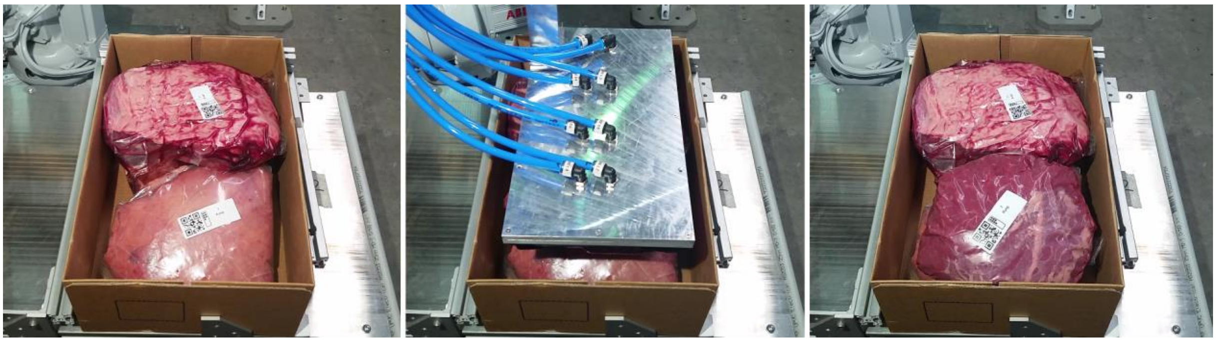

Figure 37: Shingled packing of Rump

Figure 38: Shingled packing of Knuckle

Figure 39: Shingled packing of Tenderloin

5.1.2 Sideways Packing

Sideways packing trials were undertaken on both the Short Ribs and Striploin primal cuts. These primal cuts were successfully picked and packed efficiently into their respective cartons. Figure 40 highlights the pick, intermediary, and pack position of the robot for sideways packing.

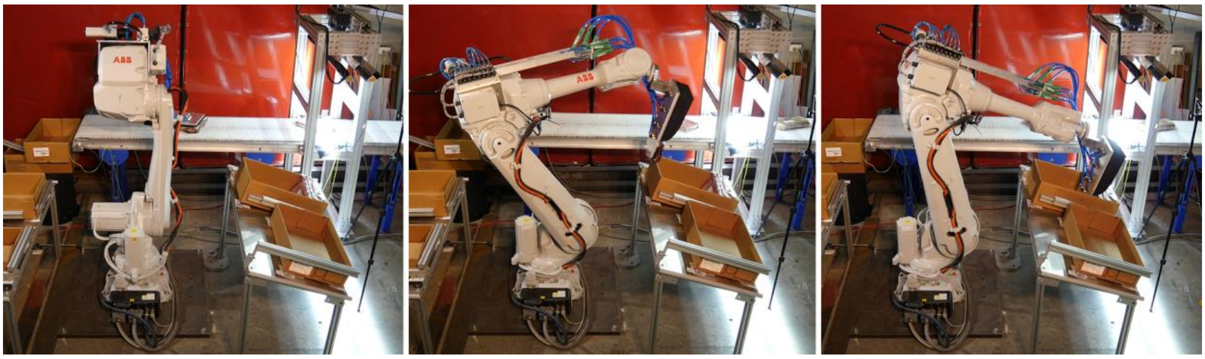

Figure 40: In-house trial system overview highlighting the pick, intermediary, and pack positions for sideways packing.

Figure 41 and Figure 42 showcase the packing sequence of the sideways packed primal cuts. It can be seen in the second last image of each figure, that the primal cut is gripped significantly offset to centroid of the vacuum pad gripper. This enabled the primal cut to slot into the final pack position of the carton, allowing the carton to be packed to its maximum capacity without the potential for damage to the primal cut or the carton.

Figure 41: Side-long packing of Striploin

Figure 42: Side-short packing of Short Ribs

5.2 Cycle Time Analysis

Following the successful full speed pick and packing trials, subsequent cycle time analysis was performed on all ten primal cuts in order to determine the average time for a round trip pick and pack cycle. The obtained average cycle times are shown below in Table 3, with an average calculated cycle time of 7.157 seconds for all the primal cuts.

Table 3: Average cycle time for picking and packing of the primal cuts

Primal Cut Type	Average Cycle Time (s)	Top Surface Area Density (kg/m^2)
Topside	7.637	68.6
Chuck Roll	7.010	56.9
Clod	7.536	46.6
Bolar Blade	6.441	66.7
Point End	6.578	40.0
Striploin	7.332	41.9
Rump	7.746	62.5
Knuckle	7.483	75.7
Tenderloin	6.972	28.7
Short Ribs	6.833	35.4

From these results, it was determined that the chosen packing configuration (whether flat, shingled, sideways long, or sideways short) had a minimal influence on the cycle time. As discussed in Section 4.5.3, the factor which most significantly influenced the cycle time was the topography of the primal cut. It was identified that the roundness of the topside, knuckle and rump reduced the effective vacuum contact area between the primal cut and the foam pad, resulting in a higher potential for 'peeling' of the primal cut off the pad to occur. These primal cuts, especially the knuckle, had large area densities, also shown in Table 3. Additionally, the clod, being the heaviest primal cut in our sample, required a longer suction time and slower travel speed so it would not jerk off the gripper. The striploin and short ribs maintained a strong vacuum grip with the foam pad gripper, regardless of their orientation, allowing them to be rotated and packed sideways at full speed without falling.

Despite the differences in the grip strength between the different primal cuts, a difference of only 1.305 seconds between the fastest and slowest average cycle time of the primal cuts was observed during the trails.

6.0 DISCUSSION

6.1 Primal Cut and Gripper Selection Suitability

The subset of ten primal cuts selected for this project reflects the range of weights, sizes, and shapes of all beef primal cuts. Additionally, the different packing configurations required by the selected primal cuts highlight the adaptability of the developed system to pick and pack primal cuts in virtually any desired configuration. Within the range of primal cuts, the knuckle was identified as the most difficult to successfully pick and pack due to its large top surface area density, and lack of internal structural rigidity caused by the absence of any bone or major fat sections. From this, it was determined that the grip strength of the gripper was not directly related to the overall weight of the primal cut but by the surface area in contact with the gripper and hence its area density.

The gripper developed for this project maintained vacuum bag integrity by evenly distributing gripping stresses along the entire contact surface area of the primal cut. This alleviated product handling issues such as puckering and bag stretching, which has been observed with other mechanical or vacuum grippers such as developed in AMPC 2014-1010 “Pick and Pack - End Effector Gripper Development”. Additionally, the same gripper design was able to handle all the trialled primal cuts, regardless of weight or size, due to its modular design. The gripper was able to maintain an adequate vacuum by automatically closing off the ports which were not in contact with the primal cut. It was observed that the foam used was able to provide a better vacuum seal with the primal cut, as the top surface contours of the primal cut were able to be matched by the foam. However, it was observed that ‘ridging’ occurs due to vacuum on the plastic while the primal cut is held which settles naturally on placement after a few seconds. The ‘ridging’ does not seem to affect the condition of the plastic during or after picking and packing.

6.2 Vision System and Tool Path Algorithms

The vision system was able to provide high resolution images and height maps. This allowed for the proper identification of the primal cut dimensions required for picking and packing the cuts into cartons efficiently. As the vision system relied mostly on the software implementation for packing, parameters could easily be altered to suit the needs of a commercial plant. It was observed that the vision system was able to handle the conveyor speed easily with no issues and without falling behind in processing. The system could also handle backlogs of primal cuts on the conveyor and drop primal cuts from the robot picking queue. Dropping primal cuts from the queue is required when there is no available box for primal cut type or no label on the primal cut.

The tool path was generated from the primal cut pick point to one of the four cartons. As both the flat and side packing orientations are utilised, the robot calculated the intermediary points and rotations for the tooling required to approach the carton avoiding collision with the conveyor and any other obstacle, and then placed the primal cut in the next empty carton position. This position was dynamic and changed depending on the number of primal cuts already in the carton. To return to the idle position above the conveyor for the next primal cut, the robot moves execute in reverse from the packing carton location.

6.3 Optimisation Strategies

While this project has supported the ability for a robotic system to efficiently pick and pack individual primal cuts of meat into cartons, potential modifications which could optimise the system include improving the cycle time and improving the packing density.

In order to improve the cycle time of the system several strategies could be implemented:

- The physical layout of the robot and cartons with respect to the conveyor could be optimised in order to reduce the total travel distance of the robot from the pick to the pack position. During the trials, the robot needed to rotate approximately 90 degrees about its first axis to move from the pick to the pack position. By aligning the conveyor directly next to the cartons, the movement space of the robot would be significantly reduced. Additionally, if the robot were to be mounted overhead this travel distance would be further reduced.
- Further development of the cycle time optimisation system for each individual type of primal cut. Movement speeds for the lower density primal cuts such as short ribs, tenderloin and striploin could be significantly increased. Maximum speeds for the other primal cuts could be refined if given a larger sample size to trial.
- Reducing the foam thickness for use with thinner and flatter primal cuts would reduce the time required to obtain a vacuum as the gripper is pressed onto the primal cut when it is on the conveyor.

6.4 Efficacy and Suitability for Plant Implementation

The results demonstrated in this project have significantly reduced the risks associated with a future implementation of a similar pick and pack system into a commercial plant. It was observed during the in-house trails that the test primal cuts would soften as their internal temperature raised to room temperature. In turn, this reduced the rigidity of the primal cuts, increasing the gripping difficultly by the vacuum gripper. Despite this, the robotic system successfully picked and packed the primal cuts. Hence, in a commercial plant operating at refrigerated temperatures, the increased rigidity of the primal cuts should allow the robotic pick and pack process to operate at higher speeds due to an improved grip between the primal cut and the vacuum pad gripper.

In a commercial plant, there is the potential for multiple robots to be placed within a robotic cell to completely automate the pick and pack process of primal cuts when combined with an appropriate computer vision system as developed in this project. As the range of primal cuts selected for this project was a good representation of the range of primal cuts, it is envisioned that a wider selection of primal cuts would be able to be handled by the developed system without major design modifications. However, additional system tests on such primal cuts should be performed if they are required to be handled as part of a commercial plant implementation.

An additional consideration for future plant implementation may involve the integration of an upstream/downstream tracking system. This would allow the system to track which primal cuts have been packed into their respective cartons.

7.0 CONCLUSIONS/RECOMMENDATIONS

Through the development of this project, a subset of ten primal cuts was successfully identified to be suitable for demonstrating the feasibility of a completely integrated robotic pick and pack system. While a range of End of Arm Tooling gripping mechanisms was evaluated, a foam pad vacuum gripper developed and supplied by Strategic Engineering was utilised for performing the pick and pack functionality of individual vacuum sealed primal cuts into their respective cartons.

For all ten primal cut types, the developed system has demonstrated the ability to:

- Identify the type, mass, and volumetric signature of an individual primal cut moving along a conveyor, and determine which carton it should be packed into.
- Determine an optimal pack position, and hence determine an ideal pick position for the gripper given the existing packing configuration of the destination carton.
- Pick up and transport the primal cut at high speeds to the desired packing position.
- Accurately position, place and pack the primal cuts into cartons, regardless of the gripper angle required for packing.
- Maintain vacuum bag integrity over repeated pick and pack operations.
- Handle the wide range of sizes, shapes, mass, as well as significant surface contouring of the primal cuts without further modifications to the vacuum foam pad gripper.

Immediate future work in the system can be made to the following:

- Expand the list of primal cuts the system is able to pick and pack into cartons.
- Integration into up/downstream systems for tracking inventory as it moves through the plant.
- Shorten the cycle time of the picking and packing by improving the placement of the loading carton to shorten the distance the robot needs to move from the conveyor to pack a primal cut.

7.1 Suggested Next Step Points of Action

- In-plant trails of robotic picking and packing system in order to further develop the system's potential for commercial implementation.
- Expansion of robotic picking and packing system using the results obtained through this research project to handle a greater range of primal cuts.
- Automated method for bagging primal cuts.

8.0 APPENDICES

8.1 Hardware Components

Table 4: Off the shelf computer components for vision system

Image	Component Name	Part
	Intel Core i7 6900k	CPU
	MSI X99A Gaming Pro Carbon RGB Motherboard	Mainboard
	NVIDIA TITAN Xp 12GB	GPU
	Corsair Vengeance LPX CMK16GX4M2B3200C16 16	RAM
	Samsung 850 EVO 1TB SSD	Disk Storage
	Corsair HX1200i 1200W 80 Plus Platinum Power Supply	Power Supply

	Noctua NH-D15 CPU Cooler	CPU Cooler
	Corsair Carbide 270R ATX Mid-Tower Case	PC Enclosure
	BitFlow Dual Camera Frame Grabber; AXN-PC2-CL-2xE	Expansion Card
	Digilent Analog Discovery, Multi-functional Analog and Digital Instrument	USB Device

Table 5: Sensory and transportation hardware for the conveyor system

Image	Component Name	Part
	Bongshin DBBP series S Type Load Cell 50kg	Load Cell
	SICK Incremental Encoder DFS60 10,000 PPR	Encoder
	SICK Photoelectric Sensor W12G	Sensor
	UNI S-MPB PP Modular White Belting	Conveyor Belt
	SEW WA37/T 0.37kW Spiroplan Gearmotor	Gearmotor