Final Report

AUSTRALIAN MEAT PROCESSOR CORPORATION

Collaborative Robots Evaluation – Stage 2

Project Code
2021-1218

Prepared by
Jonathan Cook, Todd Enfield, Oscar Aspite

Date Submitted
28/09/2022

Published by
AMPC

Date Published
28/09/2022

1 Contents

1.0 Executive Summary

This project focused on commencing the understanding of how current, and pending, collaborative robots may be deployed within the Australian red meat processing sector. Initially AMPC would like to understand where they can be deployed today. AMPC will also like to understand where they might also be deployed in the future and what additional developments are required of either the collaborative robot platform, end effectors, sensing/visioning, guarding and or changes to current meat processing practices are required to realise future opportunities identified.

The objectives of this project are to ascertain:

(1) An understanding of where collaborative robots could be deployed today within a meat processing business.

(2) An understanding of where collaborative robots may be utilised in the future in the industry, and what is preventing this from occurring today. Outcomes from this step will feed into future development.

Initially the use-case of Whole of Pallet barcode scanning was selected for demonstration due to its ideal nature for a collaborative robot task. The application itself was also thought to possess a number of significant future value-add opportunities for future development. The initial trials performed demonstrated that a collaborative robot could feasibly be used in a system to scan the barcodes on a pallet. The robot was able to accurately drive a camera to various positions, dictated by a dynamic set of vision results, to allow the barcodes to be read on a pallet of cartons. As this is a non-contact task using a safe end effector (i.e. a camera), it would be suitable for guardless operation adjacent to human operators. The next steps for such a system would be to develop a prototype which is tested on-site. Unfortunately, there was not significant market interest in this system at the time of performing this project. If this situation changes in the future and the business case for such a solution evolves, then it would be technically feasible and suited to a collaborative robot.

Following this industry feedback, the project was pivoted to investigate alternative applications: the marking of rib scribe lines on a carcase, the painting of rib scribe lines on carcase, and vacuum-packed primal pick and pack. Initial trials were performed at Intelligent Robotics's facility for each of these applications to demonstrate their feasibility and confirm the design of the trials. These trials demonstrated that the collaborative robot was able to perform all of these tasks without presenting any issues (there were particular concerns about the ability to deal with the external forces required for marking and painting). The results of these initial trials were presented to AMPC and a processor, and a site visit was organised to perform trials on the scribe marking and the pick and pack. There were concerns over the impact to product presentation in performing painting trials, but it was agreed that the learnings from the marking trials could be applied to this application.

For scribe line marking site trials, the collaborative robot was able to successfully score markings on the carcase without any issues (e.g. tripping out). There were however concerns around the safety of the marking operation, and whether it would still require guarding. Painting of the scribe lines would address this to some extent, but the ideal technology would be to utilise a printhead. A development roadmap was presented on the next steps for collaborative scribe line marking.

For vacuum-packed primal pick and pack, the collaborative robot was able to successfully pick and pack a carton of beef eye round primals. There were a number of other primals and packing patterns which were able to be successfully trialled and demonstrated. Collision tests with the robot were also performed successfully to confirm the safety of the collaborative robot performing this task without needing guarding. The collaborative robot appears to be a good enabler for automation of this task in the red meat industry. A development roadmap, including proposed minimum viable product specification, was presented to outline next steps for the technology in this area.

2.0 Introduction

AMPC (and the industry) have an innovation vision, and support R&D program, to eliminate all WHS incidents from processing operations. Where possible dangerous tasks will be fully automated. Where automation is not currently viable (either due to technology limitations or ROI), semi-automated/remote solutions will be developed that will remove the operator from dangerous tools and implements. Where semi-automated solutions are not viable then the remaining hands-on tools will be made as safe as possible (i.e. BladeStop and Guardian).

This Project

This project focuses on commencing the understanding of how current, and pending, collaborative robots may be deployed within the Australian red meat processing sector. Initially AMPC would like to understand where they can be deployed today. AMPC will also like to understand where they might also be deployed in the future and what additional developments are required of either the collaborative robot platform, end effectors, sensing/visioning, guarding and or changes to current meat processing practices are required to realise future opportunities identified.

An Innovation Theme on a Page (ToaP) has been developed for this program of work (depicted within the Project Description) and shows both the proposed development stages of the area as well as implementing an innovation competition where more than one provider may be supported in the early stages to evaluate different approaches to the primary goal of automating beef HQ butt deboning.

Note: It is anticipated that by the time that Stage 3 is being supported the number of providers being supported will have significantly reduced, and eventually probably only one selected for Stage 4 developments onwards.

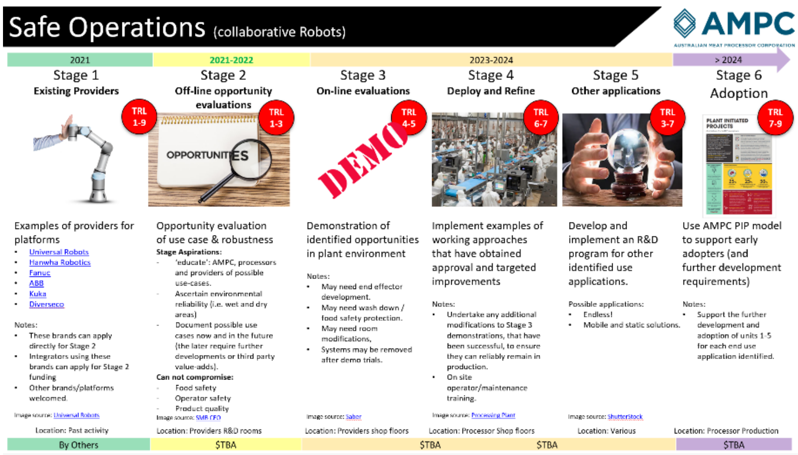
Primary Goal

Reduce the human operator risks and effort in material handling and meat processing activities.

Secondary Goal(s)

Additional goals include: (1) improving yield, if possible, (2) developing opportunities for the number of engineering and technical staff to join the industry, (3) increasing food safety, and resulting shelf life product extensions, (4) extending the working life of staff, (5) applications outside of the meat processing chain / logistics, such as in maintenance, rendering, laboratories, office, etc, and (6) changing the image perception of the industry from a pure manual sector to a high-tech sector that has a strategic blend of equipment and human operational staff intertwined in daily processing operations.

This project is focused on Stage 2 development scope only (refer ToaP).



3.0 Project Objectives

Collaborative robots have been in their current commercial form for many years now. Although they are finding great applications in the research and commercial world, AMPC are not seeing their potential being either demonstrated or realised within the Australian red meat processing sector. Why is this?

The Australian Meat Processor Corporation (AMPCs) current Strategic Plan 2020-2025 has the following seven sub-strategic components which we believe Collaborative Robots / Cobots should be able to make an impact on now:

Advanced Manufacturing sub-strategy

- Removing staff from dangerous operations, via Hands-Off processing (not this does not necessarily mean full automation, and why collaborative robots is an interesting proposition platform for the industry to consider).
- Carcase Primal Profitability Optimisation, via increased accurate processing.
- Digitisation, via acquiring product information and leveraging data insights.

People and Culture sub-strategy

- Safety and Wellbeing, via reducing the high-risk nature of some processing operations.
- Attraction, via demonstration and developing a wide range of operations.
- Retention, via improving working conditions and making tasks exciting.
- Development, via developing tasks that require higher skills and intellect – operational & technical.

The objectives of this project are to ascertain:

(1) An understanding as to where collaborative robots could be deployed today within a meat processing business.

(2) An understanding as to where collaborative robots may be utilised in the future in the industry, and what is preventing this from occurring today. For example payload, washdown, speed, end-effectors, guarding, process changes. Outcomes from this step will feed into Stage 5.

To engage with possible meat processing customers who, by seeing the potential of the deployment of collaborative robots, engage with AMPC and providers/integrators to then deploy demonstration solutions at a range of Australian red meat processing facilities against the range of identified ‘today’ opportunities.

The output of the project will be a report that demonstrates the following understanding by the provider when applied to the Australian red meat processing sector:

(1) An understanding as to where collaborative robots could be deployed today within a meat processing business.

(2) Demonstration of 1-2 possible use cases

(3) An understanding as to where collaborative robots may be utilised in the future in the industry, and what is preventing this from occurring today. For example payload, washdown, speed, end-effectors, guarding, process changes. Outcomes from this step will feed into Stage 5.

(4) Engagement with possible meat processing customers who by seeing the potential of the deployment of collaborative robots engage with AMPC and providers/integrators to then deploy demonstration solutions at a range of Australian red meat processing facilities against the range of identified 'today' opportunities.

(5) Development and submission of Stage 3 deployment projects for funding consideration by AMPC.

3.1 Project Methodology

The project methodology is as follows:

1) Purchase a collaborative robot for the purposes of demonstration
2) Undertake opportunity analysis with AMPC on a number of potential red meat use-cases for collaborative robots and select 1-2 for demonstration
3) Perform a demonstration of the use-case(s) to AMPC
4) Present development pathway to AMPC for next steps

4.0 Methodology and Discussion

4.1 Initial Exploration of Use Cases – Whole of Pallet Barcode Scanning

A number of potential use-cases were explored and considered, with the use case of whole of pallet barcode scanning being selected as the target application for this project. In this case, the collaborative robot would be on a stand or trolley and can be positioned in front of a pallet.

- The pallet could either be positioned in front of the system in a variety of arrangements
- Once in position, the UR would perform a routine to identify the barcodes
- Once the pallet is completed, a list of all the cartons will be displayed
    - This could also be cross-referenced to a sales order or manifest

This application was found to hold a number of significant benefits:

- It operates in a completely non-washdown area
- It can replace a labour unit performing this task
- The robot will perform the task more reliably and can interface directly with the customer's data systems in real-time if needed in the future, including potentially export portals such as the Meat Messaging Portal
- The end effector on the robot (a camera and lighting) will be safe for a collaborative environment
- The system can be portable and setup easily on plants for demonstrations, or able to be shifted to different areas where suitable
- There are a significant number of potential value-add opportunities in the future

These value-add opportunities allow the system to create significant value for processors above simple labour replacement.

It was proposed the following methodology occur for the remainder of the project:

- Site(s) engaged for feedback on the concept and for consulting on design / features

- A trial rig setup in the office/factory including:
    - A UR10e robot
    - Camera with lighting attached to the rollface
    - Cartons with barcodes set up in various stack patterns in front of the robot
- The robot would then perform cycles where it:
    - Identifies the cartons on the stack and required motion path
    - Performs scanning routine of all barcodes
    - Lists barcodes that were scanned
    - A development pathway would then be drafted for “Stage 3”. This may include a production prototype would being designed and manufactured and trialled on-site.

After approval from AMPC, a UR10e robot was then procured for use on the project.

4.2 Whole of Pallet Barcode Scanning Concept Development

4.2.1 Barcode Specifications

In order to ensure that the barcodes used for the trials are within industry standards, research was conducted into the barcode requirements of the red meat industry. An industry body, the RMSCC (Red Meat Supply Chain Committee) was found to have specifications for export barcodes.

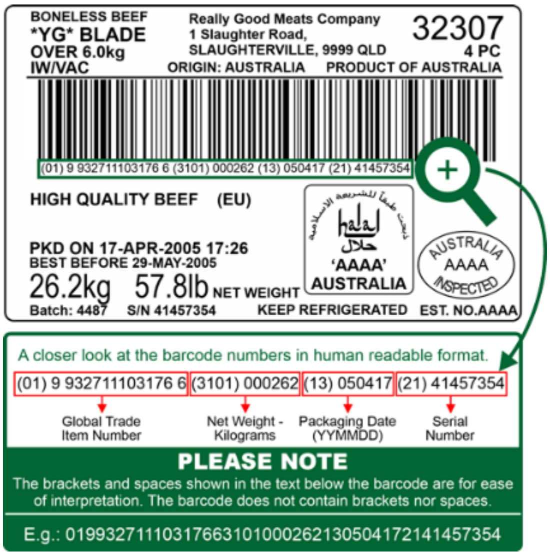


Figure 1- Minimum Barcode Information Required (Committee, 2021)

Further, the barcode size minimum requirements were also published by the RMSCC. The specifications are:

- Barcode Width: The resolution (allowable width) of each character is 0.25 – 1.02 mm (Committee, 2021)
- Barcode Height: The minimum barcode height in the meat industry is 13mm. (Committee, 2021)

As a result, the barcodes created for the trials were to follow these specifications.

4.2.2 System Development

Once the collaborative robot (Universal Robots UR10e) was received, it was installed on a stand, and the network cameras were installed onto the robot rollface, and on the stand next to the robot. This is the first camera that was to be tested for use within the system.

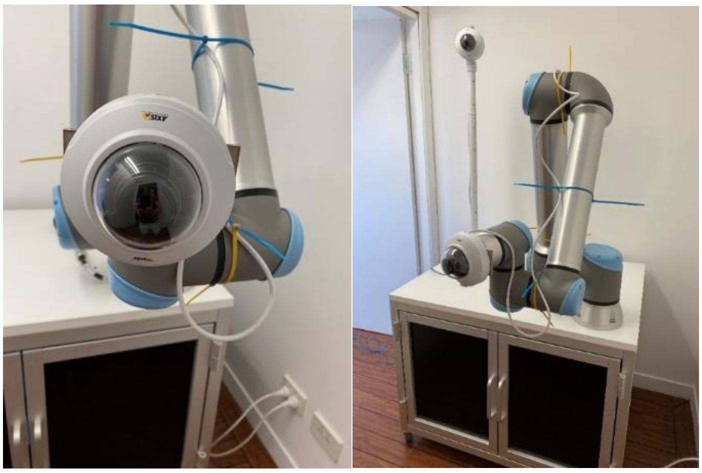


Figure 2- System Installation

A wall of cartons was also built to allow for a simulation of one side of the pallet.

Figure 3- Cartons for Pallet Emulation

Once the system was installed and setup, the development began. This involved developing:

1) The vision program
2) The robot communications program
3) The robot program

These were each developed to allow the automated barcode scanning system.

Program Overview and Interaction

For the development of this system, three main software modules had to be written, and had to interact with one another. These comprised of the vision application, the .NET container (containing calls to the vision algorithms, the GUI and communications to the robot), and the robot application. Prior to the writing of any code, the software sequence was developed following the performance of research around how to develop such an application on a Universal Robot.

Robot Communications

One of the major components of the software, both on the robot and the vision application, is the communications. It is integral as the robot must communicate to the vision application to dictate when to take images and what vision algorithms to perform.

A server application was written in C# in order to facilitate the communication between the robot and the vision application, using a TCP/IP communications structure and a server/client architecture. This architecture was used based on functions built into the Universal Robots scripting API that allows communications to a server through some easy-to-use functions.

Vision Program

The vision program was the next major component of the developing system. The algorithms were developed and implemented to identify and communicate barcode results.

Robot Program

The robot program flow was mapped and programming was structured to convert vision results into robot paths.

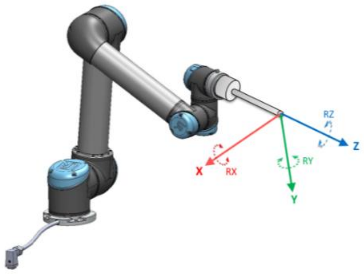


Figure 4- Robot Tool Coordinate Frame

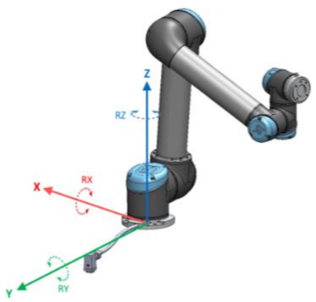


Figure 5- Robot Base Coordinate Frame

As a result, the coordinates of the barcode locations were found in the tool coordinate frame, and transformed accordingly so that URScript command movel() could be used to allow the robot to perform the required linear moves.

4.2.3 Trials with 3MP Network Camera

Trials were first carried out with the Axis M4206-V Network camera.

Figure 6- M4206-V Network Camera

This camera was chosen to start with to determine the applicability of lower resolution cameras for this barcode scanning application. Using this camera, the barcode locations were successfully found with the Barcode detection algorithm, and then the barcodes locations were travelled to by the robot, based on the robot program. This algorithm worked for a range of barcode sizes, from the minimum size required by the industry standard, up to this larger size for testing purposes.

The larger sized barcodes were 90mm long, compared to the 70mm barcodes required by the minimum specifications. This was due to the inability of the Axis camera to consistently detect and read the barcodes, even when the camera was only a short distance (around 100mm) from the barcode. The majority of the barcodes were detected on a run of the robot, but the barcodes detected changed on each robot cycle, and each image had to be taken when the robot was stationary. This points to the fact that the camera does not have the resolution required for this application, as these barcodes are significantly bigger than the required sizes by the Meat Industry. In addition, the fisheye lens adds distortion that is not favourable in barcode reading applications. It was noticed, even with image rectification, that the barcode had to be quite centred to allow for the barcode to be detected.

In addition to the issues with resolution, the camera is not fit for purpose for this circumstance. The camera is generally built to be on a stationary surface, meaning that the lens position is prone to movement if the jerk is too much, which further reduces the applicability of such a camera. This mean the image would “wobble” a little if the robot was moving quickly, which increased cycle time significantly.

As a result of the trials, it was determined that the Axis camera was not able to be used in this application, and a machine vision camera would be utilised instead.

4.3 AMPC Demonstration and Pivot in Direction

At this point in the development, Intelligent Robotics provided a demonstration to AMPC to show the intent of the development, including additional work to be performed in optimising the camera selection. This included showing the user interface coupled with the robotic assembly. The overall concept was viewed positively and, as a next step, Intelligent Robotics and AMPC conducted a number of site visits to find a partner to assist with the trialling of the concept and to get input into the concept design. While there was some interest shown in the concept during these visits, the general feedback was that there were higher impact areas that existed within the industry.

A review was performed between AMPC, IR, and a processor, to brainstorm some other use cases which may be of greater interest to industry. The outcome of this meeting was that the Whole of Pallet Barcode Scanning application should be placed on pause, and the following use-cases should be trialled:

- Marking of rib scribe lines using a marking tool
  a. Some processors use hand tools to mark the rib scribing lines on the carcase. A saw operator downstream is then meant to cut where these marks are placed. By following the marked lines, the saw operator is able to ensure parallel cuts to the correct width. In actuality, the saw operators often disregard the markings on the carcase completely.
  b. A small system with a collaborative robot performing this task could enable potentially significant yield benefits relative to the cost of the system, and the footprint required.
  c. There are uncertainties though about how well the collaborative robot will be able to mark the carcase before tripping out. Collaborative robots by their nature can undergo a protective when exposed to significant external forces.
- Painting of rib scribe lines using food grade ink
  a. Similar to the first application but placing the rib cutting guide lines using pens with food grade ink.
  b. While this application should require less force, the ability for the collaborative robot to exert sufficient force without tripping out must still be examined.
  c. Furthermore, how well the markers mark the carcase, and factors such as how often the markers need to be 'primed' need to be explored.
- Picking and packing of primal into cartons
  a. One area which is seen as a significant opportunity for collaborative robots in the meat industry is picking and packing of primals.
  b. An appropriate gripper will be designed and sourced to demonstrate the ability of the collaborative robot to perform this task in a meat industry context, keeping in mind that extensive gripper selection and evaluation lies outside the scope of this particular project.
  c. For the purpose of these trials one primal (beef eye rounds) will be targeted to demonstrate the use case.

4.4 Scribe Marking Trials with Marking Tool and Pens

4.4.1 Carcase Specifications

In order to design an appropriate end effector for the robot to perform the marking of scribe lines, the potential size variations in carcases needed to be considered. Specifically, the rib cage's depth must be taken into consideration as this will affect the robot's angles of approach and the tool design.

Furthermore, the scribing tools used to place the guide lines exist at different set widths which needs to be accounted for.

4.4.2 Program Overview and Integration

To build and develop the system programming, one main software module and one sub-module needed to be written and created. This contained the main programming functions (e.g. motion commands) and the sub-program running the force component of the force control for the robot.

4.4.3 Pre-Site Trial Design

The trials were carried out using a custom-made scribe bracket. The bracket was designed sturdy enough to deal with the external forces encountered in the application. It was also designed to enable the marking tools or pens to be mounted at the different required widths. It was noted that the spine-side rib scribes often run very close to the spine. For this reason, the bracket was designed to hold one marking tool/pen in a constant position, close to the edge of the bracket, while the mounting point for the second marking tool/pen could be placed at varying widths. The fixed position would always be used for the scribe line closest to the spine. The marking tools were also designed and manufactured.

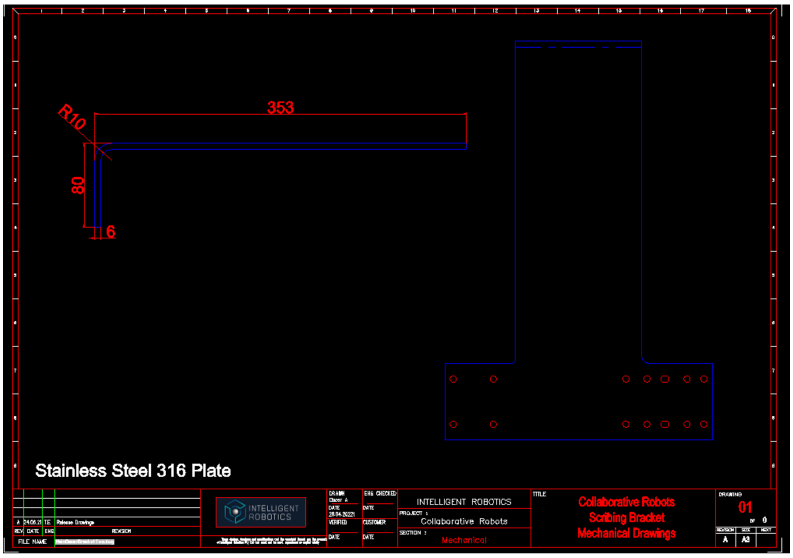


Figure 7 - Scribe Marking Tool and Pen Mounting Plate

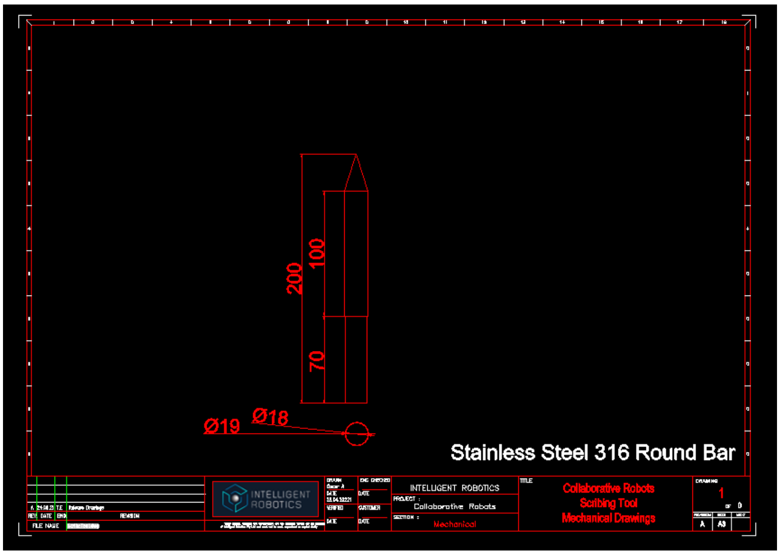


Figure 8 - Scribe Marking Tool

Figure 9 - Pump Markers for Food Grade Ink

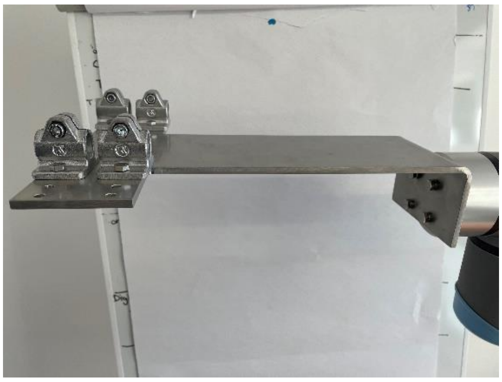


Figure 10 - Mounting plate attached to UR

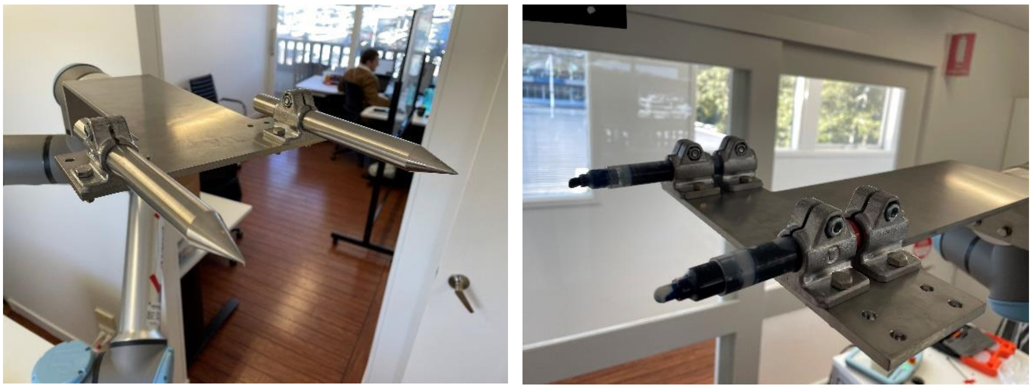


Figure 11 - Marking tools (left) and pens (right) mounted to the plate

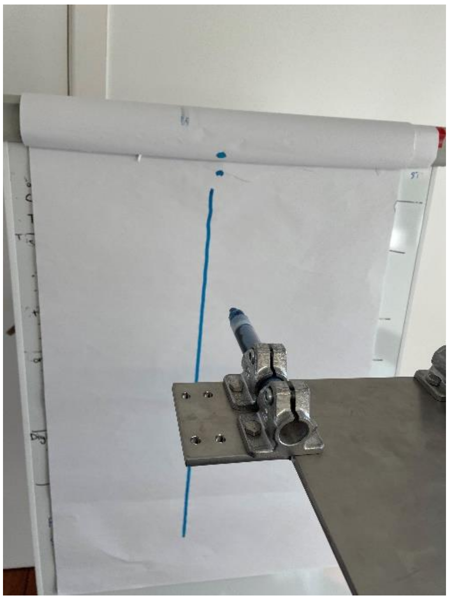
4.4.4 Scribe Tool and Pen Trial Results

Dry Tests:

Once the tools were mounted to the robot, the robot program was first run at varying speeds to make sure the weight of the end effector, particularly given its length, weren't an issue for the robot. The robot was able to run smoothly and without any issues, even up to speeds of 500mm/s.

White-board Trials:

The next set of trials involved using the pen markers to draw lines on a whiteboard. This would investigate the ability of the robot to cope with interacting with an external object to place marks without tripping out. The robot was able to perform this task successfully – drawing lines with the pen without any issues.



It is known that the surface of a beef rib cage is undulating in nature and is not perfectly flat or smooth. This trial was then modified to include rolled up sections of paper to simulate an exaggerated rib cage contour. A sheet of paper was placed over the top of the rolled paper sections.

Once again, the robot did not have any issues navigating the raised sections. However, this gave an opportunity to test an alternative method of path programming in the robot. After experimenting with this concept, it was felt that this would give better results for this application and the robot programming was modified fully.

Short Rib Trials – Marking Trials:

After the aforementioned trials were completed successfully, beef short ribs were procured and secured to the backing board. The marking tools were installed on the mounting plate and a number of trials were performed using the marking tool to mark scribe lines across the ribs.

Figure 12 - Setup for short rib marking trials

A number of key learnings were obtained from these trials:

- The UR robot was able to mark scribe guide lines across the ribs without tripping out, further reinforcing that this is a viable application for a collaborative robot
- Paths containing a varying number of points were trialled, together with varying degrees of force compliance.
- It can get quite challenging to get marks on all ribs. It should be noted however that the current manual process also doesn't achieve this, and it may be unnecessary as long as the scriber can sufficiently tell where the scribe lines need to be placed.

Overall, the trials were successful in demonstrating the feasibility of using a collaborative robot for marking the scribe lines on a beef rib cage.

Figure 13 - The result of varying scribe marking trials

Short Rib Trials – Ink Trials:

The scribe marking tools were then replaced with the food grade ink pens and the trials were repeated. Similar learnings were experienced with the key difference being there was no risk of damage to the project with varying force control parameters. Instead, the ink lines would become more pronounced in sections where the force was excessive. This did however risk damage to the pen nibs themselves. The force needed for the pens is less than half that needed for the marking tools. This makes sense given that the pen is drawing whereas the marking tool must score the fat and surface of the bone to leave a visible enough line.

Again, the trials were successful and showed it is feasible to use a collaborative robot to paint the required marks on ribs.

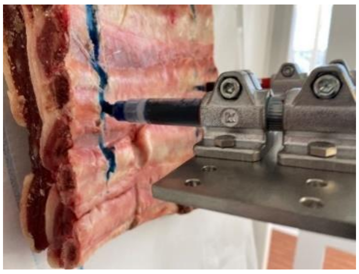


Figure 14 - Painting of scribe lines with food grade ink

Conclusions:

The key conclusions drawn from the office trials are as follows:

- A collaborative robot can be used to mark or paint scribe lines on a beef rib cage without tripping out
- Using certain features available with collaborative robots is optimal for this application and provide a benefit over an industrial robot which would require a separate hardware to achieve the same functionality
- Defining the ideal movement profile can be tricky, particularly given the two fixed pens or scribing tools interacting with a curved surface. However, it is felt like this could be optimised with the correct 3D sensing and motion planning algorithms. This work lies outside the scope of this project but, given what has been achieved in other areas, it is felt that this is surmountable.

4.4.5 Debrief of results with AMPC, Processor

Upon completion of the initial trials, a review meeting was held between Intelligent Robotics, AMPC, and the processor. With the marking trials it was felt that the results were positive and warranted a set of site trials to be performed to further investigate the application. When performing the site trials however, these would be performed quite conservatively to ensure no damage to the product being tested with. This would involve starting with very light markings in the carcases and incrementing slowly, acknowledging that not every rib would be marked. Not damaging the product would be given the highest priority.

For the pen marking trials, while the results were similar in performance, there were concerns over the thickness of the lines produced. Intelligent Robotics did some trials attempting to wash the ink off the product which were unsuccessful. Given the risk to the presentation of the product it was decided that the pen marking trials would not be performed on site. However, it was acknowledged that the learnings from the marking tools could be applied to ink marking in another form if the application proceeded to the next steps (e.g. with an inkjet head).

Based on this feedback, site trials were organised to be performed at the processor's site for the scribe marking of beef carcases.

4.4.6 Site Trials

The collaborative scribe marking prototype was transported to a processor site and setup inside one of the beef chillers. The robot was mounted to a moveable base with wheels, with the controller enclosed below. While setting up for the first trial an issue was immediately uncovered. The carcase dressing at the site at which the trials were being performed has the skirt being pulled into the rib cage. This results in it hanging right where the scribe lines must be placed. The current manual operator moves this out of the way with one hand while performing the marking operation with the other.

This was addressed by stringing the skirt to the rear of the carcase, although it still protruded slightly into the rib cage. If this application were to proceed, ideally the skirt would not be pulled, or would be removed before entering the marking system. Alternatively, it will need to be strung as per the trials.

The other factor regarding carcase presentation which was relevant for this particular site was the fact that one side from each body was significantly ribbed out for grading. This was seen as a positive opportunity however to investigate the differences in carcase stability and how a system might have to handle ribbed carcases. The other side of a given carcase had just the spine broken at the grading site, with the underlying eye muscle still intact.

One other challenge which arose during the trials was to do with the curvature of the rib cage. As aforementioned from the initial trials with the short rib, there was the need for more smarts in the motion planning to deal with the curvature of the ribs. This was more pronounced with the full carcase, particularly if it had a deep rib cage. It is also largely a result of using a tool with two long, fixed pointers to mark the rib cage. In order to make contact with both markers on the rib cage, significant tool rotation and reorientation is required as the tool moves down the ribs. When the carcase side is intact this can cause the tool to angle so much it hits the spine. This is most pronounced around the brisket. One of the carcases encountered was also significantly soft-sided, resulting in a much 'deeper' brisket than its opposite side which further pronounced this issue.

In order to overcome this issue in a commercial system, there are a number of avenues which could be taken which have been proposed.

Carcase stability was another consideration during the trials. The process of manually teaching the paths on carcase was difficult to do accurately without bumping it while it was free-hanging, thus affecting the position of the previously taught points. This in and of itself is not a major hurdle for an automated system however, which would utilise vision to generate the robot path in a non-contact fashion.

While performing the actual scribe marking on the carcase sides there was slight carcase movement observed, but not enough to significantly alter the outcome of the scribe placement. There was more noticeable movement in the ribbed-out carcase sides than the non-ribbed out sides. It should be noted however that, as previously mentioned, the amount of force used was carefully regulated so as to not risk damaging the sides during the trials. The force applied was still enough to present visible lines however along the ribs.

Based on what was observed, factors for a commercial system include the following:

- The forces required by the robot itself to mark the carcase don’t induce significant motion, as long as the paths are determined accurately and to an appropriate depth/force.
- While it may be feasible to perform the action on free-hanging carcases, it would be lower risk to incorporate some form of stabilisation.

The trials were ultimately successful in demonstrating the feasibility of using a collaborative robot to perform the task of marking scribe lines. The robot itself had no issues with the task and there were no issues of trip outs or faulting.

While the robot was able to perform the task successfully, there would be some consideration needed as to the safety of the end effector attached to it to perform the marking. The sharp points, necessary to score the bone and fat while limiting carcase movement, may pose a significant enough safety hazard to warrant guarding of the system. This is particularly the case when coupled with the crush/puncture hazard between the tool and the carcase – while the collaborative robot’s force control could generally address this, the sharp nature of the tool would require this to be considered further. There may be a way to design the scribing tool such that these safety risks could be minimised.

4.4.7 Site Trials – Demonstration to Processor

Once the system was setup and tested, a demonstration was performed to a member of the processor’s team and a debrief was performed. Overall, the customer was satisfied that the concept was shown to be feasible, with the collaborative robot shown to be able to perform the task.

The discussion then pivoted onto the marking process itself and whether drawing would be a better implementation of the task. The issues with drawing using food grade ink markers were revisited – namely the thickness of the lines. Even creating a custom marker with a finer nib would potentially pose issues with the nib eventually deteriorating and becoming ‘blunt’, resulting in a thicker line again. The most promising path forward for the application would be printing of the lines using a printhead. Being a non-contact application, this would also be more suitable for a collaborative robot application. Unlike the marking tool concept, a printhead would likely be safe enough to not require safety guarding around the robot. The final benefit in the printhead would be the ease of replenishing the ink. One issue with using a marker or brush is the need to refill or reapply ink relatively regularly. A printhead largely takes care of this issue, being able to print on many more carcases before requiring the ink to be topped up. It would also be more efficient in the volume of ink used per carcase.

Investigating the best means to apply the scribing lines to the carcases however lies beyond the scope of this particular project. The key outcome is that the marking of scribe lines on a beef carcase is feasible with a collaborative robot from a robotic perspective.

4.5 Vacuum-packed Primal Pick and Pack

4.5.1 Site Trials – Demonstration to Processor

The cut of primal that was chosen for the pick and pack trials was the 'eye round'. The trial will focus on vacuum-packed primals, seeking to pack them within a carton.

Figure 15 - Beef Eye Round

4.5.2 Gripper Selection

A significantly important aspect to the success of the pick-and-pack trials is the selection of the ideal gripper for picking of the beef primals. It must be stated however that the focus of this particular project is the collaborative robot itself, and thorough examination of gripper options, and design of an ideal gripper, lies outside the scope of this project. A number of gripper options were explored before being selected. This gripper was selected due to a number of reasons:

1) It is a vacuum gripper. One key benefit of collaborative robots is the ability to use them without guarding, which significantly reduces the footprint required for a robotic cell. However, it must be ensured that the end effector attached to them is also safe enough to not warrant safety guarding. A vacuum gripper is extremely safe, with no potential pinch points or hard edges to warrant a safety risk.
2) It is a food safe material which can also be used with raw meat as well as vacuum packed primals. While picking of raw meat is outside the scope of these trials, it is an attractive and feasible option in the broader roadmap of collaborative pick-and-place tasks for the red meat industry. It also ensures that the gripper is hygienic and fit-for-purpose in the environment.
3) The manufacturer was able to supply videos of the gripper being able to pick vacuum packed meat product. It is known from previous experience that the task of picking damp, floppy, vacuum-packed primals is quite challenging for a lot of vacuum grippers despite the assurances of various manufacturers in the past

In order to operate the gripper, an appropriate vacuum source was needed. A vacuum pump was first trialled with the gripper but this was found to have insufficient flow to allow the gripper to hold a high enough payload. A vacuum blower was then sourced, together with a filter and silencer. This was found to adequately hold the ~2kg maximum payload that was targeted.

To allow the gripper to quickly release the primal, a small air compressor was sourced and plumbed through a valve to give the gripper assembly a blow-off function.

4.5.1 Initial Trial Results

Once all items were procured and the robot programming was completed, initial trials were performed. The gripper was installed on the robot and plumbed into a large pneumatic valve. This valve allowed the actuation between the vacuum blower (to allow suction), and the compressed air line (for blow off). A smaller pneumatic valve was used to actuate the vacuum valve using an output from the robot.

Figure 16 - Collaborative Robot with Gripper Installed

A beef eye round primal was procured and the robot was tested for its ability to successfully be able to pick the primal and place it inside a box. Dry cycles were also performed to simulate picking multiple primals to pack them into a carton with a certain packing pattern. The robot had no issues with picking the primal and placing it into the carton, even when pushing the speed up to 100%. This demonstrated that the collaborative robot could be suitable for performing this application.

Figure 17 - Initial primal pick and pack trials

With the initial trials being performed successfully, there was confidence that the robot wouldn't have any issues with tripping, the gripping setup and robot programming structure were optimised. A site visit was then planned to perform trials at a processor site, examining the packing of beef eye rounds in a greater quantity, as well as exploring what other primals may be suitable.

4.5.1 Site Trial Results

Beef Eye Round Trials

The trial system was transported to site and setup in a room adjacent to the boning room. A carton of eye rounds was provided by the site for testing. The system was setup to perform a continuous pick and place cycle with a placement pattern of 5x1, 2 layers high, as per the packing pattern used by the customer.

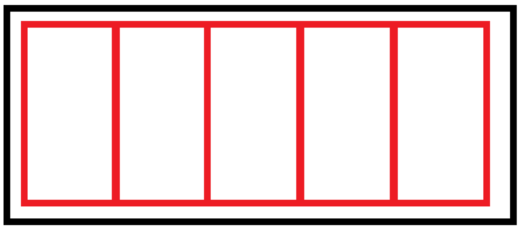


Figure 18 - Packing pattern for beef eye rounds

A number of the primals which were trialled were significantly smaller than the primal used during the initial trials at Intelligent Robotics's facility previously. This resulted in quite a few instances where the gripper would not seal properly on the primal before attempting to pick the primal up, resulting in a missed pick. An attempt was then made to modify the robot program to convert the type of motion used. Once this change was implemented the robot was able to pick and pack all the primals which were in the carton, despite their differences in size.

The benefit of this change highlighted an area where not only is the collaborative robot suitable for the application but may in fact be beneficial over a standard industrial robot.

One other issue experienced with achieving consistent picking was positioning the primals correctly on the table. The robot was programmed with one pick position, and this pick position had the gripper oriented parallel to the surface of the table. In a production system, vision would be used to direct the robot accurately to the optimal pick position for a given primal. These aspects are outside the scope of this project but entirely feasible and required for a commercial system.

While the focus of the trial is on the robot rather than the gripper, one key thing that was noticed about the selected gripper was the lack of impact it had on the vacuum-packed meat. Experience in the past with vacuum grippers picking meat has seen significant 'puckering' in the vacuum bag and the meat at the site where the gripper has picked it up. This has always been a concern regarding altering the presentation of the primal, and the potential to burst a bag. This wasn't seen with the selected gripper – despite performing multiple pick routines on the primals over the course of a few hours, there were no visible signs of the primals having been handled. Similarly, there were no instances of bursting any of the primal bags. This lends significant confidence that the collaborative robot can be paired with a high-performing, safe, vacuum gripper to achieve guardless pick and packing for the meat industry.

Figure 19 - Image showing deformation of meat by suction cups (Scott Technology, 2016)

The speed of the packing operation was increased to 100% without any issues in terms of the robot tripping, even while handling primals of varying weights. This suggests the collaborative robot, despite its safety monitoring functions, is able to handle the task of picking and packing primals while moving at speed without faulting.

AMPC Demonstration

With the packing of the eye rounds setup, a demonstration was performed to AMPC on the picking routine. It was agreed that the packing routine looked good, and that the collaborative robot was performing well at the task of picking and packing the eye rounds into the carton.

It was then suggested to explore the tripping characteristics of the robot. One of the key benefits of using a collaborative robot is that they can work side-by-side with humans without needing guarding. This is due to the safety monitoring within the robots which detect when a collision has occurred and to perform a protective stop.

It was also suggested to explore how the system operates when trying to pick and pack other types of primals, in different packing orientations. This would assist in formulating the roadmap of next steps for the technology upon completion of this project.

Collaborative Tripping Trials

As aforementioned, one of the key benefits in utilising a collaborative robot is that they are designed to operate without needing guarding. In order to test this functionality in the context of picking and packing, a number of collisions with the robot were trialled while it was performing the routine at full speed.

In all instances which were tested, the robot performed a protective stop once the collision with the person was detected at a force which was not harmful, despite operating at full speed. This reinforces the feasibility of designing a collaborative pick and pack system without safety guarding.

Alternative Primal Trials

With the successful packing of the eye round primal, investigations then turned to exploring which other primals could be picked, and whether the robot would have any issues with them. A preliminary investigation explored the following primals, and their results:

- Striploin piece – successful
- Butt Tender – successful
- Chuck Rib – successful
- Topside – unsuccessful. Despite sealing to create a vacuum the primal fell when trying to lift it from the table. The robot itself was happy with the load but the gripper was unable to maintain enough vacuum.
- Eye Round (2 Primals in one bag) – partially successful. Successful and unsuccessful picks when positioned diagonally across the two primals. In this instance the gap between the two primals can cause the gripper to struggle to obtain suction. Successful and unsuccessful picks when positioned across one primal. In this case, the uneven weight distribution can cause the gripper to fail to hold onto the primals, or the gripper was unable to seal across the gap. In all instances the robot failed to fault – the issue lay with the gripper.
- Tomahawk – unsuccessful. After multiple attempts trying to pick on both the rib surface and the lateral surface of the primal, the gripper was unable to achieve sufficient suction to pick the primal. It is thought

that this is due to the ridges of the ribs/the contour of the fat preventing the gripper from being able to 'seal' against the primal.

- Rib cap – partially successful. The surface of the primal was particularly contoured and varied significantly in height on one side, and smoother on the other. The robot had failed and successful picks on both sides. When it failed, despite pulling a vacuum, it doesn't look like the vacuum was strong enough to pick a primal of this weight. There were no issues with the robot faulting, even when the vacuum did hold, with the robot able to complete a pick and place cycle
- Beef Heel Muscle – successful
- Oyster Blade – successful
- Rump – partially successful. There were both successful and unsuccessful picks of the rump, which was a large primal. Even with the successful pick, when the primal bumped the edge of the carton during the place movement it fell from the gripper, indicating that it was at the limits of what the gripper could hold. More accurate positioning of the robot would help with ensuring consistency of the pick by locating and orienting the gripper in the ideal position on the primal. The robot had no issues with tripping.

Preliminary Conclusions

Some key conclusions from the first round of alternative primal picking indicates:

- There were never any primals for which the robot was the limiting factor
- There are a number of primals which could be coupled with eye rounds for picking
- Incorporating vision will improve the consistency of picks by enabling the robot to locate itself to the ideal pick location
- Using collaborative robot motion features greatly improved the picking performance of the system
- It is possible that heavier primals could be lifted more consistently with a stronger vacuum setup than the one utilised for the trial

Vacuum Hose Damage

While performing the aforementioned picking trials, it was noticed that damage had been sustained to the vacuum hose attached to the gripper. This damage was significant and would have resulted in a significant reduction in vacuum. It is unknown when the damage could have occurred, or if it occurred progressively over time. The damaged section of hose was removed, and the rest of the hose was checked for integrity.

Additional Alternative Primal and Alternative Pack Pattern Trials

It was thought that the damaged hose may have been the reason some of the primals unable to be successfully picked during the first round of trialling. Another round of trials was performed, attempting to focus on some of the 'difficult' cases from the previous trials – namely heavier primals, and those with heavily contoured surfaces. For these trials, some of the primals were weighed as well (when access to scales was available). Alternative packing patterns to the 5x1x2 pattern used by the eye round primals were also explored.

- Chuck Roll
    - Packing Pattern: 3 to a carton (2 on first layer, 1 on second layer)

  - Weights: 4.67kg, 5.03kg, 5.32kg
  - Successful – robot able to pick all three primals and pack in the desired pattern
- Point End Brisket (Deckle Off)
  - Packing Pattern: 3 to a carton (1 layer, overlapping)
  - Weights: 3.41kg, 3.73kg, 4.47kg
  - Successful – robot able to pick all three primals and pack in the desired pattern. There were some issues in the earlier attempts with consistently picking the primal, but this was due to the varying height profiles of the primals, and the inconsistency in positioning them on the table. Vision-based picking would solve these issues for a commercial system.
- Striploins
  - Packing Pattern: 3 to a carton (sideways)
  - Weights: unknown (scales unavailable, est. 5-7kg each)
  - Partially successful – the robot was eventually able to pack the primals in the carton in the desired pattern, but consistency would need to be improved. The gripper and robot were able to continue holding the primal while rotated at a fairly sharp angle which was positive. For this trial the carton was maintained on a flat surface. With a commercial system, it's likely the carton would need to be in an angled fixture to achieve the best results. But the fact it was shown that the gripper and robot can hold the primal at steep angles allows for significant flexibility in the final system.
- Striploins
  - Packing pattern: 5 to a carton
  - Weights: 3.75kg, 3.76kg, 3.80kg, 4.78kg, 4.83kg
  - Successful – even with a flat carton and without needing to tilt the primals, by using an overlapping pack pattern the primals were able to slot successfully within the carton. The consistency of this approach would have to be assessed over a greater range of primals though. The packing routine for a commercial system would have a bit more complexity to space the top layer more evenly. There were no issues with picking, holding, or moving the primals.
- Short Ribs
  - Packing Pattern: ~8 to a carton, stacked on their side (partial carton shown below)
  - Weights: 1.39kg to 2.28kg
  - Unsuccessful – A number of different packing orientations were attempted which included rotating the gripper as much as possible and tilting the carton. Consistently placing the primals in the sideways orientation was not able to be achieved. It is feasible however. The main challenge was the robot / gripper hitting the carton when placing the latter primals into the carton. This could be remedied by designing a rollface end-effector spaces the gripper away from the robot in the packing orientation. The gripper's ability to maintain hold on the primal even when tilted at steep angles is seen as a key enabler. A tilted fixture would need to be used to pack primals in this orientation. The gripper was able to pick the primals from both the meat side and the rib side, even with the rigidity and curvature of the ribs.
- Short Ribs (two per bag)

  - Packing pattern: 6 to a carton (2 bags per layer x 3 layers)
  - Weights: 1.95kg – 2.35kg
  - Successful – able to pick and pack all primals successfully, even coping with the gap between the two primals and picking on both the rib and the fat side of the primal. Handling the extra material from the oversized vacuum bag would have to be considered however as it does pose a risk for long-term, consistent operation.
- Trim Pieces
  - Packing pattern: 2 to a carton
  - Weights: 9.56kg, 10.39kg
  - Unsuccessful – gripper was unable to hold the weight of the primal, even when trying to position the 'flattest' face of the primal directly into the gripper by hand. Suction would be engaged, but the primal would drop once the primal was released by hand.
- Tenderloin
  - Packing pattern: 8 to a carton (4 by 2 layers). Primals are alternated about its length due to the 'teardrop' shape of the primal.
  - Weights: 1.74kg – 2.53kg
  - Partially successful – the main challenge in packing the tenderloins was consistently picking them. This was due to two main factors – 1) the primals were quite skinny meaning the gripper had to be well centred across the width of the primal during a pick and, 2) the primals had a significant variation in thickness from one end to the other meaning that a single pick orientation parallel to the table didn't always ensure good positioning of the gripper to pull vacuum. These issues would be readily solved by implementing vision guidance to accurately define how the robot would position to perform a pick. There was also an occasion issue with maintaining vacuum on the primal if it was picked too far along its length from the centrepoint - the tenderloin's long length coupled with its lack of rigidity would cause the primal to 'peel' out of the gripper during a placement move.
    This primal was demonstrated to AMPC and to the customer, with it successfully packing 7 of the 8 primals. The last primal it missed as it was a smaller primal which wasn't positioned well enough on the table to allow the robot to pick it, due to the aforementioned factors. The packing routine successfully navigated the alternating orientation of the primals into the carton.

5.0 Conclusions and Next Steps

5.1 Whole of Pallet Barcode Scanning

The initial trials performed demonstrated that a collaborative robot could feasibly be used in a system to scan the barcodes on a pallet. The robot was able to accurately drive a camera to various positions, dictated by a dynamic set of vision results, to allow the barcodes to be read on a pallet of cartons. As this is a non-contact task using a safe end effector (i.e. a camera) it would be suitable for guardless operation adjacent to human operators.

The next steps for such a system would be to develop a prototype which is tested on site. Such a prototype could be 'wheeled in' and positioned adjacent to a turntable upon which pallets of cartons are placed. The list of carton details would then be displayed to the operator to be ticked off against a manifest.

The minimum viable product (MVP) prototype could then be expanded upon in a number of areas, as outlined with AMPC.

The collaborative robot is the ideal technology to use in this application for a number of reasons:

- The flexibility of the robot allows the system to be able to cope with a variety of different carton sizes and pallet stack patterns
- Since it is a collaborative robot, no guarding is required which keeps the footprint of the system minimal
- The payload of the camera (and potential printhead) is well within the payload capacity of a collaborative robot

Unfortunately, there was not significant market interest in this system at the time of performing this project. If this situation changes in the future and the business case for such a solution evolves, then it would be technically feasible and suited to a collaborative robot.

5.2 Scribe Line Marking

Key learnings

From the trials performed there were a number of key learnings:

- *The collaborative robot (UR10e) was able to perform marks on beef ribs with a marking tool and with pens without tripping out under a protective stop*. This was a key concern for the technology given the safety features it possesses – collaborative robots are designed to detect any unexpected forces and trip out to ensure the safety of people in the surrounding area. Once the system is setup correctly this risk was shown to not be an issue, which was critical in confirming the viability of using a collaborative robot for this task.
- *The collaborative robot was able to cope with the extended length of the marking tools, and the forces required to perform both types of marking.* Collaborative robots generally come with limited payload capacities. One concern was that the forces required to hold the stainless-steel tool, coupled with the marking forces acting along the long pointer tools (resulting in a long lever arm) would be outside the payload capacity of the robot. This was shown not to be an issue however.
- *The robot could successfully navigate the contouring of the ribs.* One key benefit of a collaborative robot is the ability to perform certain movements without additional hardware. This functionality was able to be used

to allow the robot to successfully navigate the undulating nature of the inside of the rib cage without damaging the carcase.

- *The curved nature of the rib cage makes it difficult to keep both marking tools/pens in contact with the ribs at all times if they are at a fixed length.* Due to the geometry of the rib cage, when two marking tools/pens are positioned at a fixed length from the rollface it can be difficult to keep both in contact in areas where there is a significant height difference between the two sides (e.g. around the brisket). This requires the robot to perform some quite large reorientations which can cause the tools to collide with other parts of the carcase (e.g. the spine). This could be addressed to some extent with sensing and motion planning algorithms, by modifying the tool, and/or by placing one scribe at a time.
- *Carcases were fairly stable while free-hanging during the marking operations.* This was due to the fact that the marking tool doesn't need to exert much force onto the carcase to leave a visible mark. There was slightly less stability with carcases which were ribbed out. However, consistent performance would likely require some form of stabilisation.
- *The marking pens may not be suitable due to the width of the lines created.* The marking pens used for the initial trials to demonstrate feasibility were unable to be used on-site due to the impact on carcase presentation for a trial activity. Even if the system were setup perfectly such that the placement of the lines was accurate, the width of the cutting blades is still narrower than the lines drawn, resulting in ink being present on the final product and affecting its presentation and saleability. The ink is unable to be washed off the primal completely. A custom fine-nib marker may be feasible, but over continued use the markers tend to 'flatten', resulting in a thicker line again. The ideal marking solution would be able to consistently draw lines only as thin as necessary to be visible by the operator, ideally <1mm wide, and would disappear when the cut is placed.
- *The marking tool, due to its sharp nature and contact with the carcase, may not be 'safe enough' for a collaborative application.* While the robot is designed such that it can safely be used around humans without needing guarding, the end-effector on the robot must similarly be safe enough that guarding is not warranted. The concerns with the marking tool are around its sharpness (required to create the marks) which results in a cutting/puncture risk, coupled with the fact that the tool must contact a surface which also creates a puncture risk despite the robot's force monitoring (the force required to mark a carcase is more than the force required to inflict an injury with this tool). For these reasons, while the collaborative robot is technically able to perform the task with the marking tools, it isn't truly a collaborative operation and would likely require some form of guarding or protection.
- *The ideal marking technology to couple with the robot is likely printing.* Putting a printhead on the robot to print the scribe lines on the carcase would likely be the ideal marking solution for a scribe marking system, as per the debrief with the customer. It would be safe and would enable a thin line to be transferred to the carcase. Furthermore, the issue of ink replenishment would be catered for, something which is also a key consideration with the pen marking. It can also be performed faster than marking or using a pen.

In summary, the collaborative robot performed well with the trials. It was shown that this application could be achieved using a collaborative robot, with the relevant risks being shown to not be an issue.

Next Steps

It would be proposed that an iterative approach to development occurred, consisting first of designing a minimum viable product with a partner plant. This would allow the technology risk to be minimised and spread over successive iterations, including dealing with unforeseen risks and issues which emerge in an efficient manner. It would also enable feedback from the industry to be effectively considered to ensure the design follows what industry values to the level that it requires. This minimises the risk of over-developing the system into something which becomes commercially unviable, or missing key elements which are unknown to Intelligent Robotics currently but of high value to the industry.

A roadmap was developed and presented to AMPC.

5.3 Primal Pick and Pack

Key Learnings:

The following key learnings were obtained from the trials that have been performed:

- *The collaborative robot (UR10e) was able to pick and move all the trialled primals which the gripper was able to hold.* This was the key takeaway for this project – confirming that the application was suitable for a collaborative robot in the red meat industry. Even moving the heaviest primals which were able to be held by the gripper didn't result in any false protective stops from the robot.
- *The motion functionality of the collaborative robot improved picking consistency.* Utilising this functionality improved the consistency of the gripper forming a successful vacuum with the primals and is a benefit over standard industrial robots.
- *The collaborative robot was able to trip out under a protective stop when coming in contact with a person during a pick and pack routine at 100% speed.* A key benefit in using collaborative robots is that they don't require guarding. In order to confirm the safety of this functionality, collisions were trialled while having the robot perform pick and pack cycles at 100% speed. The robot was able to trip out without causing harm.
- *The application is feasible for a large number of primals using a soft vacuum gripper.* While gripper selection and design are outside the scope of this project, it was important to select something which is safe to use collaboratively. While the robot may be safe to operate unguarded, if an end effector is attached to it which is unsafe (e.g. possesses sharp corners, poses pinch hazards, etc) then guarding may still be required. A soft vacuum gripper enables a guarding-free pick and pack system to be feasible. The gripper selected is also suitable for an abattoir environment in terms of hygiene and ability to withstand the cleaning regime.
- *Extra sensing to optimise the pick position will further improve the consistency of the system.* The initial trials were performed with the robot picking from a fixed position, at a fixed orientation. The consistency of the gripper drawing a vacuum on a primal will be significantly improved by including simple vision.
- *The robot was able to consistently pick and place the following beef primals: eye rounds, striploins, butt tenders, chuck ribs, beef heel muscle, oyster blade, chuck roll, point end brisket, short ribs.*
- *The robot was able to pack a number of different packing configurations. There were issues packing primals on their side.* When packing primals on their side, the gripper was able to handle angling the primals at quite a steep angle. In order to allow the primals to remain sideways while packing the carton a special angled fixture would need to be designed to keep the carton angled during the pack routine.

While focussing on the gripping requirements of the system lay outside the scope of investigation for this project, the following learnings were observed and can be built upon for the next stages of development:

- *A vacuum blower was required to successfully pick a large range of primals up to ~7kg. Further optimisation of the vacuum setup may enable the gripper to hold even larger primals.* A vacuum pump was initially used with the gripper but wasn't able to generate the suction needed to hold the initial targeted primal (beef eye rounds). This was replaced with a blower which was more successful. There is still room to improve the vacuum setup to allow the gripper to hold even larger primals.
- *The vacuum gripper did not appear to deform the primal significantly. There was no visible damage to the bag and there were no issues with burst bags, even with primals which were repeatedly picked by the robot over successive trials.* Previous projects with vacuum grippers have resulted in deformation in the product and posed a risk of damaging the bag. The gripper trialled did not demonstrate these issues which makes it an optimal candidate for a commercial system.
- *The gripper struggled to pick some of the bone-in primals with significant curvature (e.g. Tomahawk on the 'rib side'), and with some of the bags with multiple primals inside.* This was due to the gripper not being able to pull a seal properly. In the case of multiple primals in a bag, the gap between the primals caused the vacuum to leak which prevented the primal from being held.
- *The gripper could handle orienting the primals at steep angles after they've been picked.* This provides more flexibility in how the packing operation can be performed for different carton pack patterns.

Next Steps

The key outcome from these trials is the confirmation that the picking and packing of primals is a viable task for collaborative robots within the red meat industry. As with the scribe marking system, it would be proposed that a minimum viable production approach be undertaken through the development pathway.

A roadmap was developed and presented to AMPC.

6.0 Bibliography

Committee, R. M. (2021, 08 18). *RMSCC Supply Chain Information Standard*. Retrieved from RMSCC: https://www.rmscc.com.au/scis_1.asp

Scott Technology. (2016). *2014/1010 Pick and Pack – End Effector Gripper Development.* AMPC.