Final Report

AUSTRALIAN MEAT PROCESSOR CORPORATION

Remote Operations – Shadow Robots (Stage 1)

Full Project Title

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2021-1158

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1.0 Executive Summary

This project is a proof-of-concept example of robots being used to replace personnel in bandsaw meat cutting. The work has been undertaken in response to a call from AMPC for a staged programme of development work on Remote Operations/Shadow Robots. This report covers Stage 1, that is, to Demonstrate the Concept

The objectives of this project were to:

- Design a concept
- Build and test a prototype and
- Demonstrate the system to AMPC

The contracted project methodology was detailed as:

1. Concept design and part selection
2. Purchase parts and modifications to purchased parts
3. Assemble platform
4. Test, evaluate and evolve demonstration platform
5. Successful demonstration to AMPC staff.

We completed the project in line with this methodology but in addition, we overlayed a rapid prototype approach. That is, we borrowed and leased part of the equipment, conducted minimal coding and made a simple set up to prove the core of the approach i.e: controlling the robot through a separate object tracking system. After successfully rapid prototyping the system we progressed with steps 2-5 (above).

Our system included the following equipment:

- A robot, controller and robot control software
- Bandsaw
- Cameras
- Object Tracking Table
- Safety equipment
- Laser pointer for remote operator guidance.
- Control Software/interfaces
- User Interface
- A simple temporary end effector – a clamp to hold the meat

The system set up is a robot situated adjacent to the bandsaw and the meat to be cut is held by the robot using a temporary custom-built end-effector. The position of the robot end-effector is controlled by an operator who is situated at an operator’s workspace out of reach of the robot and bandsaw. The operator moves a tracked object on a 2-D plane within the operator’s workspace. The robot end-effector “shadows” the motion of the tracked object in real-time such that the operator can manipulate the meat to be cut by the bandsaw. The system can scale the motion of the tracked object such that the robot movements are enlarged or reduced by a specified scale factor. The system also incorporates some features such as constraining sideways motion when the meat is moving through the blade and feedback to the operator of the current width/thickness of the cut.

In terms of performance of the system, guidance was provided by AMPC regarding speed and accuracy. These were not key performance indicators but rather direction to ensure that work stayed broadly relevant with industry needs. The guidance was cutting accuracy of ±10mm and 10 cuts within 15 seconds.

Early results show that:

- accuracy of cutting in the order of a few millimeters is easily obtained, and
- speed of cutting is reasonable for the stage of development and is controlled at this time primarily by the operation. With an operator, 6 chops were cut in 45 seconds. There are many opportunities for increasing the speed.

This work has successfully proven the application of a shadow-robot concept to cutting meat on a bandsaw. So there is good potential for removing staff from dangerous bandsaw operations.

A provisional patent covering this system was filed in January 2022.

It is our recommendation that this work continues to Stage 2, where Stage 2 includes both increasing useability and develops a specific application with associated end effector, allowing the earliest potential uptake of the approach.

2.0 Introduction

This project is a proof-of-concept example of robots being used to replace personnel in bandsaw meat cutting. The work has been undertaken in response to a call from AMPC for a staged programme of development work, see Appendix 1. This report covers Stage 1, that is, to Demonstrate the Concept. Future work that is beyond the scope of this project includes: Stage 2- Improve the concept, Stage 3 – Gripper Development, Stage 4 (a-f) - boning room & slaughter floor application (in processor facilities) and Stage 5 – Adoption.

This Remote Operation – Shadow Robot project fits within the Advanced Manufacturing and Safety and Wellbeing innovation themes of AMPC's 2020-2025 Strategic Plan, where the goals are:

1. Removing staff from dangerous operations, via Hands-Off processing (Adv. Mft.),
2. Safety and Wellbeing, via reducing the high-risk nature of processing operations (People & Culture),

More specifically, a successful development will enable operational staff to undertake bandsaw cutting operations without having to hold onto the meat part being cut. Then once developed the concept should be considered for both boning room and slaughter floor use.

The request for proposals proposed the concept demonstration could target cutting Osso Bucco (or similar); as shown in this video https://www.youtube.com/watch?v=VeNzK3RHZXs. Suggested targets, guidance only, for this application were 10 parts cut from a single shank at 50mm width within 15 seconds, with an accuracy of +/- 10mm. This guidance was provided to ensure that

- implementation did not introduce significant additional labour costs (Opex) on top of the cost of the equipment (Capex), and
- the speed is relevant to processing line speeds, and
- the accuracy would be better than the manual used today.

Notably gaming strategies, such as placing cut-line were mentioned as a proposed strategy to achieve accuracy.

Further direction from AMPC regarding the scope of work included that if necessary for simplicity for Stage 1 could include guides bolted to the bandsaw at a fixed distance (i.e. 50mm) from the blade to simulate the right hand of the operator within the video. It was expected that the shadow robot will replace the left hand of the operator in the video.

Following discussion with AMPC, we opted for an alternate application that was, cutting frozen lamb chops and we used the cutting rate and accuracy proposed as guides i.e: 10 cuts within 15 seconds.

Mimeo Industrial is a new start up so there was no prior work being leveraged for this project and we did not find information specifically relevant to this application in either industry reports or literature. Therefore, no references are listed.

3.0 Project Objectives

The objectives of this project were to:

- Design a concept
- Build and test a prototype and
- Demonstrate the system to AMPC

Effectively showing that shadow robots are a viable technology for the meat processing sector to be developing.

4.0 Methodology

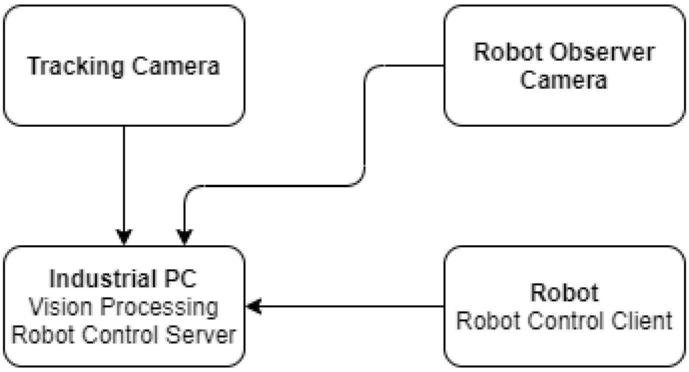
The contracted project methodology was detailed as:

1. Concept design and part selection
2. Purchase parts and modifications to purchased parts
3. Assemble platform
4. Test, evaluate and evolve demonstration platform
5. Successful demonstration to AMPC staff.

We completed the project in line with this methodology but in addition, we overlayed a rapid prototype approach. That is, we borrowed and leased part of the equipment, conducted minimal coding and made a simple set up to prove the core of the approach i.e: controlling the robot through a separate object tracking system. After successfully rapid prototyping the system we progressed with steps 2-5 (above).

4.1 Robot Vision Control

We opted for a robotic system controlled by machine vision. The system controls can be summarised with the following diagram:



4.2 Equipment & Set up

Our system included the following equipment:

- Robot - Kuka, KR10 R1100-2
- Robot Controller - KRC5 micro
- Robot Control Software - KSS 8.7
- Bandsaw -1.5kW motor, Footprint: 700mmx550mm, Throat size 460mm H x 285mm W
- Robot base – designed and built to fixture robot base with the bandsaw
- Cameras – Basler Ace, 1 x a2A1920-160ucBAS and 1 x a2A1920-160ucPRO. One for tracking an object and the other for over the bandsaw.
- Object Tracking Table – in-house build out of timber with lasers projecting ‘cross-hairs’ onto the table. The table is painted black to provide good vision tracking.
- Safety equipment – Satech Greenfast fencing, 1xBAM02HA E-Stop from Balluff and 1xSTR-SAFM03P8 gate switch from SICK chained together into an RLY3 unit from SICK and looped through the robot’s in-built safety. If any safety element is activated, both the robot and the bandsaw are stopped.
- Laser pointer for remote operator guidance.
- Control Software/interfaces - in-house built code using JopenShowVar; with the option to convert to mxAutomation (Kuka) for a fully supported option.
- User Interface – a basic system built in-house for the purpose

The following two figures show the floor plan (Fig. 1) and set up of the robot, bandsaw and base (Fig. 2). The footprint of the cage is 3.1m by 1.6m.

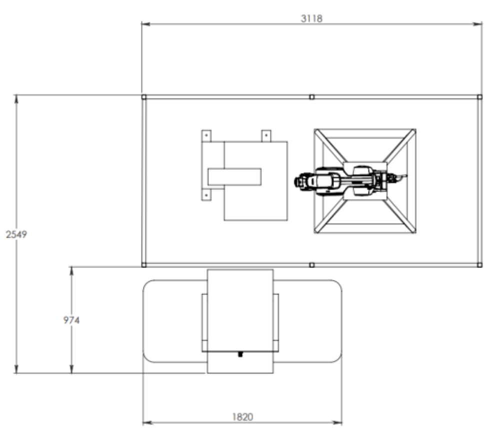


Figure 1 – Floorplan for the system. Within the safety cage is the Robot and Bandsaw and outside the cage is the Object Tracking Table.

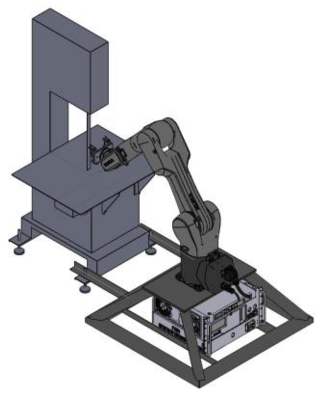


Figure 2 – CAD drawing of Robot and Bandsaw. The Robot base is fixed to the Bandsaw. The Robot controller sits under the robot.

Pictures of the setup are shown in Figures 3. The cameras are located above the bandsaw and above the object tracking table. Images from the two cameras are displayed in the user interface, see Figure 4.

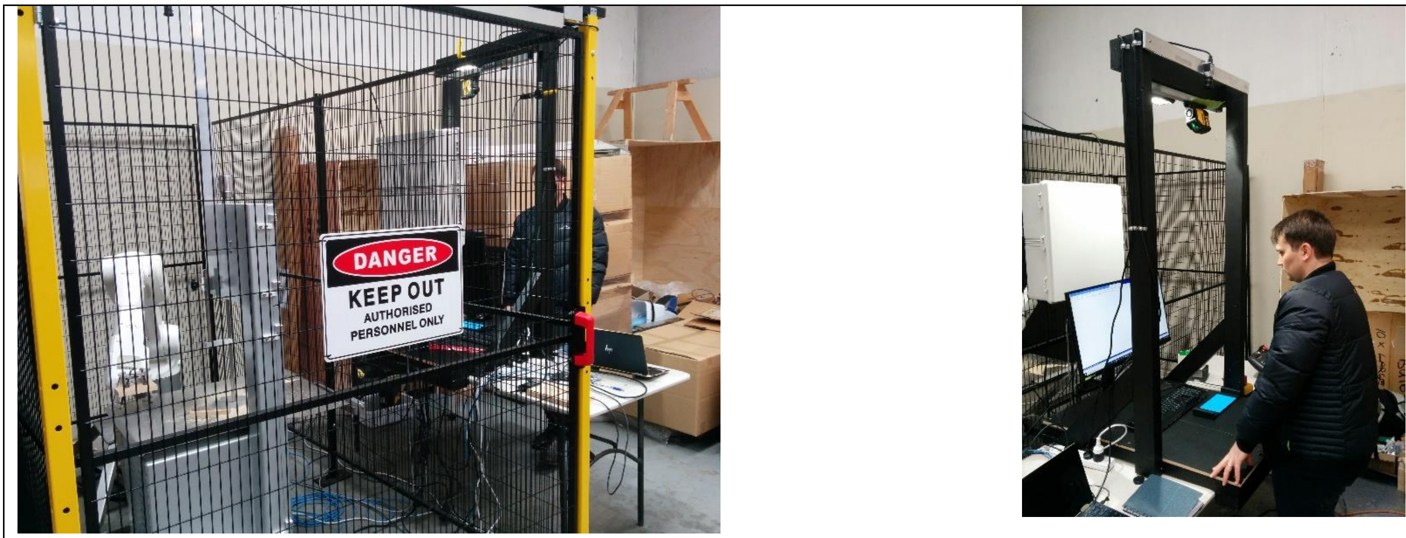


Figure 3 – Photo's of the set-up including the safety fencing within which sits the robot and bandsaw and outside the cage, the object tracking table (right).

4.3 Development Path

The system has been developed iteratively. Reference points along the development path included:

1. Moving the robot slowly using the tracking system with a proxy for the bandsaw (another simple wooden proxy)
2. Putting the bandsaw into the system, initially without a blade, then once confidence was built, then the blade was installed.
3. Defining and setting up scaling between the bandsaw and robot.
4. Cutting wood with increasing accuracy – where lines were drawn on the wood.
5. Cutting a lamb rack into chops while the operator aligned manually with the saw-blade, then
6. The addition of features so that the operator could cut without watching the sawblade. Effectively the last step was mimicking an operator that might be sitting in a control room.

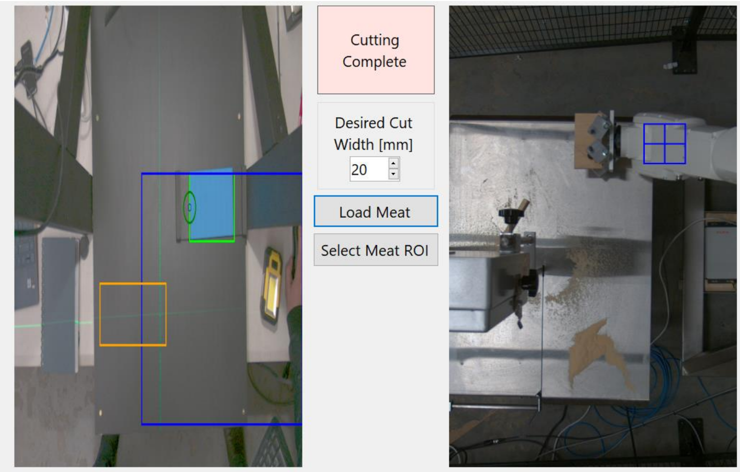


Figure 4 – Screenshot of the user interface showing the two camera images. Image on the left is above the object tracking table. The vision system is tracking the blue-coloured block.

To this point the system was being used with the operator watching the bandsaw, where the alignment of the object to be cut was by 'eye', as shown in Figure 5. This method worked quite well, as shown by the chops cut in Figure 6.

Figure 5 – Image of the system operating (extracted from a video) at an intermediate stage of development. The operator is lining up the cuts by 'eye', by watching the saw blade and adjusting the position of the meat by moving the 'box' in his hands.

Figure 6 – Frozen chops cut using the system**.**

7. Improving the set-up, user interfaces and vision systems so cutting could proceed 'blind' i.e. without watching the saw table but rather watching information on the computer screen. This mode of operation required referencing the robot/object to be cut with known co-ordinates in the tracking system.

4.3 System Set up, Referencing, Scaling

There are some features of the system that require some description/detail.

System Overview

The robot is situated adjacent to the bandsaw and the meat to be cut is held by the robot using a temporary custom-built end-effector (see bottom left of Figure 5). The position of the robot end-effector is controlled by an operator who is situated at an operator's workspace out of reach of the robot and bandsaw. The operator moves a tracked object on a 2-D plane within the operator's workspace. The robot end-effector "shadows" the motion of the tracked object in real-time such that the operator can manipulate the meat to be cut by the bandsaw. The system can scale the motion of the tracked object such that the robot movements are enlarged or reduced by a specified scale factor. For example, a scale factor of 0.5 would result in robot movements that are half the distance of the movements of the tracked object. Consequently, a scale factor below 1 gives the operator finer position control of the robot. The system also incorporates some features such as constraining sideways motion when the meat is moving through the blade and feedback to the operator of the current width/thickness of the cut.

Object Tracking

The operator's workspace utilises a Basler Ace a2A1920-160ucPRO camera to capture overhead images of the workspace in real-time. In-house developed software is used to perform real-time processing of the camera images to identify and track the position of a blue coloured 2-D rectangular object (approximately 100mm x 150mm in size) in the workspace (see left side of Figure 4). The position of the tracked object is first identified as a rectangular region of interest (ROI) that surrounds the object in the image (see green rectangle in Figure 4). For simplicity, the tracking algorithm then represents the position of the tracked object as the single point/pixel that corresponds to the centre of the left edge of the identified ROI (see green circle in Figure 4).

Robot Coordinate Directions and Limits

For the purposes of the current cutting task, the robot's global x- and y-axes were aligned with the plane of the bandsaw table such that moving the robot in the x direction would change the thickness of a cut and moving in the y direction would perform a cut. The height above the bandsaw table (the global z-axis) was held constant. Limits were established for the robot x- and y-axes such that the robot had sufficient range of motion to perform the required cutting actions whilst not allowing the end-effector (or robot) to contact the bandsaw blade. Consequently, the limits that were applied to the robot x- and y-axes formed a rectangle boundary within which the robot was allowed to operate. Furthermore, the position of the bandsaw blade in the robot's global x and y coordinates is known and does not change.

Mapping Object Tracking to Robot

To control the position of the robot with the tracked object, a rectangle tracking ROI was applied to the camera image of the operator's workspace (see blue rectangle in left side of Figure 4). The tracking ROI was then used to map each point/pixel within the tracking ROI to a corresponding robot x and y coordinate within the rectangle boundary formed by the robot x- and y-axes limits. Figure 7 shows a diagram demonstrating how pixels within the tracking ROI correspond to robot positions within the robot limit boundary. For example, it can be seen from the diagram of Figure 7 that any of the four pixels within the red region of the tracking camera ROI ((1,10),(2,10),(1,9),(2,9)) would map to the robot position indicated by the red region of the robot position diagram (1,5).

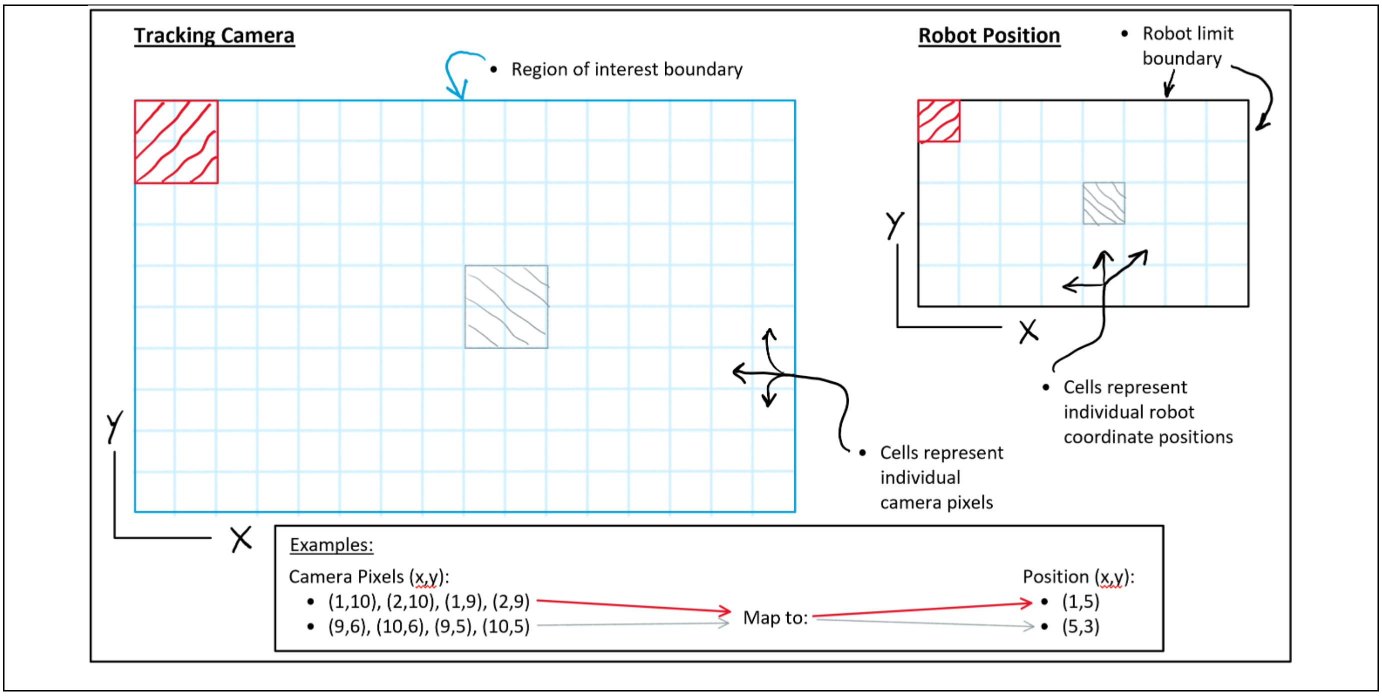


Figure 7 – Diagram showing how the tracking camera region of interest pixels (left) map to a corresponding robot position within the robot x- and y-axes boundaries. (right).

Scaling between Tracking and Robot

An initial calibration was performed to determine the pixels per millimetre constant for the tracking camera image. The system resizes the tracking ROI based on the pixels per millimetre constant and the chosen scale factor. Consequently, when the operator moves the tracked object a known distance, the robot will move the known distance multiplied by the scale factor.

Bandsaw Region of Interest & Straight Cuts

The current system is configured to perform straight cuts only (see cut chops in Figure 6). This is implemented by restricting the motion of the robot x-axis (the axis perpendicular to the blade) when the meat is within the vicinity of the blade. To determine when the meat is within the vicinity of the blade a meat ROI is configured after the meat is loaded into the robot. The meat ROI allows the system to know where the edges of the meat are in the robot global coordinate system. Therefore, a bandsaw ROI can be determined that indicates the region around the bandsaw blade when the meat would be in contact with the blade (see orange rectangle in left side of Figure 4). When the robot moves into the bandsaw ROI, any operator movement perpendicular to the blade is no longer communicated to the robot. Consequently, it is not possible for the operator to inadvertently damage the bandsaw by sideways motion while cutting.

5.0 Project Outcomes

Results show that the system can cut with good accuracy. For example, Table 1 shows data from remotely cutting wood. The robot position is that set by the operator on the screen. The resulting cuts compared well with a maximum difference of 3.5 mm and typically much less. These results were obtained without adjusting for the 1mm blade thickness, so actual cuts should be undersized. We have further work to do on factoring blade-width into the cut measurements.

Table 1 – results from remotely cutting wood (from on-line demonstration to AMPC)

	Robot Position (mm)	Actual cut (mm)	Variation (mm)
Cut 1	21	21	0
Cut 2	19	18	1
Cut 3	22	18.5	3.5
Cut 4	21	21	0
Cut 5	19	21	-2
Cut 6	18	17	1
Cut 7	25	24	1

Table 2 provides example results from cutting a lamb rack; this was the rack cut during our on-line demonstration to AMPC staff. These results show good accuracy and consistency (again, no allowance for blade thickness).

Table 2 – Results from cutting a frozen lamb rack (from the online demonstration to AMPC)

	Robot Position (mm)	Actual cut (mm)	Variation (mm)
Cut 1	20	20.5	-0.5
Cut 2	21	20.5	0.5
Cut 3	20	19	1
Cut 4	19	17.5	1.5
Cut 5	22	21.5	0.5
Cut 6	21	19	2

In terms of speed of cutting, we have not done a lot of timing work. In the recent demonstration to AMPC, six chops were but in 45 seconds. This is not particularly fast but is reasonable for the stage of development of the system.

The system is far from optimised for either accuracy or speed. The further work section (Section 7.0) discusses proposed next steps.

6.0 Discussion

We have proven the concept of cutting using a shadow robot style of set up.

In terms of performance of the system, guidance was provided in AMPC regarding speed and accuracy. These were not key performance indicators but rather direction to ensure that work stayed broadly relevant with industry needs. The guidance was cutting accuracy of ±10mm and 10 cuts within 15 seconds.

Early results show that:

- accuracy of cutting in the order of a few millimeters is easily obtained, and
- speed of cutting needs further work; with an operator running the system i.e: 6 chops were cut in 45 seconds. In work to date, speed of cutting was not a priority with the speed being controlled by the operator. If the system is controlled less by the operator and more by the computer/system, then the speed of cutting could be much faster. We see this as a future operating mode (see Section 7).

In Stage 1 of the “Remote Operations” R&D Theme the goal was to prove the concept. Next stages proposed by AMPC include Stage 2 – Improve the concept, Stage 3 – Gripper Development, Stage 4 – Boning Room Solution etc. As we seek to engage with a processor at the earliest opportunity, it would be useful to develop a specific boning room cutting application as part of Stage 2. That is, we’d consult with industry, identify a particular applications of need, then design a robot end-effector specific for holding the meat for that cutting application. This would mean a Stage 2 that touches on application-specific Stages 3 and 4. We propose this approach as holding a range of different cuts of meat would require a very flexible/adaptable end-effector; a potentially expensive and time-consuming development step. Further, by getting an application in-use in the industry, further development can be industry-led and return the earliest benefits.

The next Stage is to improve the useability. In this regard, during our work we identified several areas for improvement, including, image-based cutting and an operator-informed mode. We parked these options and opted for the simplest system for proving the concept.

6.1 2D Operation

Our work to date has shown that we can complete simple cuts, effectively cuts that only require considering two dimensions e.g: Chops, Osso Bucco, Oxtail, Bone-in steaks.

There is an opportunity to progress the complexity of the cuts e.g.:

- cuts with a requirement for 3D considerations e.g., chine bone and feather bone removal or
- cuts that need to consider features in the cut e.g., cutting between rib bones (Frenched Rib Roasts)
- extremely challenging/dangerous cuts e.g., canoe cut (Femur/Humerus bone cutting for access to marrow)
- splitting forequarters and middles
- lamb shanks, hock removal

The system could be developed for 3D cutting. Such a system could be developed to undertake vision/algorithm-based cutting, potentially breaking down large cuts but whilst using methods that leverage the agility and accuracy of 6-axis robotics and the knowledge of boning-room saw operators.

6.2 Smarter System

Many of the automated cutting machines use informed cutting, that is:

- Weight-based cutting for retail cuts
- Optimised cutting to maximise value (and minimise waste)

Using this shadow-robot style of system, could be an alternate way to similar outcomes without the high equipment costs and large equipment footprints of linear automated machines.

Into the future, thinking about work being conducted by others, there is also the possibility of even smarter applications.

Further flexibility could also be added with the addition of machine learning. Using a machine learning framework could speed up the path to market for a wider range of cutting applications.

7.0 Conclusions / Recommendations

This work has successfully proven the application of a shadow-robot concept to cutting meat on a bandsaw. So there is good potential for removing staff from dangerous bandsaw operations.

We are not aware of similar systems so we have proceeded with a provisional patent to cover the work described here. A provisional patent was filed in January 2022.

It is our recommendation that this work continues to Stage 2, where Stage 2 includes both increasing useability and develops a specific application with associated end effector, allowing the earliest potential uptake of the approach.

The recommended improvements of useability are covered in the next section.

8.0 Future Work

As noted in the AMPC, theme on a page (Appendix 1), it was proposed that Stage 2 focus on aspects such as speed and useability, with later stages considering the end effector and applications in processor facilities. We would seek to:

- **Extend Software and Robot programming** to include:
    - Blade Protection
    - Extend the User Interface
    - Improved Vision Code
    - Improve the speed and accuracy of the Robot Operation
- **Improving Usability & New operating modes to include:**
    - 3D cutting.
    - Operator-informed mode
    - Use of the Meat Image
- **Develop needs of Specific Applications**
    - Consult with industry to develop a list of applications for beef and lamb/ cuts and saw size.
    - Develop and build an end-effector for this application; this getting the system into use faster.
    - Out feed conveyor – removing cut product
    - Consider swarf/debris removal

There is also the potential to make the system smarter but this would be work in the longer term.

9.0 Appendices – AMPC R&D Theme on a page