AMPC
AUSTRALIAN MEAT PROCESSOR CORPORATION

Remote Operations (Shadow Robots) – Stage 1

PUBLIC FINAL REPORT

Contents

1.0 Executive Summary

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).

An Innovation Theme on a Page (ToaP) has been developed for this program of work and shows both the proposed development stages of the area. At the conclusion of all development stages, Australian beef processing facilities can aim to have operational staff undertaking certain processing tasks using a type of shadow robot concept. The operator may be in the processing room, e.g. at-line or in a control room, whilst eliminating potential for injuries. Other focus areas for desired achievement include: (1) provide a wider pool of staff suitable for the task, and or, a role for light duty staff, and or, staff with less mobility, (2) evaluate if the task can be performed remote from site, (3) using vision systems place virtual marks on the meat part to be cut to guide cutting the meat part to the required specification, and (4) using visions systems or AI ascertain the accuracy of the operator performing the activity for both training and different remuneration considerations. This project is focused on Stage 1 development scope only.

When initially embarking upon the technology assessment journey for shadow robotics in the meat industry, Intelligent Robotics examined a number of possible technological approaches. These were assessed against the potential red meat industry use cases for shadow technology. IR took the specific path of seeking to use the technology for the purposes of (semi)automation, as opposed to focussing on potential training applications. In IR's view, the key value drivers for the technology lay with the following considerations:

- Force multiplication – using an operator to leverage the strength of remotely controlled robotic arms to
  perform tasks. This would have the benefit of expanding the available workforce (operators selected on skill
  rather than strength or mobility), improvement in production efficiency (less fatigue), and increasing safety;
- Remote operation – the potential to draw upon labour in locations which are remote from the plant, thus
  increasing the labour pool available; and
- Best suited for applications which are challenging to fully automate.

In considering all the relevant factors when assessing the technology available in this space, it was thought that the most promising technology to explore would be the Haptic Controller. It's a novel technology which, to the best of IR's knowledge at the commencement of its exploration, hadn't yet been explored in Australian for the red meat industry, and seemed to fit the key value drivers. Its use-cases could include any task requiring "grasping" of a knife or tool, and requiring some form of force feedback to the operator during operation. It could also be used to take advantage of the force multiplication advantage of robots. As a starting point, the technology could be evaluated at-line to understand the technology itself, before progressing to being operated in a more remote environment such as in front of screens or through VR. As a new, "blue-sky" technology, the task was to understand where the limitations currently lay against the goals for the technology for the red meat industry.

During initial assessments the technology, the first big challenge which arose was the usability of the device to accurately control the robot. Initial trials were performed with a collaborative robot which the manufacturer of the Haptic Controller had not had much experience with previously. At the commencement of this project, the robot was switched to a Universal Robots UR10e. This is a robot which the manufacturer had the most experience with and, therefore, could best showcase the capabilities of the technology in its current stage of development. The usability of the unit was significantly better. However, the lack of finesse was still apparent and indicative of further development required for the technology.

When considering a trial use-case for the technology in this project, initially "deboning" was chosen. It was envisaged that the haptic-controlled robot would demonstrate, individually, the tasks of: 1) "hooking" and "pulling" meat, and 2) slicing of meat. Soon into design it was realised that this application was too complex as a starting point for the technology, given the high level of control required.

After significant contemplation, the next use-case chosen was Meat Inspection. This demonstration would use the haptic controller to control a robot with a camera attached to the end of it to emulate a meat inspection task. This would investigate the feasibility of using the shadow technology to leverage a trained meat inspector across multiple sites. The technical requirements of the application were a softer entry-point for the technology into the red meat industry. The factory trials and demonstration of the application to AMPC were positive, although the challenge of using 2D screens and lacking depth perception was apparent. This was manageable in this particular task however due to not needing a high level of accuracy. While this was a good use-case to demonstrate the potential use of the technology, industry interest in the application itself was limited.

Based on this feedback, the use-case for demonstration was pivoted towards fat trimming. This was a reversion back towards the initial deboning application, but seen as a simpler entry point to investigating cutting as it involved putting less external inertias on the robot. As a standalone application, it also holds potential given the large number of operators performing this task on a processing line - the potential to draw upon a wider and/or remotely located workforce to perform these tasks in a plant could be valuable to the industry.

The final milestone of the project saw the demonstration of the technology to AMPC. The assessment from this demonstration was that the technology is currently sitting at a Technology Readiness Level of 3 or 4. AMPC were able to quickly come up to speed with using the device, and were able to successfully control the Whiztrim knife mounted to the robot to perform fat trimming passes on a beef brisket primal. However, the usability and finesse of the technology was still an area that needed significant improvement before being ready for a plant environment. It was acknowledged that further training and practice with the device would improve this, but not to the extent necessary with the technology in its current form.

Intelligent Robotics agrees with this assessment and, while it was hoped the technology was further advanced, this was a journey that was required to be able to assess this firsthand. A number of technology options were available to choose from when embarking upon the Shadow Robot investigation, and the haptic controller device, with its joystick-like interface and force feedback was felt to be the most promising when considering red meat applications. It was also a novel technology which, to the best of IR's knowledge, hadn't yet been assessed for the red meat industry.

In reviewing the history of the project work in this space, the ideal space for this technology within the red meat industry is likely smaller than what was first envisioned. In parallel with this project, IR has been investigating the use of semi-automated user interfaces to drive robotics, whereby an operator selects points of interest on a screen (AMPC project 2021-1194). The success and evolution of this technology through that project makes it a stronger and more feasible contender in the space of shadow robotics when compared to the haptic controller. That said, there are still use-cases where the "point-and-click" method may be too simple to adequately direct robotics, particularly in instances where an element of "feel" is required. In these areas, the haptic controller may still be the most promising for achieving remote operation. However the technology needs to improve significantly in terms of its usability and control to become viable for plant use.

Work is ongoing with the manufacturer, including integrating the controller with larger, industrial hygienic robots. This will enable the technology to be fit-for-purpose in terms of environmental requirements in an abattoir, while also unlocking greater force multiplication benefits. The feedback of a robot rollface load cell into the control algorithms may also improve the usability of the technology, which will be critical for progressing it further into the industry.

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).

An Innovation Theme on a Page (ToaP) has been developed for this program of work 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 and secondary goals of Remote Operations via Shadow Robots.

Primary Goal

At the conclusion of all development stages, Australian beef processing facilities can have operational staff undertaking certain processing tasks using a type of shadow robot concept. The operator may be in the processing room, e.g. beside the robot or in a control room, whilst eliminating potential for injuries.

Secondary Goals

Other focus areas for desired achievement include: (1) provide a wider pool of staff suitable for the task, and or, a role for light duty staff, and or, staff with less mobility, (2) evaluate if the task can be performed remote from site, (3) using vision systems place virtual marks on the meat part to be cut to guide cutting the meat part to the required specification, and (4) using visions systems or AI ascertain the accuracy of the operator performing the activity for both training and different remuneration considerations.

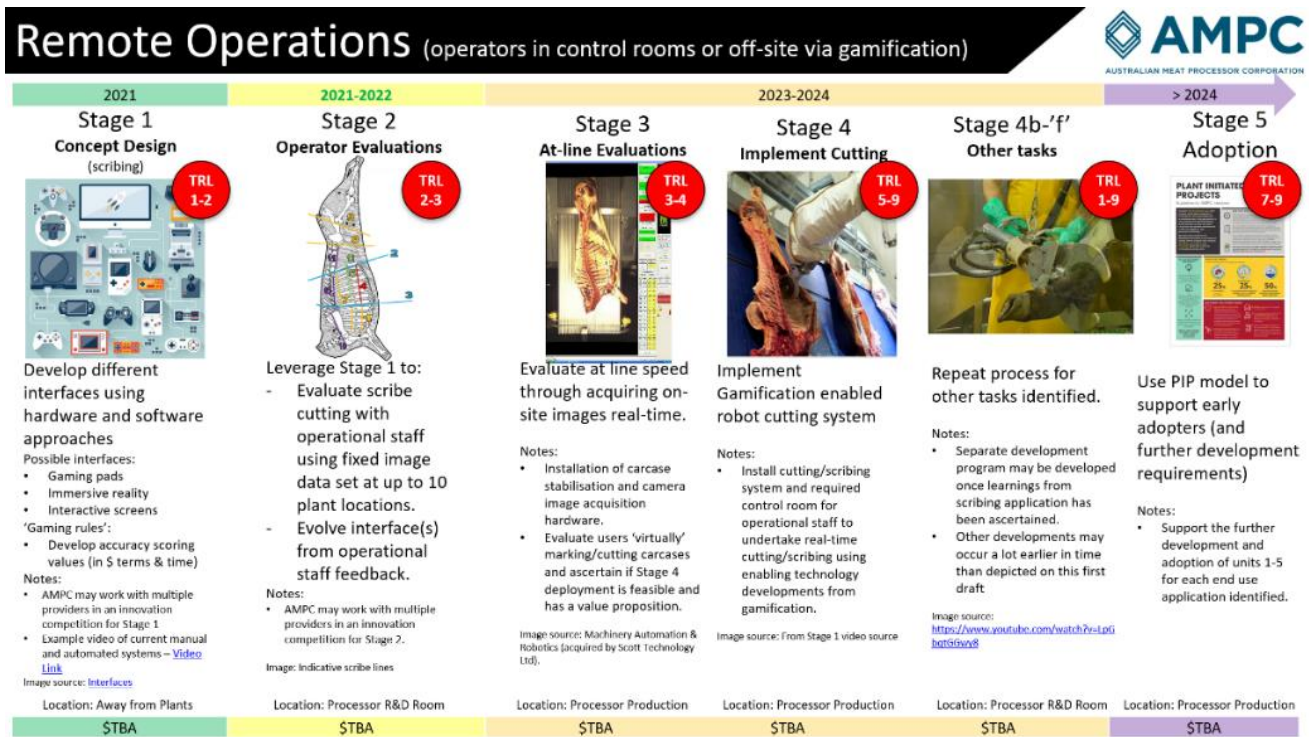This project is focused on Stage 1 development scope only (refer ToaP).

Figure 1 - Shadow Robotics Theme on a Page (ToaP)

3.0 Project Objectives

The outcome of Stage 1 of Shadow Robots is to demonstrate that Tele-remote Operated Robots are a viable technology for the processing sector to consider developing. The result of Stage 5 of the Remote Operation Pathway will aim to have a range of different Tele-remote Operated Robot systems, performing a range of different tasks adopted and installed in multiple sites across Australia.

There are a range of benefits behind the use of Tele-remote Operated Robots that is inline within AMPC's 2020-2025 Strategic plan, including:

1) Removing staff from dangerous operations, via hands-off processing.
2) Increasing safety and wellbeing, by reducing the high-risk nature or certain processing operations.
3) Attraction of people to the industry via demonstrating a wide range of technological operations.
4) Retention of people within the industry by improving working conditions.
5) Development, via developing tasks that require higher skills and intellect.
6) Increasing carcase primal profitability through optimisation
7) Enabler for acquiring product and processing formation in order to leverage data insights.

Stage 1 of Shadow Robots will allow for the evaluation of tele-remote operated robot use cases, with the aim to have one use to develop and deploy within industry in the short term.

The objectives of this project are to evaluate the concept of shadow robot-enabled solutions and ascertain:

1. Where the solution can be deployed now within industry
2. Where the solution could be deployed now, with minor changes (e.g. additional vision and sensing required)
3. Where the solution could be evolved for future deployment

3.1 Project Methodology

The project methodology was as follows:

1) Concept design and part selection (Milestones 1 & 2)
2) Purchase parts and modification to any purchased parts (Milestones 2 & 3)
3) Assemble proof of concept system in the factory (Milestone 3)
4) Testing, evolving system (using action learning cycle). (Milestone 4).
5) Successful demonstration to AMPC staff (Milestone 5).

4.0 Methodology and Discussion

4.1 Technology Selection

When initially embarking upon the technology assessment journey for shadow robotics in the meat industry, Intelligent Robotics examined a number of possible technological approaches. These were assessed against the potential red meat industry use cases for shadow technology. IR took the specific path of seeking to use the technology for the purposes of (semi)automation – i.e. having robots ultimately performing tasks on a processing line with physical product, and ideally with a potential pathway from semi-automation (operator-driven) to full automation, by having the operator inputs train processing algorithms. This is in contrast with focusing specifically on it as a training tool.

In IR's view, the key value drivers for the technology lay with the following considerations:

- Force multiplication – using an operator to leverage the strength of remotely controlled robotic arms to perform tasks. This would have the benefit of expanding the available workforce (operators could be selected purely based on skill rather than strength or mobility), improvement in production efficiency (operator performance wouldn't drop due to fatigue), and increasing safety (particularly regarding repetitive stress type injuries);
- Remote operation – the potential to draw upon labour in locations which are remote from the plant, thus increasing the labour pool available. One potential iteration of this would be a "central control room" based in a capital city or foreign country, with workers able to service multiple plants in remote locations; and
- Best suited for applications which are challenging in terms of sensing, and therefore not likely to be fully automated in the near-term.

There were two dimensions to the technology selection – the technology used by the operator to drive the robotic movements, and the way in which they interacted with the environment. Starting with the latter point, four key mechanisms were seen as providing this interaction:

1) Direct observation – whereby the operator is still located adjacent to the physical operating line ("at-line") and directly observing the robot performing the task as the operator is controlling it. This approach would have the greatest level of control and feedback, and would be possible to perform over extended periods of time. The main issue with this approach is that it isn't truly remote, and would likely lock the operator into performing single tasks, thereby minimising the potential for increased labour efficiency. That said, there would still be the potential of using a single operator for a particular task where two or more are currently utilised on the processing line due to improved efficiency and lower fatigue. Direct observation may however be a feasible 'first step' for the technology.

Figure 2 - Direction observation use of shadow robots

2) Screen – whereby the operator is located remotely from the operating line, but controlling the robot by observing camera feeds on a screen. This approach would result in a truly remote implementation of the technology, and could be realised as the "remote control room" environment seen in mining. However the primary concern would be the usability given the lack of depth perception.

Figure 3 - Remote operation of mining equipment

3) 3D Screen – similar to the screen implementation, a 3D screen can be used to allow the operator to have depth perception when performing the task. This appears to be the implementation used in some cases of robotic surgery. The number of technology providers in this space however is limited, and the ability for an operator to work for extended periods of time in front of 3D screens is questionable.

Figure 4 - Surgery using Polarised 3D screen technology

4) Virtual Reality Environment – whereby the operator wears VR headsets and performs the tasks in a virtual emulation of the real-world environment. This approach would have the benefit of the operator being truly remote to the operating line, while being able to interact in a 3D environment. The primary concern with this approach would be the ability for people to operate in this environment for extended periods of time.

Figure 5 - Surgery using VR

In terms of the technology used to drive the robotic arm, a number of technologies were evaluated:

1) Tracking sensors – whereby the operator has tracking sensors on their hands, which are used to relay motion into the VR world and ultimately to direct robotic motion. This would allow the robot to move, matching the hand motions of the operator, to do things like performing cuts. This would require operating in the VR world, and the operator would not receive any form of physical feedback on the task they are performing (e.g. they wouldn't be able to "feel" the engagement of their knife or saw with a piece of meat, and couldn't adjust their movements accordingly). Given how important physical feedback is to many red meat processing tasks, it was felt that this would be too limiting for the use-cases IR was looking to explore.

Figure 6 – Driving a robot using Tracking Sensors in VR

2) Gloves – whereby operators are wearing gloves which are used to move a robotic arm and control a hand-like end effector. These can be used with all four of the aforementioned environmental options. These can be provided with tactile feedback, as well as force feedback through the gloves themselves. In theory, this would enable the operator to perform tasks with significant dexterity, and allow a range of haptic feedback mechanisms. The costs of this technology when coupled with the haptic feedback is significant however. When considering the range of tasks in a meat processing plant as well, the individual finger dexterity and force feedback through each finger may be overkill. The operator, wearing thick gloves, will tend to "grasp" a knife and tool and work with their entire upper limb. Furthermore, due to wearing gloves, the utility in tactile feedback on the fingertips is likely limited. One potential use-case for this however could be inspection tasks requiring palpation.

Figure 7 - Driving robots using Gloves

3) Haptic Controller Arm – whereby operators grasp a controller joystick and use it to direct a robot's motion. Force feedback can be provided through the joystick back to the operator based on the resistance the robot is feeling while interacting. These can be used with all four of the aforementioned environmental options. This type of controller doesn't enable hand-level dexterity or feedback, but allows good emulation of tasks involving the upper limb. The costs of the technology, while still significant, is much less than the haptic-enabled gloves.

Figure 8 - Robotic surgery using Haptic Controller Arm

4) "Point and click" semi-automated interface – whereby operators click key points on images displayed on a screen to guide a robot to perform a task. This wouldn't give any physical feedback to the operator, but would allow the robot to be guided through operations for which the sensing algorithms haven't yet been developed. The cost of the technology is relatively low and would most easily lend itself to a "remote control room" or even decentralised workforce environment due to the lack of requirement for any specialised equipment.
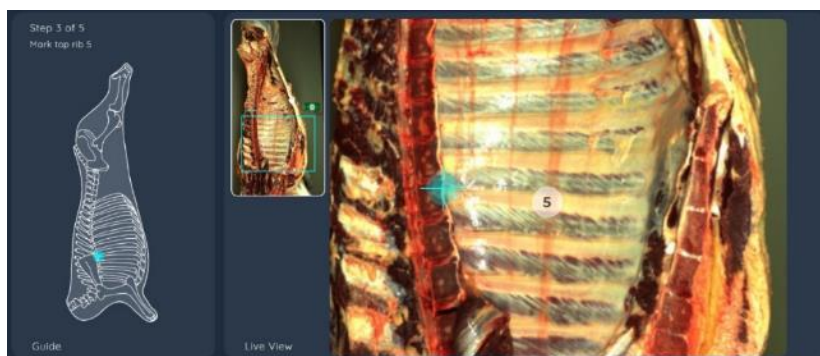

Figure 9 - Performing beef scribing using a semi-automated user interface

In considering all these factors, it was thought that the most promising technology to explore would be the Haptic Controller. It's a novel technology which, to the best of IR's knowledge at the commencement of its exploration, hadn't yet been explored in Australian for the red meat industry, and seemed to fit the key value drivers. Its use-cases could include any task requiring "grasping" of a knife or tool, and requiring some form of force feedback to the operator regarding the engagement with the piece of meat being worked upon. This seems to cover a large range of tasks, particularly on the slaughter and boning room processing lines. It could also be used to take advantage of the force multiplication advantage of robots to allow a larger workforce access to more processing tasks. As a starting

point, the technology could be evaluated at-line to understand the technology itself, before progressing to being operated in a more remote environment such as in front of screens or through VR.

It should also be noted that IR is investigating the semi-automated user interface option as well through AMPC project 2021-1194.

As a new, "blue-sky" technology, the task was to understand where the limitations currently lay against the goals for the technology for the red meat industry.

4.2 Deboning Task Investigation

4.2.1 Evaluation of Deboning Tasks

Initially, deboning tasks were researched and evaluated in order to come to a conclusion of what deboning tasks should be attempted as part of the test, evaluate and evolve step of the project. This was carried out through watching a range of different videos to determine a lower risk deboning task to trial. The result of the investigations was that some of the deboning processes on the butt was to be carried out. This was chosen due to the less intricate knife work, and the large pulling forces required to pull off certain parts of the meat while nicking the muscle seams.

Figure 10: Beef Butt Deboning

4.2.2 Initial Design of Trials

Once the deboning tasks had been investigated and evaluated, the initial trials were designed. These trials were planned to be an initial approach that would evolve based on trial results, rather than being plans set in stone. The designs allowed for the determination of what would be required for the initial trials, so that components could be designed and acquired for testing. These trials were designed with the use of the haptic controller device, to allow for the haptic feedback required for beef deboning. The initial trials designed were:

Trial Number	Trial Name	Trial Description	Questions Answered
1	Cutting of meat	Mount a knife to the robot roll-face and attempt to cut meat, to see what we can learn.	• How does it feel to cut the meat? • Does the robot have the strength to cut the meat? • How much force feedback to we get? • Are there any other considerations before continuing trialling?
2	Dexterity evaluation- shape tracing	Draw a shape on a piece of cardboard and attempt to trace it from the robot, with a pen in the gripper. Compare this to a manual trace.	• How well are we able to trace the shape with a robot? • How does it compare to a person attempting to trace a shape?
3	Pulling testing	Use the hook mounted to the robot to pull on surfaces.	• How hard can the robot pull? • Does the robot trip out at all while pulling with large forces? • How does the force feedback feel?
4	Ham leg cutting	Hang a ham leg on a stand and perform some cuts and pulls on a ham leg.	• What can we learn? • Is there anything we need to take into account before trying beef deboning? • How well can we cut and pull on the ham leg? How easy is it?
5	Beef Butt Deboning	Hang a beef butt on a stand and perform some cuts and pulls in line with Deboning tasks	• How well can we debone the beef butt? • How easy is it and how does it feel? • Is this worth pursuing? • Is there any other tasks that could be performed?

Figure 11- Initial Trial Design

Based on the designed trial, the components required were identified, designed and acquired.

4.2.3 Design of End Effector

For deboning tasks, two end effectors had to be developed for trialling the technology. The two end effectors required were a hook to be mounted to the robot roll-face, and a knife.

Boning Knife End Effector

To keep in line with what is used within industry, a Victorinox boning knife was chosen and acquired for the trial.

Figure 12- Boning Knife

Based on the requirement to hold this knife in a "Gripper", a small mountable clamp was found and acquired to hold the knife.

Figure 13- Knife Gripper Clamp

Based on this, an adapter plate was designed to allow for this clamp to be mounted to the robot roll-face.
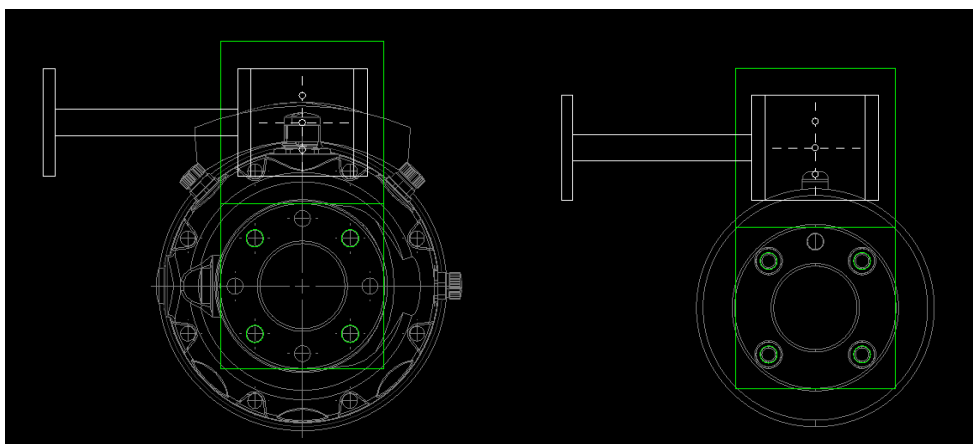

Figure 14- Gripper Adapter Plate for Iiwa (Left) and UR10E (Right)

Boning Hook End Effector

The boning hook end effector was the next end effector to be designed. In addition to the knife, a boning hook was purchased for the pulling parts of the trials.
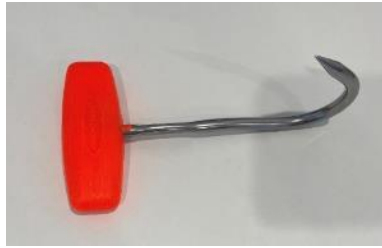
Figure 15- Purchased Boning Hook

Based on the larger forces required on the hook relative to the knife, it was decided that holes would be drilled into the handle of the boning hook, so that it could be mounted directly to the rollface of each robot.

4.2.4 Design of Stand

In order to make the trial as applicable to the real world as possible, a stand was designed to allow for the beef butt to hang from a hook, as would occur in a processing plant. In order to assist with supporting the meat, a slanted backing board was also included to make the cutting easier. The stand was designed to allow meat to hang from a hook as in current processing plants, so that it could be cut while the robot and haptic controller were mounted on a stand.

A hook and skid was purchased to replicate hanging methods in processor facilities. The hook purchased was suitable for 12mm rail, which influenced the design.
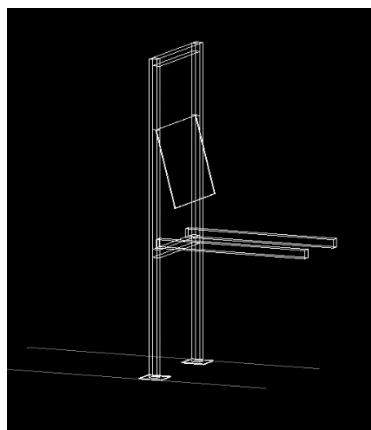

Figure 16- 12" Beef Skid hook

Figure 17- Designed Stand

4.2.5 Trial Design Setup

As a result of each of the steps prior, the final setup for the trials were designed. The visual representation of the trial setup can be seen below.
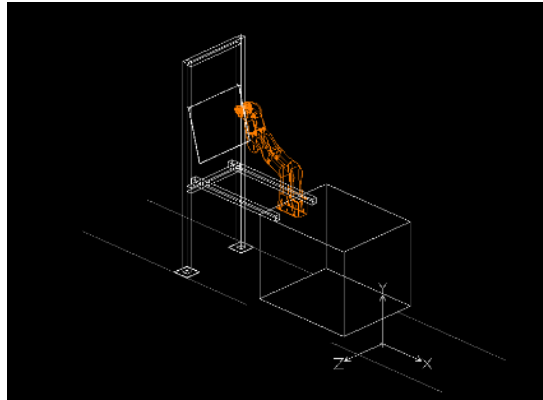
Figure 18- Trial Setup

4.3   Redirection: Inspection Robot

At this stage of the project, it was decided that there would be a redirection in the application to be carried out by the Tele-remote Operated Robotic System, to expedite the path to adoption. This redirection arose through a conversation with AMPC, to provide a lower risk task to allow IR to get to the installation of a system on a processor's site quicker. An issue was also identified whereby the forces required by this application were not suitable for a collaborative robot. As a result, the deboning trialling activities were put on hold to then allow for the redesign of the system based around the new application.

The chosen application, based on discussions between IR and AMPC, was decided to be carcase inspection. On the processing line, operators are required to inspect a carcase for faeces, ingesta or other contaminants. This is a relatively skilled job, due to the training required to identify contaminants on a carcase. As a result, if this job is able to be done remotely, it could assist in widening the labour pool and help in retention of skilled workers.

Figure 19- On Line Beef Carcase Inspection

Based on this new application, the concept was developed. The final concept, after stages of development, will involve a UR10E robot on a stainless-steel stand, with a streaming camera connected to the robot's roll-face, and a camera behind the robot to replicate where the human head would be. As this is a non-contact task, it would be ideal for demonstration with a collaborative robot.

Figure 20- Possible UR Stand Concept

The robot system could be battery powered, to allow for the system to be moved around easily without excessive cabling causing problems on the processing floor. This will mean multiple WIFI systems to allow for the passing of data between the control centre, and the robot unit.

In addition to the robot stand, there could be a control centre for operation. The operator will be in a separate room (away from the processing floor) with a haptic controller device and a large monitor to show the two camera views for the operator. The operator would then be able to perform the carcase inspections from a location away from the line.

In addition to previously stated benefits, there is likely extra assistance able to be given to operators. Through AI, an assistive mode may be able to be built in the future, helping identify regions of interest where possible contaminants may lie. Using such a system is advantageous as the robot does not have to be fully washed down as it is not a food contact surface, opening up the ability to use collaborative robots for such a purpose. This allows for a movable, smaller footprint robotic system that is safe enough to be placed on a line next to operators.

As a result of the redirection, the new requirements for this project are:

1) Concept design of the system.
2) Electrical design of the system.
3) Mechanical design of the system.
4) Being prepared for purchase and manufacture of the required components.

4.3.1 Electrical Design

Robot Roll-Face and Shoulder Camera Selection

The camera selection is integral to the system design. If the image is not sharp enough, the operators will not be able to detect the contaminants on the meat. Conversely, if the frame rate is not good enough, the robot will be harder to control. As a result, there needs to be a happy medium between the frame rate and the pixel size of the camera. Several, different camera types were evaluated, and an IP camera was chosen. This type of camera was

chosen over a typical industrial camera due to the varifocal lens that will allow the camera to focus differently, rather than the fixed focal lengths typically used in industrial applications. A network camera was chosen, due to the FOV relative to the carcase at around 2m from the carcase. At this distance, the rear camera allows for a 3m vertical span, which will be enough for the inspection.

Visualisation Selection

The visualisation is quite an important part of the system, as the operator needs to be able to clearly see what they are doing, to be able to properly inspect the carcases. As a result, the image needs to be large enough for the operator to see both the roll-face camera, and the over-the-shoulder camera simultaneously. As a result, a 50" UHD TV was chosen (to use the HDMI interface to display the high-resolution images) and a stand.

4.3.2 Mechanical Design

Robot Stand Design

The robot stand is another important component, which needed to be designed up for the next stage of the system. The Robot stand needs to be movable, able to be levelled out and allow for some protection of electrical components from water ingress. As a result, a stand was chosen to be purchased for the collaborative robot and modified to fit the requirements of the movable system.

This allowed for the robot to be moved around the trial location easily.

Camera Adapter Plate Design

Based on the camera selection, an adapter plate was designed for the Robot Rollface to allow for the camera to be mounted to the robot.
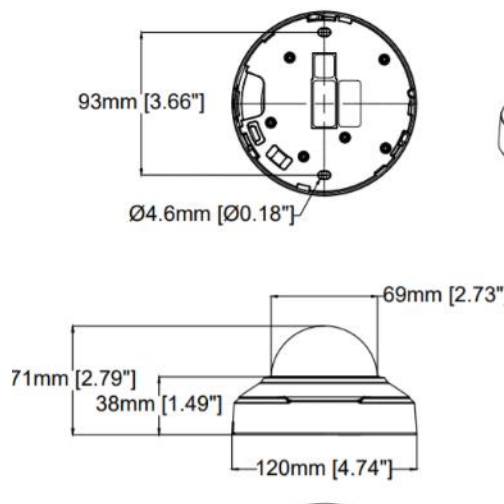

Figure 21- Camera Base Mounting

An adapter plate and a right angle bracket was designed to perform the mounting. These two brackets were designed to allow for two possible mounting angles to determine which was easier to use with the robot.
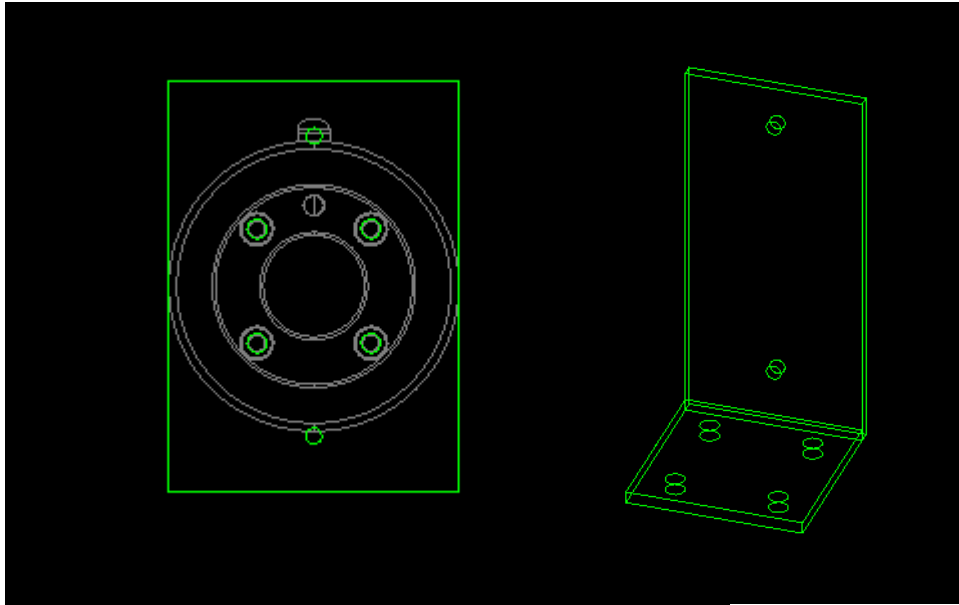
Figure 22- Adapter Plate and Right-Angle Bracket

4.3.3 Software Design - Streaming Program

In addition to the mechanical and electrical design, there is some software design to be carried out. The TV display must be able to show the feed from the cameras, and as a result programming will be carried out in order to give the user a clear visualisation of the carcase they are inspecting.

As a result, there will be GUI, streaming and image acquisition software modules created, for the next stage of development for shadow robots. Based on the decision to use network cameras, the cameras' streaming platform will be used for these trials.

4.3.4 Roll-Face Camera Installation

Next the roll-face camera was installed, using the previously procured adapter plate. An ethernet cable was also run down the length of the robot, to power and communicate to the network camera.

Figure 23- Installation of roll-face Network Camera

The ethernet cable was run into a POE switch to allow communication to an external PC.

4.3.5   Overview Camera Installation

Next, the overview camera was installed. The idea behind this camera is to allow for a more comprehensive view of the robot in space, so that there is more depth perception for an operator. The telescopic mount was mounted to the stand's surface behind the robot, and the camera was subsequently mounted on the stand.

Figure 24- Installation of Overview Network Camera

This camera was also plugged into the POE switch for communications to the base station for the next stage of the project.

4.3.6   Full System Installation

Finally, the complete robot system was finished by turning on all of the electrical components, placing the banner in front of the stand and moving the robot. This ensured that the system was able to be powered up, connected and moving as per requirements.
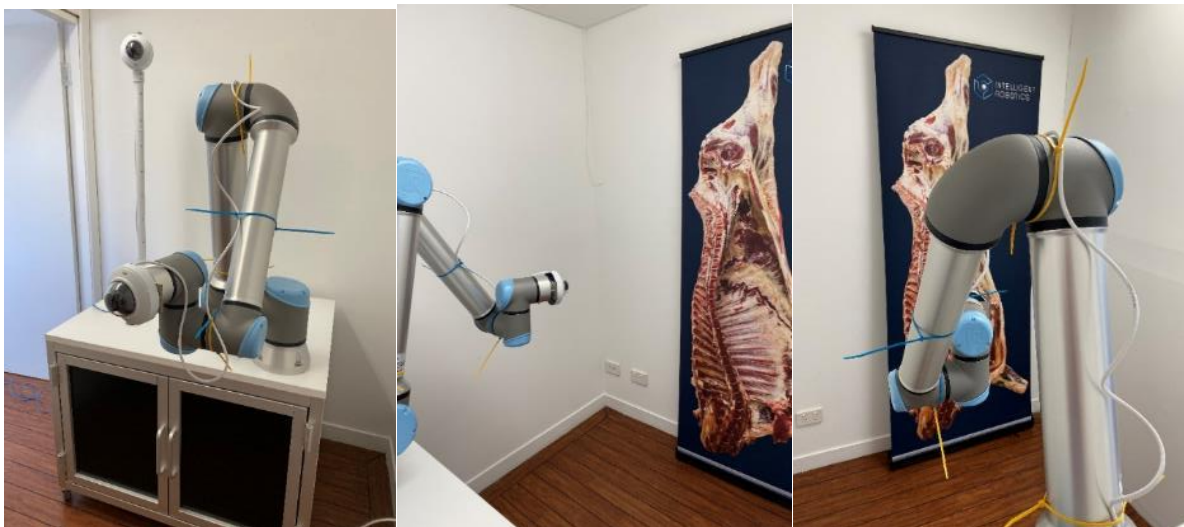

Figure 25- Whole Robotic System Assembly

Once setup, the robot is ready to begin programming for the next section of this report, where the evolution of the system is begun.

4.3.7 Workstation Setup

The next stage was the setup of the workstation. The workstation is the location where the operator will sit and control the robot, while it is on the abattoir floor. It is important that it is comfortable, and ergonomic. For this trial, one of the desks at the office were set up as this workstation, with the Force Feedback Control unit.

Now setup, the workstation is ready for the development of the software and evolution of the system as a whole.

4.3.8 Viewing of Camera Footage

The last component of the setup was to connect to the cameras and ensure that they had the correct field of view for the completion of the assembly. The cameras were connected to and given IP addresses. Once setup, a Project Server was used to view the images coming from the cameras.

4.3.9 Demonstration to AMPC

The setup was demonstrated to the AMPC team for review. The general feedback was positive, and that it appeared to be a good entry point for examining the technology within the red meat industry. There were some comments made however regarding the ability to control the robot through the haptic controller. The usability of the system was significantly better than the setup used during the Beef Week demonstration, which involved an iiwa robot. This was due to the extensive testing and tuning performed by the manufacturer and IR on the unit with a UR10e robot. The UR robot is also a robot with which the manufacturer had more experience interfacing with. That being said, it was still challenging to get used to some of the anomalies in the motion. It was acknowledged that, with proper training and more time to familiarise with the device, this could improve. It did however reinforce that the technology was not yet ready for the intricacies required in the deboning task initially targeted.

The other point raised was the somewhat challenging nature of operating the unit through the 2D screen. While the second camera offered some positioning feedback, the lack of direct depth perception was definitely noticeable and took some getting used to. Given this particular application does not require a high-level of accuracy however, it was still perfectly suitable for this use-case. It is a consideration that should be taken on board however in the future where higher levels of accuracy are required.

4.4 Redirection: Fat Trimming Application Trial

In continuing the work described in the previous sections, the Shadow Meat Inspection use-case continued to be developed. In parallel with these activities, Intelligent Robotics visited a number of sites with AMPC in order to gauge industry interest in the use case, and to find a suitable partner for the trials. During these visits and processor discussions however, it became clear that this use case had limited interest.

In reviewing the Shadow technology with AMPC once more, the use case of fat trimming was suggested. In this instance, the UR robot would be fit with a Whizard-type trimming knife, and the haptic controller would be controlled to trim the fat off beef primal. In discussing this application with a processor, it was concluded between AMPC, IR, and the processor that, while the use case would be a good demonstration of the technology, the technology itself was premature for exposure to the industry. A site demonstration may therefore be counterproductive to trying to progress the technology, with processors potentially "switching off" from the technology by focusing on what it can't do, rather than where it could be headed. Based on this discussion, it was therefore decided to:

- Progress with Fat Trimming as a use case demonstration for the Shadow technology
- Demonstrate this use case to AMPC at IR's facility, in a controlled environment

This change in direction brought us back to a similar use case originally envisaged – boning of a beef quarter – but with lower force requirements allowing it to be demonstrated with a UR.

4.4.1   Beef Primal and Fat Trimming Knife Specifications

To perform the trials successfully, a 'fatty' beef primal needed to be chosen. That is, a primal with sufficient sub-cutaneous fat coverage to allow for significant fat trimming to be performed. After doing research and investigating with a number of butchers the Beef Brisket was chosen as the best beef primal. This led to the standard Fat Trimmers being chosen with the model of 1000 and 1300.

In regard to the fat trimmer, a pneumatic one was chosen as after talking with various suppliers that was the recommended type. The blade size of 80-85mm was also recommended for the testing purposes that we were using it for. The trimmer met the industry standards for fat trimming beef primal cuts in Australia. The Bettcher Whizard AIRMAX MACH 3 trimmer took a flow rate of 14CFM at a pressure of 6 bar and was procured.

The below figures show the tools and cuts of meat used in more detail:

Figure 26: All meat related tools that were used

Figure 27: Beef Brisket (primal cut used for trials)

4.4.2   Design of Trials

To start the planning for the trials, the investigation into the applications of how the robot would be used needed to be completed first. This is such that a proper trial plan can be developed for what trials are necessary to test for the desired task.

With the goal in mind for the robot to trim fat, the trials were designed around achieving this task. The trials that where designed are as follows:

Trial Number:	Trial Name:	Trial Description:	Questions that need to be answered:
1	Dry Test	Run the robot with no tools attached and see how the robot would interact with the Shadow Controller.	• Is the robot responsive to the Shadow Controller? • Does the Controller work as intended? • Is the robot working as intended? • Is the speed and force feedback working with the scale factors of the program? • Is the program set-up quick and of a reasonable difficulty?
2	Cutting of Meat	Running the robot with the Fat Trimmer and see how both the robot and tools act in conjunction with the task.	• Does the Trimmer fit securely into the bracket for the robot? • Does the Trimmer sit at a good angle for cutting fat? • Is the controller responsive with the tool on the roll-face of the robot? • When trimming fat, is enough being trimmed? • Does the robot trip out with not enough force to cut the fat? If not, then when does it trip out?
3	Force Feedback Test	Pushing the tool using the robot to see how sensitive the force feedback to the controller as well as the Shadow Controller.	• How hard does the tool push against the meat when turn off before it trips out? If not, then why? • Does the Trimmer slice the fat and not trip out the robot when on? • Is the force felt to the specified scale on the Shadow Controller? • Does the Force Feedback feel accurate?

4.4.3   System Installation

For this installation, the bracket needs to be attached to the role face of the robot in the correct manner. The bracket has one bolt hole where a M6 bolt can be thread through. The bracket needed to be installed on the top left corner of the rollface.

Figure 28: Brackets used to hold the trimmer in place

Fat trimmer:

The Fat Trimmer will need to be slotted into the holding bracket from the top facing upwards.

Figure 29: The Bettcher Trimmer (Side Profile)

Figure 30: The Bettcher Trimmer (Top Profile)

Once the Trimmer is in place the bolt that will hold the trimmer in place needs to be tightened. This bolt needs to be extremely tight as the Trimmer will shake and vibrate when cutting or turned on. Getting the bolt checked by another person to check if it is tight is necessary due to safety concerns.

When the Trimmer is in place it will look like the following:

Figure 31: The mounted fat trimming knife

Tray:

A stainless-steel tray is needed to ensure that the testing is as hygienic as possible, and the equipment also stays hygienic. For testing the tray needed to be secured to the testing table so that it does not move when fat trimming. The meat also needed to be secured to the tray, this was done by using a tray that had built in metal spikes allowing the meat to be effectively, impaled onto the tray.

Figure 32: Stainless Steel Tray with Spikes

This was done by using double sided tape to keep the tray in place.

Industrial Strength Double Sided Tape

Figure 33: Tape placed on the tray

Compressor:

Due to the requirements of the fat trimmer being 6bar at 14CFM the Chicago Air Hush100 Compressor was chosen to ensure the blade ran to its requirements.

Figure 34: Chicago Air HUSH100 Compressor

To set it up the Trimmer needs to be first be connected to the compressor via the compressor cable.

Figure 35: Compressor and Fat Trimmer hose connection

The final the compressor gages should be as follows:

Figure 36: Compressor showing the gauge settings

4.4.4   System Development

To set up the whole system there are four main steps that need to be carried out. These steps are necessary to allow the robot to meet the requirements. The following steps are:

1.   Robot Programming and Calibration
2.   Robot Force Control Calibration
3.   Robot Fat Trimmer Tool Calibration
4.   Shadow Controller Calibration

4.4.5   Safety Risk Assessment

For testing and trialling to being a safety risk assessment needed to be carried out to ensure that any and all handling or work done with/to the robot is conducted in a safe and careful manner. Having designed the trials already meant that a functional and well-rounded safety risk assessment can be performed.

Below is the safety risk assessment for the trials to be carried out for this report:

Hazards

Work equipment

Possible harm

Hit, Crushed, Cut and Pierced by moving robot

Existing control measures

- The robot is collaborative and therefore will stop on a collision.

- Operation is always handled by an IR engineer with an E-Stop nearby.

- Warning near-by people before starting.

- Ensuring workspace is free of dangerous objects before starting.

Electrical

Possible harm

Electrocuted by cables

Existing control measures

- Ensure that the wall plugs are turned off and unplugged before opening electrical cupboard

- Check all live wires before starting the robot

- Turn off the socket switch before unplugging or plugging into the mains power.

Uneven, Wet or Slippery Floors

Possible harm

Tripping Over Objects/Cables

Existing control measures

- Watch where you are walking

- Include signage around all the cables and other dangerous objects around the work area

- Add safety foam on sharp edges

Manual handling

Possible harm

Pneumatic or electronic knife perceiving/slicing

Existing control measures

- Ensure workspace is free of people before activating the knife

- Ensure an E-stop is within reach when starting knife and performing the knifes process

- Put up signage with the relevant warnings

- Verbally warn anyone in the workspace before starting

Public or Visitor Access

Possible harm

Injured by robot/robot tools

Existing control measures

- Watch robot while actions are being performed

- Limit use and access to the robot's work area

4.4.6   Trial Results

Pre-Trial Preparation:

Before the trial can begin, some small examinations and exercises needed to be performed. First, the stainless-steel tray needed to be checked to ensure that it would not move when the beef primal was being trimmed. This was done by attempting to move the primal and the tray by hand with more force than the robot would be able to exert. Once confirmed that it would not move, the fat trimmer then needs to be checked. When turning on the trimmer there should be minimal to no vibration through the bracket. This is to ensure that the bracket has gripped the Trimmer properly and it will not fall out during operation.

A safety risk assessment was carried out before any trial would take place.

Pre-Trial Training:

While driving the robot is very easy to learn and quick to get operational, there is still a learning curve. Therefore, some small training exercises took place before the trial began. This included the following:

1. Using the Shadow Controller and Calibrating it to the Robot rollface.
2. Training the motion of Trimmer using the Shadow Controller with no meat.

Figure 37: Potential meat trimming point A

Figure 38: Potential meat trimming point B

Trial Results:

The Fat Trimmer was able to successfully trim the fat on the trial primal. Below are examples of this:

Figure 39: Meat and Trimmer before fat had been trimmed (Side angle)

Figure 40:Meat and Trimmer before fat had been trimmed (Top angle)

Figure 41: Close-up of trimmed fat

Figure 42: All fat trimmed for the trial

Expected Results:

Before beginning and performing trials some expected results where first outline and then the trial was designed. This 'working backwards' approach allowed us to build and design the trial in a way that we can ensure we will meet the requirements of this report, while also attempting to accurately predict the outcome of the results.

When thinking about the desired results there where a few main factors that needed to be taken into consideration to ensure that the requirements where met. These where:

1. The type of meat used to Fat Trim.
2. The type of industrial Fat Trimmer that was going to be used.
3. How the Trimmer will be mounted to the Robot.

The three above considerations where researched and discussed carefully. The first being the type of meat used meant that some investigation into where the meat could be bought and what type of meat is usually fat trimmed, as well as some smaller other factors.

Achieved Results:

As mentioned above, the trial achieved all the tasks laid out. First off, the "Dry Test" accomplished and answered all the questions set out for the trial. These questions being:

- Is the robot responsive to the Shadow Controller?
    - i. Yes, the controller was responsive and there was almost no visible lag between the Shadow controller movement and the movements of the Robot.
- Does the Controller work as intended?
    - ii. The controller worked exactly as was specified. However, was challenging to control.
- Is the robot working as intended?
    - iii. The robot worked as specified.
- Is the speed and force feedback working with the scale factors of the program?
    - iv. The force feedback was working. As per previous experiences however, but the level of finesse requires improvement.
- Is the program set-up quick and of a reasonable difficulty?
    - v. The set up was not as fast as expected but still within the bounds of reasonable and the difficulty was more challenging and required some programming knowledge.

The next trial was "Cutting the Meat" and this trial had overall great results. They were as follows:

- Does the Trimmer fit securely into the bracket on the robot?
    - i. Yes, the trimmer was very secure with very little vibration.
- Does the Trimmer sit at a good angle for cutting fat?
    - ii. The angle became irrelevant as the robot can just rotate to the required angle.
- Is the controller responsive with the tool on the role-face of the robot?
    - iii. The controller is responsive with the tool; however, the program needed some fine tuning to make the controller this way. The controller was also a little difficult to control.
- When trimming fat, is enough being trimmed?

  iv. Yes, the Trimmer works well and is trimming more than enough.

- Does the robot trip out with not enough force to cut the fat? If not, then when does it trip out?

  v. No, the robot can cut fat without tripping out due to the force required. However, when applying a strong sudden force (much stronger than required for trimming fat) the robot will trip usually in-between 150-200N of force.

Another trial that was performed was "Force Feedback" trial. The questions that needed to be answered where:

- How hard does the tool push against the meat when turn off before it trips out? If not, then why?

  i. The robot will usually trip out the robot will trip usually in-between 150-200N of force.

- Does the Trimmer slice the fat and not trip out the robot when on?

  ii. Yes, it does.

- Is the force felt to the specified scale on the Shadow Controller?

  iii. The force feedback is accurate and even feels accurate to the scale set in the program.

- Does the Force Feedback feel accurate?

  iv. Yes, it does.

4.5 AMPC Demonstration

This project was aimed at one specific task of being able to effectively trim fat off a beef primal using the Shadow Controller and an industrial fat trimmer attached to the end of the robot. The demonstrative goal is to give a wider eye into how the technology can be used in its current state but also future pathways for the technology.

Initial set-up

The trial was setup as follows:

1. Firstly, the robot and the work area was to be cleaned and all tools sanitised. This is to allow for a well-preserved hygiene standard.
2. The stainless-steel tray then needed to be stuck to the work area using double-sided tape.
3. Following Step 2, the bracket that holds the Fat Trimmer then needs to be attached to the robot roll-face using the screws provided.
4. The Fat Trimmer can then be placed into the bracket and the bracket can be tightened.
5. The compressor then needs to be connected to the Fat Trimmer via the trimmer tube ensure that the on/off fitting is in between the trimmer and the compressor line.
6. Finally, the meat can be placed on the tray.

UR Robot and Shadow Controller Program overview

In respect to the final Milestone Report a brief overview of how the program for the Shadow Controller and how the program for UR Series 10e works to give the result of the trial performed. Both programs work in conjunction with each other to allow for communication between the controller and the robot.

Starting with the Shadow controller program. The program has been prebuilt and designed to run on a PC using an ethernet connection. The connection runs through the program with parameters such as Force Feedback and

Movement Scale being able to be set in the program. This then runs into the connection box to then communicate with the robot and controller. The controller will also send data to the program such as position location and movement speed.

The robot's program allows for the data sent from the controller and controller program to be feed-in and understood by the robot. The program is just a simple loop that waits for the movement data from the controller to then move the robot to the specified location. The loop also allows data to be sent back to the controller. This data is mostly the joint forces of the robot to enable force feedback to the Shadow Controller. The robots program loop is as follows:

1. Check connection to the Shadow Controller Program.
2. Wait for the Shadow Controller's movement data.
3. Move to location and send updated force feedback information to controller.
4. Wait for new movement data.

Trial Preparation

Before the trial began, some preparation steps and practice needed to take place before the final trial showcase. First, the beef primal needed to be checked to see if it was secured properly to the stainless-steel plate. This is because if the beef primal is not properly secured then the primal may dislodge itself and could even eject around the trial work area. Secondly, the bracket that holds the Fat Trimmer needs to be tightened to ensured that the Fat Trimmer cannot leave the brackets grasp. These are the two main preparation steps for this trial.

A safety risk assessment was also carried out for this trial to limit the risk to people and machinery as much as possible. The main changes where:

- Precautions around the visitors and protection for the visitors.
- Precautions around cables and tripping hazards.

Fat Trimming Demonstration Results and Debrief

First the Fat Trimming application was demonstrated to AMPC by an IR operator. After the demonstration, AMPC then took on the endeavour of trying the Fat Trimming process.

The first notable feedback that was presented by AMPC was that the controller was difficult to use. Issues of the force not feeling quite right and the controller not being intuitive were raised, although it was acknowledged that with proper training and experience the ability to control the robot could improve. There are still some significant improvements that need to occur with the haptic controller technology, and its interfacing with the robot, to enable more finessed manipulation of the robot and to deal with certain motions and areas of the work envelope more smoothly and consistently. There is also the factor of how fast the operator will ultimately be able to perform tasks with the technology in its current state despite extensive training and a high level of familiarity.

As a result, it was assessed that the technology is likely sitting at a Technology Readiness Level (TRL) of between 3 or 4, and still in need of significant development before progressing to commercial feasibility for plant operation. AMPC and Intelligent Robotics then discussed further the development pathway for the technology.

Figure 43: TRL Diagram

The demonstration itself was performed in an "at line" configuration. That is, with the operator directly observing the robot trimming the meat. The reason for this was to best show the capabilities of the technology itself, in its current form. Directly observing the robot allows for the most intuitive operation to be performed. The application could have been presented using cameras and the operator looking at the screen, similar to the Meat Inspection demonstration that was performed. This would have been closer to demonstrating how the technology would ideally be used at a meat processing facility, but would also require to get used to operating through a camera and without depth perception while also getting used to controlling the robot itself through the haptic controller. This is certainly something that can be implemented however quite easily as a next step with the technology. Furthermore, the possibility of using 3D screens or VR could also be examined, although the concerns about being able to operate in these environments for extended periods of time would need to be addressed – something which IR and AMPC both agreed.

4.6   Extra Application Investigation: Scribe Line Marking

Some additional applications were briefly investigated using the same basis as the prior demonstration. This investigation led to a brief look into the applications of remote scribe guild lines as a possible use-case. A trial was then set up to investigate this possibility.

The area then had to be first prepared for the investigation into this use-case. The following show the steps and the setup of the trial and the results yielded:

Figure 44: Scribe tool setup in bracket attached to robot rollface
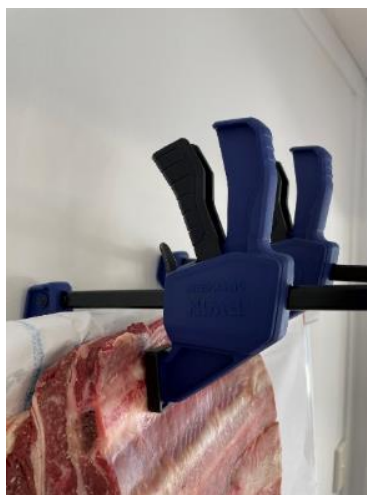
Figure 45: The Beef Ribs hanging in test area
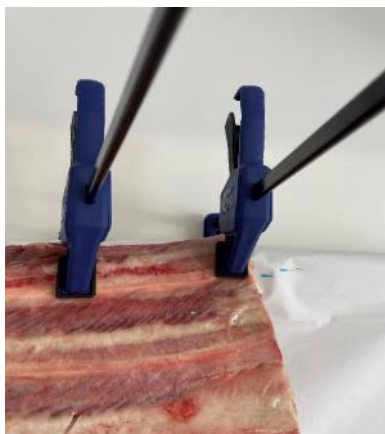

Figure 46: The clamps used to hold Beef Ribs (Side View)

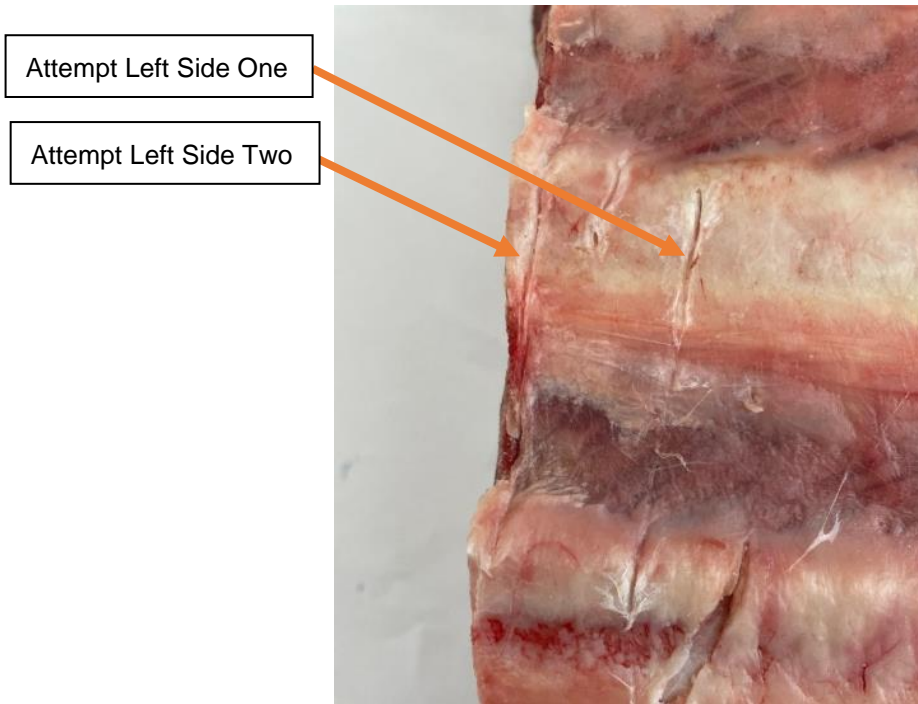*Figure 47: The clamps used to hold Beef Ribs (Front View)*
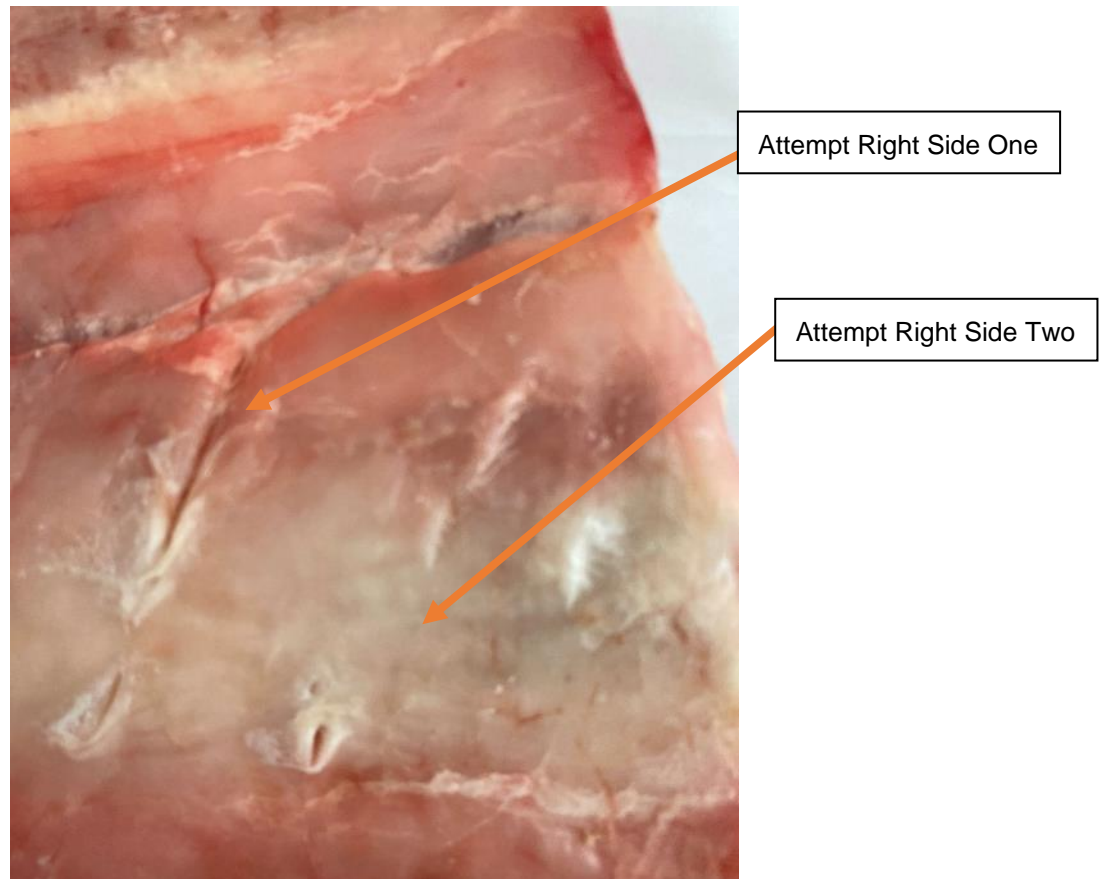
Figure 48: Attempted Shadow Scribe Results

Figure 49: Close-up Shadow Scribe Results

To summarise the investigation into this application, it was not very easy to use or do. The controller was not accurate or fluid enough to be able to perform such a high-precision task. The controller while adequate for fat trimming was not capable of handling the finer smaller movements needed to scribe the lines down with ribs. The rib scribe also needs a constant force and with the controller pushing back with its force it did not handle the task well. Significant improvement in the technology would be required for this to become a plant-ready application.

4.7   Next Steps for the Technology

As described above, the haptic controller technology itself in controlling the robot was rated at a TRL 3 or 4. The technology works in principle but still requires significant development in its usability before becoming "plant-ready". It must also be eventually paired with an industrial robot to be of most value. The manufacturer has commenced work with a robot manufacturer to be able to control their hygienic robot range with the controller, and developments in this area will hopefully continue to drive the technology higher in technology readiness. The controls feedback in this instance would involve a load cell at the rollface, rather than purely relying on motor current values, and it is hoped that this would further improve the usability of the technology.

While the technology readiness level of the technology is lower than IR would have liked in the context of the red meat industry, this is a journey that needed to be embarked upon. AMPC agreed that it was work that needed to be done as the technology does show promise, to explore its viability firsthand.

In debriefing on the demonstration, the alternative approach of utilising "point and click" through a semi-automated interface was also discussed. This is something Intelligent Robotics explored in AMPC project 2021-1194 for the use-case of beef scribing. One other consideration which was raised by AMPC was the feasibility of having remotely located haptic controllers, when compared to the alternative of screens with mouse or joystick control. Certainly from this perspective the pathway of the semi-automated interface seems more promising for the purposes of guiding robotics. Furthermore, the pathway for full automation through the semi-automated interface to teach AI algorithms to "learn" the tasks is also clearer than it is with haptic-controlled robotics. This has been evidenced through the progress the 2021-1194 project has encountered, which transformed from a completely passive interface driven entirely by the operator, into an AI-assisted tool where the operator only adjusts the result as necessary. IR agrees that, for many (if not most) applications, the semi-automated user interface seems to be the most viable path forward for shadow robotics. However there will still likely be applications where this may prove challenging to implement, particularly those requiring an element of "feel" from the operator (such as seam boning).

5.0 Conclusion

When initially embarking upon the technology assessment journey for shadow robotics in the meat industry, Intelligent Robotics examined a number of possible technological approaches. These were assessed against the potential red meat industry use cases for shadow technology. IR took the specific path of seeking to use the technology for the purposes of (semi)automation – i.e. having robots ultimately performing tasks on a processing line with physical product, and ideally with a potential pathway from semi-automation (operator-driven) to full automation, by having the operator inputs train processing algorithms. This is in contrast with focusing specifically on it as a training tool.

In IR's view, the key value drivers for the technology lay with the following considerations:

- Force multiplication – using an operator to leverage the strength of remotely controlled robotic arms to perform tasks. This would have the benefit of expanding the available workforce (operators could be selected purely based on skill rather than strength or mobility), improvement in production efficiency

(operator performance wouldn't drop due to fatigue), and increasing safety (particularly regarding repetitive stress type injuries);

- Remote operation – the potential to draw upon labour in locations which are remote from the plant, thus increasing the labour pool available. One potential iteration of this would be a "central control room" based in a capital city or foreign country, with workers able to service multiple plants in remote locations; and

- Best suited for applications which are challenging in terms of sensing, and therefore not likely to be fully automated in the near-term.

There were two dimensions to the technology selection – the technology used by the operator to drive the robotic movements, and the way in which they interacted with the environment. In considering all the relevant factors, it was thought that the most promising technology to explore would be the Haptic Controller. It's a novel technology which, to the best of IR's knowledge at the commencement of its exploration, hadn't yet been explored in Australian for the red meat industry, and seemed to fit the key value drivers. Its use-cases could include any task requiring "grasping" of a knife or tool, and requiring some form of force feedback to the operator regarding the engagement with the piece of meat being worked upon. This seems to cover a large range of tasks, particularly on the slaughter and boning room processing lines. It could also be used to take advantage of the force multiplication advantage of robots to allow a larger workforce access to more processing tasks. As a starting point, the technology could be evaluated at-line to understand the technology itself, before progressing to being operated in a more remote environment such as in front of screens or through VR.

It should also be noted that IR is investigating the semi-automated user interface option as well through AMPC project 2021-1194.

As a new, "blue-sky" technology, the task was to understand where the limitations currently lay against the goals for the technology for the red meat industry.

During initial assessments the technology, the first big challenge which arose was the usability of the device to accurately control the robot. Initial trials were performed with a collaborative robot which the haptic controller manufacturer had not had much experience with previously. When using the haptic controller to direct the robot, it was difficult to get the robot to smoothly follow the intended path, with lots of "fighting" and "kick-back" by the controller, as well as irregular motion. Extensive tuning was performed to get the technology in a useable state to demonstrate the technology, but it was still short of the expectations for what would be required to perform basic red meat industry tasks.

At the commencement of this project, the robot was switched to a Universal Robots UR10e. This is a robot which the manufacturer had the most experience with and, therefore, could best showcase the capabilities of the technology in its current form. The usability of the unit was significantly better. However the lack of finesse was still apparent and indicative of further development required for the technology.

When considering a trial use-case for the technology in this project, initially "deboning" was chosen. It was envisaged that the haptic-controlled robot would demonstrate, individually, the tasks of: 1) "hooking" and "pulling" meat, and 2) slicing of meat. These two operations together achieve deboning, with the potential future of the application being an operator controlling two robots using two haptic controller units, one in each hand, to perform remote deboning of a beef quarter. Soon into design it was realised that this application was too complex as a starting point for the technology, given the high level of control required. It was also unable to be performed with the UR due to the external inertias involved. The UR is a collaborative robot, with its safety functionality unable to be disabled, meaning that it would be unable to cope with the loads required from the two applications, particularly the "pulling".

After significant contemplation, the next use-case chosen was Meat Inspection. This demonstration would use the haptic controller to control a robot with a camera attached to the end of it to emulate a meat inspection task. This would investigate the feasibility of using the shadow technology to leverage a trained meat inspector across multiple sites to address labour shortages and issues finding and maintaining local inspectors for abattoirs. The technical requirements of the application were thought to be a softer entry-point for the technology into the red meat industry. It's an application which, in theory, could also lend itself well to the idea of a "centralised control room" based off-site, servicing multiple plants in different locations. Using the haptic controller, the camera on the end of the robot could serve as a set of eyes for the inspector, moving around as required to inspect different parts of the carcase in different levels of detail. The development roadmap for the technology could include augmenting the cameras with additional sensing (such as hyperspectral imaging) and using the operator inputs to teach an AI network to eventually flag potential contamination automatically. This application also suited the UR robot as it didn't require any contact or external forces. The factory trials of the application were positive, although the challenge of using 2D screens and lacking depth perception was apparent. This was manageable in this particular task however due to not needing a high level of accuracy when controlling the camera. While this was a good use-case to demonstrate the potential use of the technology in its current form, industry interest in the application itself was limited.

Based on this feedback, the use-case for demonstration was pivoted towards fat trimming. This was a reversion back towards the initial deboning application, but seen as a simpler entry point to investigating cutting as it involved putting less external inertias on the robot. A test with a Whiztrim knife on the UR10e to trim fat confirmed the ability of the robot to cope with these loads. It also requires less finesse and accurate positioning than performing a proper seam-boning task. As a standalone application, it also holds potential – there is currently an army of people performing various trimming operations on beef primals and the ability to draw upon a wider and/or remotely located workforce to perform these tasks in a plant could be valuable to the industry.

The final milestone of the project saw the demonstration of the technology to AMPC through the use-case of Fat Trimming. The assessment from this demonstration was that the technology is currently sitting at a Technology Readiness Level of 3 or 4. AMPC were able to quickly come up to speed with using the device, and were able to successfully control the Whiztrim knife mounted to the robot to perform fat trimming passes on a beef brisket primal. However, the usability and finesse of the technology was still an area that needed significant improvement before being ready for a plant environment. It was acknowledged that further training and practice with the device would improve this, but not to the extent necessary with the technology in its current form.

Intelligent Robotics agrees with this assessment and, while it was hoped the technology was further advanced, this was a journey that was required to be able to assess this firsthand. A number of technology options were available to choose from when embarking upon the Shadow Robot investigation, and the haptic controller, with its joystick-like interface and force feedback was felt to be the most promising when considering red meat applications. It was also a novel technology which, to the best of IR's knowledge, hadn't yet been assessed for the red meat industry.

In reviewing the history of the project work in this space, which has included examining deboning, meat inspection, and scribe mark placing, as well as fat trimming, the ideal space for this technology within the red meat industry is likely smaller than what was first envisioned. In parallel with this project, IR has been investigating the use of semi-automated user interfaces to drive robotics, whereby an operator selects points of interest on a screen (AMPC project 2021-1194). The success and evolution of this technology through that project makes it a stronger and more feasible contender in the space of shadow robotics when compared to the haptic controller arm. That said, there are still use-cases where the "point-and-click" method may be too simple to adequately direct robotics, particularly in instances where an element of "feel" is required. It is thought seam-boning may be an example of this. In these areas, the haptic controller may still be the most promising for achieving remote operation. However the technology needs to improve significantly in terms of its usability and control to become viable in this space.

Work is ongoing with the manufacturer of the haptic controller, including integrating the controller with industrial hygienic robots. This will enable the technology to be fit-for-purpose in terms of environmental requirements in an abattoir, while also unlocking greater force multiplication benefits. The feedback of a robot rollface load cell into the control algorithms may also improve the usability of the technology, which will be critical for progressing it further into the industry.