Final Report

AUSTRALIAN MEAT PROCESSOR CORPORATION

Remote Operations – Shadow Robots

Remote Operations – Shadow Robots (Stage 2, Part B)

Project Code
2022-1202

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Date Submitted
28/10/22

Published by
AMPC

Date Published
28/10/22

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1.0 Executive Summary

This work contributes to a proof-of-concept of shadow-robotics for meat processing. Prior work covered the build of a system designed to remotely control a robot holding meat to be cut in a bandsaw. Further work demonstrated cutting and the implementation of operating modes: manual, semi-automated (with operator input) and operator-informed. In addition, safety features were developed to prevent backing through the bandsaw blade.

The shadow robot system integrated a Kuka industrial robot with a bandsaw using a bespoke vision-tracking and control system. The approach to development was through rapid-prototyping; get it working quickly, use, refine, improve then finalise. Initial testing was basic, cutting chops.

In the current work, the system was advanced to improve the shadow robot system robustness and useability by:

- Developing and demonstrating a 3D cutting mode (e.g. cutting down the spines of a saddle, removing the chump or similar).
- Creating a basic implementation of clearing the bandsaw table of cut meat to direct it for packaging.
- Complete designs for integrated meat in-feed and out-feed.
- Conduct preliminary work on using the bandsaw in combination with knife work (e.g. breaking/cutting/fat trimming).

3D-control of the robot was implemented using fiducial markers. Fiducial markers can be created with known size and shapes. The system has been successfully demonstrated with full 3D motion capability. The responsiveness was excellent (without lag) and the accuracy around sub-millimetre. We tested the system by making more complex cuts e.g. splitting a lamb saddle and cutting the chine bone. The success of this chine cut testing has shown that the shadow robot system, with minimal configuration changes, has the adaptability to be used for different tasks that require 3D motions. The fiducial marker tracking system, the single marker was extended to multiple-markers or “board” fiducial tracking. This increased the reliability and accuracy of the tracking. Notably tracking using fiducial markers presents the opportunity to have specific task-based markers.

Using the system with 3D-control allows more complex angular cuts to be made (e.g. chine bone removal on a beef striploin). In using the system with 3D-control to make more complex cuts we noted that useability was often improved by locking-out or defining some settings. By example, an operator could reference the tracked object against a table whilst have the robot cutting with a vertical offset in the throat of the bandsaw. It also eliminated the system being over responsive for the prescribed task.

In addition to a configuration where the operator-controlled meat to be cut, a second configuration was developed and proven. This was a trimming application where the operator controlled a tool, in this case an electric kebab trimmer. The kebab trimmer was mounted to the robot, and the system was used to trim the fat layer off fresh beef brisket meat samples. In trimming, the system performed with comparable speed and precision as it did during the bandsaw cutting tasks. These two configurations show the versatility of a shadow robot system: control the meat or control the tool.

The shadow robot was demonstrated in a trimming-configuration at the AMPC Innovation Showcase in Melbourne, Victoria in October 2022. The system proved itself to be robust with many attendees having a go at using it. The ease by which a system might be installed in a processing facility was also evident at this event - the equipment was up and running in a day using a borrowed robot. This bodes well for potential retrofits in plants.

In the future, this shadow-robot platform can be tailored for specific meat processing tasks. Doing so will assist in understanding whether the absence of haptic feedback is a limitation. In our experience, with familiarity of use, we have found working by looking only at a screen can work well for simple tasks.

Shadow robots are a great option for capturing the experience and knowledge of a skilled worker, making their job less dangerous and less tiring by having machinery do the hard work. The operator can also work remotely from a control room, either on-site or potentially off-site. Furthermore, in considering some of the repetitive tasks in the boning room, there is opportunity to add machine learning to the shadow robot system and in so doing, shadow-robots could be used on a development path to full-automation, removing staff from tasks completely.

2.0 Introduction

This work forms part of a larger Shadow Robotics project where the overall objective is to prove the use of robots to remove personnel from dangerous processing tasks. For example, a successful development would enable bandsaw cutting without an operator holding the meat part being cut.

The shadow robot included the following equipment:

- Kuka KR10 robot and controller,
- 1.5kW bandsaw,
- an object tracking camera mounted over an object tracking table,
- a robot observer camera,
- safety caging that separates the operator from the robot and saw,
- a basic clamp to hold the meat, and
- a user interface for vision and controls software

Further details about the shadow robot equipment and the application to remote bandsaw cutting can be found in the final AMPC reports for projects 2021_1158 (Mimeo Industrial Ltd, 2022) and 2022_1118 (Mimeo Industrial Ltd, 2022b). As the platform has been developed, Mimeo has chosen to demonstrate with very simple applications e.g. chop cutting. In this work (Stage 2) the focus was on increasing speed and accuracy of the system and improving the operator useability.

This project fits within the Advanced Manufacturing and Safety and Wellbeing innovation themes of AMPC's 2020-2025 Strategic Plan (2020) where the goals are:

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

The work has been staged in line with AMPC's theme on a page, see Appendix 1.

3.0 Project Objectives

The specific objectives for Stage 2, Part B (Project 2022-1202) were as follows:

- Complete a 3D cutting mode.
- Demonstrate 3D cutting (e.g. cutting down the spines of a saddle, removing the chump or similar).
- Complete a basic implementation of clearing the bandsaw table of cut meat to direct it for packaging.
- Complete designs for integrated meat in-feed and out-feed.
- Conduct preliminary work on using the bandsaw in combination with knife work (e.g. breaking/cutting/fat trimming).
- Demonstrate the system in operation

Additional work included improving the shadow robot software architecture and robot control, refining the 2D cutting system and extending the user interface.

Notably, work on the development of end-effectors was beyond the scope of this stage. However, some basic assemblies were made to either hold the meat to cut with the bandsaw or to hold trimming tools.

4.0 Methodology

Mimeo Industrial has adopted a rapid-prototype approach for developing the shadow robot technology. That is, get the system working quickly, refine, improve, and then finalise the equipment. The project objectives outlined in Section 3.0, were achieved within the following three work streams:

1. 3D tracking & cutting
2. Auxiliary Equipment
3. Augmentation of the shadow robot

The following sections outline the methodology for each workstream.

4.1 3D Tracking & Cutting

To progress the capability of the shadow robot system from 2D to 3D tracking and motions, a tracking system that utilised fiducial markers was employed. Fiducial markers can be created with known size and shapes. These markers can then be tracked by vision software and used to determine the position of the marker relative to the tracking camera in real-world coordinates. Therefore, by using a marker such as a fiducial attached to an object, 3D tracking of an object in the real-world was made possible. Figure 1 illustrates two “tracking tool” options that were built during testing: a) a multiple marker tool, and b) a single marker tool. These tracking tools were used test the tracking system and provide a means for controlling the robot remotely.

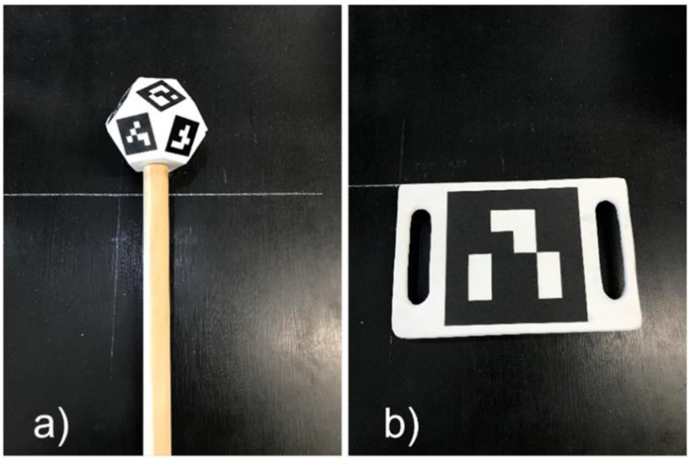

Figure 1: Photographs of a) a dodecahedron tracked object with 11 markers, and b) the original single marker tracked object.

The output from the fiducial marker tracking system was a position in millimetres of the object relative to the tracking camera and a rotation angle, in degrees, for each of the Cartesian coordinate axes of the camera system. Once the 3D tracking algorithm had been implemented, the position and rotation output from the 3D tracking was transformed to the robot operating workspace to control the robot. Due to the nature of the data output from the 3D tracking system, the transformation of the 3D tracking data to the robot workspace required only translational and rotational offsets to be applied to the tracking data.

As a means of increasing the reliability and accuracy of the fiducial tracking system the single marker was extended to multiple-markers or “board” fiducial tracking. Board fiducial tracking is simply concurrent tracking of multiple fiducial markers that are arranged in a predefined configuration on a single rigid body. Each of the markers is in a known position relative to the chosen origin position of the rigid body. Therefore, by tracking multiple markers to determine the position of a single rigid body, the accuracy and reliability of the tracked position is increased markedly since any single marker position estimation errors are reduced by comparing position estimates to the other markers. A major benefit of the “board tool” is that markers are placed on different planes which allows the tracking of the rigid body to continue when the object is rotated through angles greater than 90 degrees.

4.2 Auxiliary Equipment

The auxiliary equipment workstream considered the generic requirements of clearing the bandsaw table of cut meat, and designs for integrated meat in-feed and out-feed. As at this time the Mimeo Shadow Robot system is a technology platform, and in lieu of developing specific applications, our approach to adding auxiliary equipment has been guided by:

- a need to handle/process a wide variety of in-coming primals and subprimals,
- clearing to out-feed conveyor belts, so for now, the needs of the system can be simple, and
- focusing on modular software for the operator for functionality and useability.

In this workstream, the task of manipulating a lamb saddle to perform a cut down the spine and then a chine cut of the resulting half-saddle was targeted. To support this task, a jig-style end-effector (see Figure 2) was built to handle the lamb saddle appropriately and to enable the cuts to be made. Furthermore, a concept for a saddle in-feed was created and a prototype built to test the feasibility of such a concept. A simple table clearing attachment for the robot was built and tested to assess the feasibility of using the functionality of the robot arm to clear the table and direct the cut material to an outfeed. Finally, testing of the system’s efficacy to perform a chine bone cutting action was performed using a lamb loin mounted in the alternate temporary jig-style end-effector.

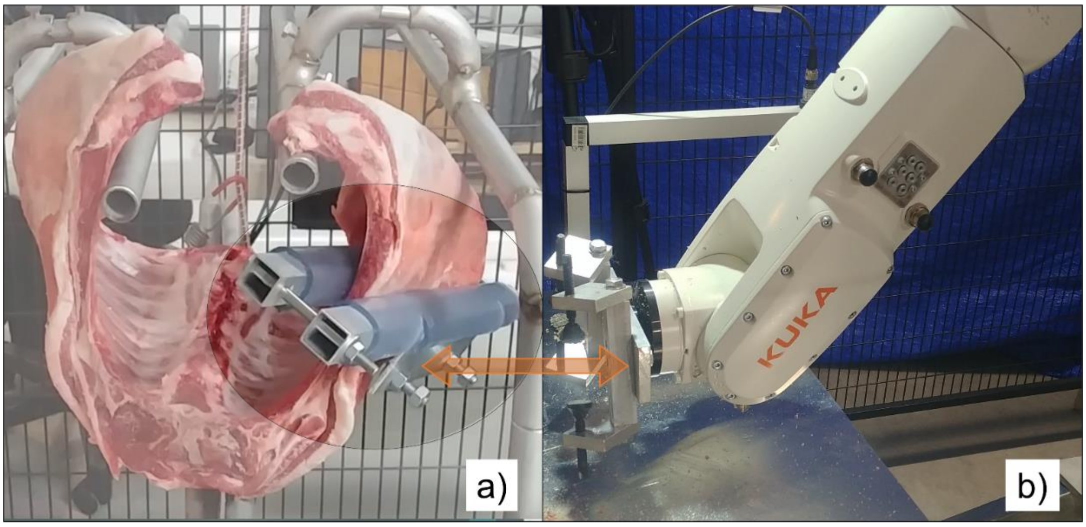

Figure 2: a) Photo of saddle handling end-effector attached to one side of a saddle, and b) robot arm that end-effector attaches to. Note, the end-effector was created to attach directly to the backplate of the existing end-effector, the surfaces indicated by the arrow are bolted together.

4.3 Augmentation of the Shadow Robot

The purpose of this objective was to extend the system from only moving meat for cutting in a bandsaw and implement knife work. Knives are used for breaking and trimming. As a first step we opted for implementation of trimming.

In line with the rapid-prototype approach, a commercially available rotary knife electric kebab trimmer was chosen (see Figure 3a) to achieve a proof-of-concept for fat trimming. A custom mounting bracket was built to fix the trimmer to the robot (see Figure 3b).

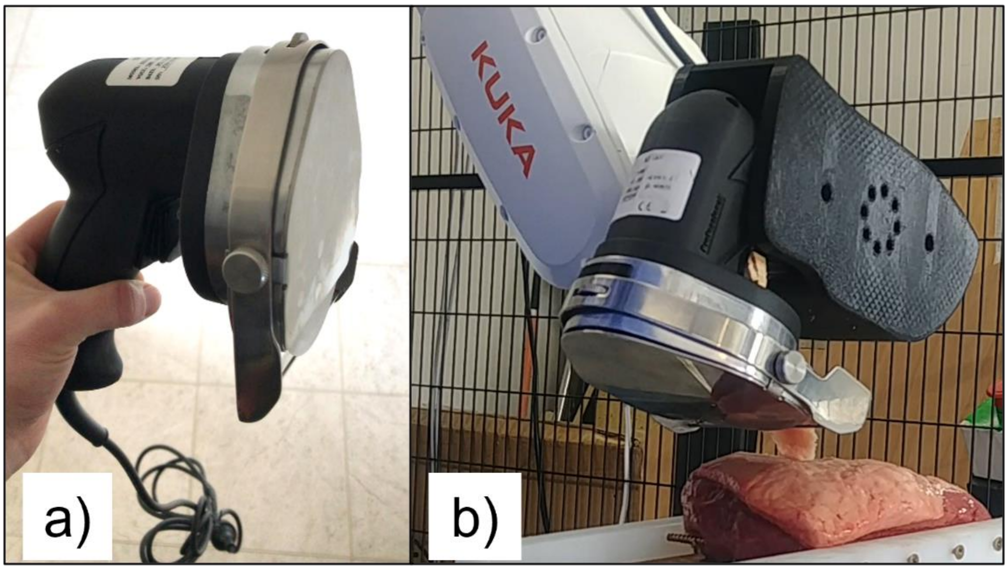

Figure 3: a) Electric kebab trimmer with 100 mm disc knife, available from Restaurant Equipment Online (https://restaurantequipment.co.nz/), and b) trimmer mounted to robot using custom built mount.

Testing of the trimming ability of the system was then carried out using a variety of material samples such as meat with a fat cap, cardboard, polystyrene, and cheese. The use of materials other than meat for the trimming tests allowed for prolonged testing and tuning of the system without needing frequent replacement of the meat sample. During testing, the system was controlled by an operator to trim fat (or one of the other test materials) in a sweeping horizontal motion. The initial testing was conducted without using additional sensing technologies to limit the thickness of the trimming cuts (i.e. the operator had control over how far they could lower the kebab trimmer onto the material being trimmed). However, the kebab trimmer had a built-in depth guide which would limit the thickness of the trimming cuts by deforming the material locally if the trimmer was lowered below the set cut depth.

5.0 Project Outcomes

5.1 The Overall Shadow Robot System

Mimeo has successfully demonstrated a prototype shadow robot platform that can perform tasks in 3D by shadowing the motion of a tracked object manipulated by an operator. The system has been demonstrated in two main configurations:

1) the operator controls the meat for bandsaw cutting, and
2) the operator controls a tool (trimmer) while the meat is held stationary.

In both configurations the system was extremely responsive and accurate. Demonstration of these configurations also highlighted the adaptability of the system.

The system was also shown to be easy to set up and to be robust. A trimming application was demonstrated at the AMPC Innovation Showcase. This was set up in a day – where a borrowed Kuka robot was fitted with a trimming knife and a vision and control system and the system brought on-line and operated for the 2.5 day event. Mimeo gratefully acknowledges KUKA Robotics Australia for the use of a robot for the duration of the Innovation Showcase. Points of significance here:

- the robustness reinforces our strategy to integrate off-the-shelf industrial equipment, and
- the ease of installation opens the door to shadow robot retrofits.

5.2 Demonstrate 3D Tracking & Cutting

The shadow robot system has been shown to track the fiducial marker consistently and with great precision. Consequently, control of the robot end-effector has been demonstrated to be responsive, smooth, and precise. The 3D tracking has successfully been used to cut wood and lamb loins at various angles determined by the operator in real-time. The system uses the same robot control software and algorithms as was used in Project 2022-1118 (Mimeo Industrial Ltd, 2022b). Therefore, when combined with the precision of the fiducial tracking algorithm, the position of the robot end-effector can be controlled to around sub-millimetre accuracy (quantitative accuracy and speed analysis yet to be completed). The initial testing has indicated that the 3D system is at least as accurate as the 2D system of Project 2022-1118 (Mimeo Industrial Ltd, 2022b) where a cut width accuracy of ±0.5mm was confirmed.

The ability to change the orientation of the end-effector in real-time using the manually controlled tracked object has not previously been possible with this system. Now that orientation changes are possible with real-time manual tracking, the system has shown great potential to be used as a remote option for more complex processing tasks where 3D motion is required and the health and safety of staff would benefit.

5.3 Useability

The shadow robot system has successfully been used to hold and manipulate a lamb half-saddle to perform a chine bone cut. Figure 4 shows a photograph of the shadow robot system during a chine cut test. The testing has shown that the shadow robot system has the adaptability to be used for different tasks that require 3D motions with minimal configuration changes. As part of this work, the operator control interface was refined for much greater control, introducing the ability to select/lock-out axes and rotations. This was of great benefit in terms of useability and to the project more generally.

Figure 4: Photograph showing demonstration of remote chine bone cutting.

The basic conceptual design and prototyping of a lamb saddle in-feed and table clearing process gave good insight into the feasibility of integrating the shadow robot into a processing line. It also assisted in identifying the requirements of an end-effector for successful loading.

The table clearing attachment that was built and tested was successfully used to clear cut materials from the bandsaw table. The testing of the attachment showed that using the robot itself to perform the table clearing was a viable and logical option. While it was evident that the table clearing attachment would need refinement of its form, the benefits of using the robot's dexterity and automation capabilities to clear the table of cut materials was clear. The two major advantages of using the robot itself to clear the table are: that minimal additional hardware would be required, and the process can be automated as an additional feature of the shadow robot system.

5.4 Augmentation of the Shadow Robot System to Trimming and Knifework

The shadow robot system was successfully adapted to perform trimming tasks. Following the mounting of an electric kebab trimmer to the robot, the system demonstrated the ability to trim the fat layer off fresh beef brisket meat samples (among other things). With minimal parameter re-tuning, the system performed with comparable speed and precision during the trimming as it did during the previous bandsaw cutting tasks. The success observed from the trimming tests, in addition to the chine bone and chop cutting tests, has shown the adaptability of this shadow robot platform in performing different processing tasks.

6.0 Discussion

6.1 Shadow Robot Benefits

In general, the shadow robot platform performs well as a remotely operated, real-time tool that "shadows" an operator's motions. The nature of the shadow robot project has led to a continual improvement of the technology as more testing and analysis is carried out. The move from 2D cutting into 3D motions has increased the potential of the system massively by opening the door to performing more complex tasks such as fat trimming and knifework.

One major learning point from the testing to date has been the need to manage the increased positioning sensitivity introduced by the flexibility of 3D motion. It was found that manually controlling the robot end-effector in 3D space required more careful attention and steady motions by the operator. Since the robot can rapidly change positions and orientations, any instability or shaking of the operator's motion is also communicated to the robot arm. The shadow robot software interface however, allows for arbitrary scaling of all translations and rotations and can therefore be easily tuned to amplify or reduce operator motions to assist with steady operator control. In this regard, when using the system, it was found best to decrease some degrees of freedom by either locking-out or specifying some parameters e.g. have the operator reference against a table but the robot operating at a vertical offset. The operator interface was adapted to allow such control.

In moving to tracking with fiducial markers there is the flexibility to create custom task-based uses. For example, a particular marker could be tailored to a specific application. The freedom to create custom-tracked object results in a more user-friendly and efficient task completion. A further benefit of the shadow robot platform is the increased protection that the system offers to plant equipment such as bandsaws. A consequence of using a computer controlled robotic system is the ability to add motion limitations during tasks. For example, bandsaw blade protection features have been demonstrated with the shadow robot system where (at the push of a button) it becomes impossible for an operator to move the meat in a motion that would cause damage to the blade (e.g. hitting the back of the blade on a return stroke). The ability of the system to incorporate such equipment protections can result in reduced maintenance costs and less equipment downtime.

6.2 Future Work

The extensive testing of the shadow robot system carried out during this project identified the need to tailor for specific applications. Such targeted development would not limit the system to a specific application but rather allow the platform to be expanded and progressed towards a product with a real-world benefit. Through the development of the platform so far, it has been recognised that the way that an operator chooses to interact with/uses the equipment will be specific to the application/task that is to be performed. Therefore, it is essential to have input from the operator to guide the development of the technology. Mimeo has found that much insight is to be gained from iterating the development process by implementing a basic system, running “real-world” tests with the system, getting feedback from the human operator, using that feedback to add new or improved features to the system, and then testing again with the additional features.

The initial testing of the 3D system highlighted the increased positioning sensitivity introduced by the flexibility of 3D motion. This flexibility raises interesting questions about whether full manual 3D control of the system is always practical and whether the user-friendliness of the system can be improved by adding “anti-shake” functionality or similar assistance algorithms. It was determined that the user-friendliness of the system was an important factor to consider and will need to influence decisions made about system behaviours on an application-by-application basis. For example, in a traditional bandsaw operation the operator might rest the piece of meat against the bandsaw table to give them steadiness and allow smooth motion. Therefore, it is likely that an operator performing the same action remotely with the shadow robot may be more comfortable and precise if they rested the tracked object against the operator’s table. However, given the computerised nature of the shadow robot system, it is possible to develop software algorithms that can assist the operator to perform the tasks more easily or even using alternative actions to achieve the same (or a better) result. It was noted during testing that after only a short time using the system, an action that initially seemed unintuitive and unnatural, quickly became easy and intuitive for the operator to perform. Therefore, it is likely that the shadow robot system could be used to perform processing tasks in more efficient ways that are not possible using conventional methods.

There are several common perceived disadvantages of the shadow robot system such as the lack of haptic feedback to the operator, and viewing perspectives limited by 2D cameras and displays. These perceived disadvantages could be rectified by using technology such as integrated or wearable haptic devices and virtual or artificial reality. However, the opportunity to perform processing tasks in new, unconventional ways, enabled by the shadow robot system, raise the question of whether physical feedback such as haptics and virtual or artificial reality is a necessity for operators to perform the task. Therefore, it would be beneficial to explore in detail whether future applications of the shadow robot technology could improve processes using novel processing methods.

Shadow robots are a great option for capturing the experience and knowledge of a skilled worker, making the job less dangerous and less tiring by having machinery do the hard work. Also, the operator can potentially work remotely. In considering some of the simple repetitive tasks where a shadow robot may be used in the boning room, there is opportunity to add machine learning and in so doing, shadow-robots could be on a development path to full-automation, removing staff from tasks completely.

7.0 Conclusions / Recommendations

The prototype shadow robot platform shows great promise as a multipurpose processing station for improving the safety and performance of tasks in meat processing. The system has a relative simplicity in design and is adaptable, responsive, precise and operates in real-time. It offers the opportunity for user-defined operating modes that either take advantage of the knowledge of an operator or take advantage of semi-automation.

The system utilises an industrial robot, a simple camera tracking system, open-source computer vision software libraries, and a bespoke software package to process tracking system data and communicate control parameters to the robot. Consequently, this system offers a relatively low cost, small footprint, and highly adaptable platform for performing dangerous or arduous meat processing tasks remotely. Furthermore, the shadow robot platform offers an intermediate step on the path towards automated processing whereby operator expertise and decision making can be actively used to reduce the complexity of automating processes.

8.0 Bibliography

Australian Meat Processor Corporation (AMPC), 2020. *Strategic Plan 2020-2025.* [Online] Available at: https://www.ampc.com.au/getmedia/4832a7b0-def8-4af4-8762-d91bb4cbac42/AMPC_StrategicPlan_2020_2025.pdf
[Accessed October 2022].

Mimeo Industrial Ltd, 2022b. *Remote Operations –Shadow Robots (Stage 2 Part A) - Project Code: 2022-1118.* [Online].

Mimeo Industrial Ltd, 2022. *Remote Operations –Shadow Robots (Stage 1) - Project Code: 2021-1158.* [Online] Available at: https://www.ampc.com.au/getmedia/849568c1-6295-41a7-9fe5-15b2c6f940ba/MIMEO-Final-Report_2021_1158-Jan-2022.pdf?ext=.pdf
[Accessed October 2022].

9.0 Appendices

9.1 Appendix 1 - AMPC Remote Operations R&D Theme on a page