Final Report

Remote Guided Robots

Remote Operations – Remote Guided Robots (Stage 1) – Strategic Engineering Pty. Ltd.

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1.0 Executive Summary

The global tele-operation and tele-robotics market is projected to reach $98.3billion (USD) by 2027. With the adaptation of 5G coverage around the world, tele-operated robots can be implemented globally via the cloud. Remote Guided Robotics has excellent potential in existing markets, attempting to remove operators from dangerous tasks and providing access to labour in remote areas, where labour is scarce. This research introduces a configuration of technology that reduces the knowledge gap of what is required to successfully achieve high accuracy and realistic control of a robot in real-time. Initially a literature review was conducted prior to procurement of each item selected for the proposed system. The system implemented in this report utilises an infrared camera from UltraLeap to capture and track hand gestures and movements, a Kuka 6 DOF robot and software packages to follow the hand movements from the Leap Motion Controller in real-time, and a HTC VR headset for a mixed reality experience where two cameras are placed in the robot work-cell to send back a 3D stereoscopic image to allow the operator to have an immersed experience when remotely controlling the robot.

The robot workspace was allocated, set-up and configuration of the KUKA RSI software package begun. Code was developed to track the co-ordinates of a user's hand in a 3D Cartesian coordinate system. The preliminary control of the robot via the LEAP motion controller was introduced to the system proving promising results. The robot's mobility had a notable jitter throughout the initial tests. This was caused by the sensor's noisy data as well as a scaling factor. To address this, a Kalman Filter was added to the system. The filter is an algorithm that generates variable estimates based on measurements taken over time. The LMC was placed inside a frame that had been purchased. The operator's hand was run internally along the frame during the tests, limiting the operator's motions to 50mm on all three axes. Each axis was tested several times, with the operators attempting to move around 50mm back and forth. The robot's movement was recorded to compare the physical movement of the hand to the physical movement of the robot. Two cameras were used to create a stereoscopic image on the VR Headset's display. This enables the operator to see the robot in real time and judge distances between items from a distance. The HTC VIVE Pro 2 was used as a visual feedback device.

The robot was set up next to a band saw, an operator was given the VR headset to assess the system's real-life capabilities. The user's hand movements controlled and transmitted the gripper's actuation in real time. The preliminary gripper first failed to consistently pick up the pieces. The original gripper fingers were short and had a 24mm actuation stroke which prompted the procurement of a new gripper. The redesigned gripper included bigger fingers and a 300mm actuation stroke. More testing was done after the new gripper was introduced. Debouncing code was added to mitigate the false state changes. This is effectively done by adding a timer, and if the input change exceeds a specific time, it triggers the new value.

The system proved to have a repeatability of approx. ±10mm, and an accuracy of 0.1mm. The gripper was able to successfully pick up 86% of the time, with a final test of gripping an item and guiding it through a bandsaw at an average rate of 24.2 seconds per grip and cut. Testing and simulations achieved by the system outline the level of accuracy and repeatability of the Remote Guided Robotic system. This tele-operated robotic system can protect operators’ safety and meet the expanding growth of needs in various industries. The suggested next steps for this system are:

- To further improve the visual feed-back by creating a system that allows the visual feedback to be displayed in first person rather than the existing third person set-up.
- Improve the motion control of the robot to improve speeds of human-robot control.
- Test networking and control with system in separate location.
- Design, develop and test a customised gripper for an appropriate task.

2.0 Introduction

Many repetitive tasks will be replaced with the collaboration of machine learning, neural networks, artificial intelligence, sensors and robotics. This will help the automation industry progress. However, in more complex, dynamic environments human intelligence is a necessity, to help control robots. This has created a demand for tele-operated robotics in many industries.

PR Newswire, C. (2020) states that the global teleoperation and tele-robotics market is projected to reach $98.3 billion (USD) by 2027. With the benefits of 5G coverage almost anywhere in the world, tele-operated robots can be implemented globally via the cloud. Coupling Virtual Reality (VR)/ Augmented Reality (AR) technologies with tele-operated robotics will open the market up and allow for many industries to take major leaps forward. This creates opportunities for smaller companies to leverage tele-operated robotics and expand their services globally.

The goal when introducing a robotic system is to not remove the operator from the task but remove the operator from a dangerous environment. This means during the design process; the engineers need to seamlessly introduce and implement new technologies that will not remove an operator from their job completely but either give them a new task or a task that does not occur in the hazardous areas in the manufacturing industry. Current solutions in the Red Meat Industry reduce risks of serious injury. However, AMPC intends to find solutions that eliminate the risks completely. Strategic Engineering's aim for this research report is to develop a solution that meets the requirements of AMPC, while also attempting to introduce technology that could revolutionize the Red Meat Industry and its existing processes. The Australian Meat Processor Corporation introduced the following problems to be solved in the Red Meat Industry:

- Removing staff from dangerous operations, via Hands-Off processing.
- Safety and Well-being, via reducing the high-risk nature of processing operations
- Attraction, via demonstration and developing a wide range of operations
- Retention, via improving working conditions and making tasks exciting
- Development, via developing tasks that require higher skills and intellect – operational and technical.

This project aims to research, develop, and design a system to remove an operator from a dangerous process, while simultaneously introducing new technologies to the red meat industry allowing operators to perform tasks in exciting manners, this also includes operators that may be at a physical disadvantage. The purpose of this design is keeping the operator safe, while concurrently allowing the operator to continue tasks that are comparable with the current operations but in a more comfortable workspace. The utilisation of technologies that analyse the operators hand movements and the mixed reality industry allow for the operator to immerse themselves to interact both with the real world and digital world simultaneously. The introduction of mixed reality and interacting with the digital world is to allow for robots to be controlled remotely. Key Requirements for this solution are:

1) Removing staff from dangerous operations, via Hands-Off processing. (Adv. Mft)
2) Safety and Well-being, via reducing the high-risk nature of processing operations (People Culture)
3) Attraction, via demonstration and developing a wide range of processing operations (People Culture)
4) Retention, via improving working conditions and making tasks exciting (People Culture)
5) Development, via developing tasks that require higher skills and intellect - operational and technical (People Culture)
6) Digitisation, via acquiring product information and leveraging data insights (Adv. Mft)

Although the vision is aimed for all processes in the Red Meat Industry, for this stage of the Research and Development project, one process will be focused on. This solution creates the opportunity to remove the operator from the task of cutting a primal cut of meat with a band saw, via the operator remotely guiding a robot to cut the primal cut of meat.

3.0 Project Objectives

To evaluate the concept of remote guided robot enabled solutions and ascertain:

- The communication protocol, and software required to allow for real-time communication between the robot and operator.
- Where the solution can be deployed now within industry
- Where the solution could be deployed now, with minor changes (for example additional vision and sensing required)
- Where the solution could be evolved for future deployment.

4.0 Methodology

The project can be broken down into the following milestones:

- Research and Rudimentary Design
- Rudimentary Integration of Motion Controller
- Complete Integration of Motion Controller
- Integration of Visual Feedback and Finalised Design
- Assembly of Prototype

This project is the perfect opportunity to introduce a robot that helps up-skill operators, allowing them to continue their current tasks. However, these tasks will be in a safer environment. This creates the opportunity for more robots to be introduced in a closer environment to help collaborate with the tele-operated robots being introduced in this project allowing for more opportunities of the production lines to become more automated and efficient while remaining compact. As stated above the solution is to develop a system where an operator can remotely control a robot in a dangerous process, or remote area. The system that is being proposed to be researched and developed will focus on introducing real time human-robot interactions. The key components that require thorough research for selection of the system are:

- The motion controller sensor that is required to accurately read data from the operator to instruct the robot how and where to move.
- The device that will provide visual feedback to the operator of the current state of the robot and the robots workspace.

4.1 Tele-operated Robotics

Tele-operated robotics refers to a robotic system controlled by an operator remotely. The system can either be controlled online in real-time or can be taught motions offline and the robot follows those instructions when commanded to, later. Gunawardane et al. (2017) attempts to control a small custom 3-Degree of Freedom (DOF) robot using hand motions. It was stated in this paper that due to the low-cost servo motors used in the custom robot, the precision of the system was not high. Korayem et al. (2021) conducted research where a 6-DOF surgical robot was conceptualised, due to a lack of resources a small custom 3-DOF robot with an Arduino micro-controller was used to test the effectiveness of a Leap Motion Controller (LMC) to track hand-motions and control the robot. It was stated that the tracking of the hand had accuracy's of approx. 0.1mm with speeds of 115 frames per second. The paper stated that for better results of tracking, it was more reliable to track the centre of the hand rather than the fingers as in some moments in time the sensor would misplace the fingers it was tracking. Rosen et al. (2020) used an AR device which utilises mixed reality to tele-operate a robot. It was concluded in this paper that operators found tasks to be more exciting and easier to control utilising mixed reality compared to the traditional method of tele-operating a robot via a PC screen and mouse or controller.

4.2 Motion Controller

The choice of the motion controller in this research project is the Leap Motion Controller by UltraLeap, shown in Fig. 1. The LMC utilises two depth cameras and multiple infrared LEDs to sense the movements of an operator's hands. The workspace of the sensor extends to 150° and 650mm in the vertical z-axis, Ultraleap (2020). The sensor is an interactive tool with software development kit (SDK) packs readily available for the user to utilise the technology to its maximum functionality. The choice of the LMC over the more commonly used Microsoft Kinect, is due to the technical differences such as greater precision. The LMC has a higher refresh rate of 200Hz, a high resolution of 1.3MP, more accessible SDKs, and constant software optimization being introduced by UltraLeap. A more detailed comparison can be seen in Pauchot et al. (2015) and Guzsvinecz et al. (2019). The motion controller captures the data from the operator's hand movements, it then generates a virtual model of the operator's hand movements. The data generated by the LMC, is the information required for the robot to determine the current pose it is being instructed to move to. A certain degree of accuracy and an intricate calibration process is required for the communication between the LMC and the robot to be successful. Through experiments, Weichert et al. (2013) was able to determine the accuracy of the controller, these concluded an overall average accuracy of 0.7mm.

Figure 1 Ultraleap Leap Motion Controller

4.3 Visual Feedback

The system in paper Liang et al. (2019), utilises the Hololens 2 by Microsoft for the AR feedback. A limitation of this device is the small field of view for the AR environment – 43.0mm x 28.5mm. It is believed that the field of view will not be ideal for operators when working, as their typical work environment is quite large and requires attention to fine details. It was decided to introduce a VR device - HTC VIVE Pro 2 (Fig. 2), to the system, which allows for a lot more detail to be created in the immersive environment. Introducing VR makes the human-robot interactions more seamless. Operators with no prior knowledge to programming or working with complex robots can utilise VR technology with human-robot interactions. Theofanidis et al. (2017), Tahriri et al. (2015), Tianhao et al. (2017), and Yap et al. (2008) outline the benefits of using this technology to teach and program a robot with just VR/AR, a sensor and an operator. A very detailed literature review was conducted by Gramado (2021), where 214 papers using VR technologies were thoroughly studied to discover how the technology was being utilised. One of the more common trends were human-robot interactions, where it was noted that the use of VR created a more intuitive interaction with clear and concise feedback from the processes. The study by Lipton et al. (2019), details the efforts and benefits of using VR as feedback to control a robot in real-time.

Figure 2 HTC Vive Pro 2 Controller

4.4 Robot and Real-Time Communication

Due to availability, the industrial robot being considered currently is a KR Agilus - Kuka KR 10 R900 sixx, Fig. 3. It consists of a robotic arm with 6 degrees-of-freedom. It can handle a payload of 10kg and has a reach of up to 900mm. The robot weighs approx. 52kg, its footprint is only 320mm x 320mm and it has a pose repeatability of ±0.03mm, Kuka (2021). By utilising the communication protocols available via the robot controller, the system can control the robot by sending the end effector the desired pose received from the operator. The paper by Aschenbrenner et al. (2015), researched different topologies to communicate over a network to tele-operate a robot in real-time. Testing of both TCP and UDP protocols were conducted, concluding UDP to be more appropriate for the system with discussion directly with Kuka's engineering team, it was suggested to purchase the software package called Robot Sensor Interface (RSI). This gives access to communicate to the robot controller via UDP communication, this real-time communication has a latency of 12ms. The PC sends instructions via XML packets and the robot reads and completes the instructed motions in real-time. Murhij et al. (2019), utilises almost all the exact same components chosen for this project. In this study they create a tele-operated system with a Kuka KR 10 robot, a leap motion controller, and a HTC

VIVE Pro headset. They concluded that VR technologies do enhance the tele-operation process. However, they did not do any extensive tests on a specific task, this project will continue the research conducted by Murhij et al. (2019) and test the possibilities of real-world tasks that exist in the Red Meat Industry. Interestingly, this paper was discovered after the selection and procurement of all components for this project and did not influence selection but confirmed that the selected components were the right choice to complete this project.

Figure 3 Kuka KR 10 R900 sixx

4.5 System Design

An operator is given a station where they are instructed to move their hand. The operator's hand movements are analysed and traced by a motion controller. The motion controller utilises infrared LEDs and depth cameras to analyse the operators hand movements, Vargas et al. (2014). The movements analysed by the motion controller generate and transposes position data legible by the robot. The transferred data is communicated from the custom Application Programming Interface (API) to the robot controller. The robot controller sends motion commands to move the end-effector corresponding to the movements of the operator in its 3D space. A stereoscopic camera set-up is added to the work cell to display in real-time 3D feed of the work cell to the operator wearing a VR headset. This allows the operator to determine where the item is in an attempt to pick up an item and guide it through the bandsaw. Fig. 4, the complete system can be broken down into the following five sections:

- Visual Feedback – The technology that will display the predicted/active motion of the robot to the operator. (HTC Vive Pro 2)
- Operator – The human operator will be given tasks to complete in their workstation.
- Motion Controller – The technology utilised to interpret the operator's tasks, which transposes the data into a format that is comprehensible for the robot. (UltraLeap Leap Motion Controller)
- Robot – The technology performing the tasks communicated by the Motion Controller. (Kuka KR 10 R900 sixx)
- PC – The PC will manage all data and signals coming from the motion controller and all outgoing data to the Robot and VR Unit. (Asus TUF Laptop)

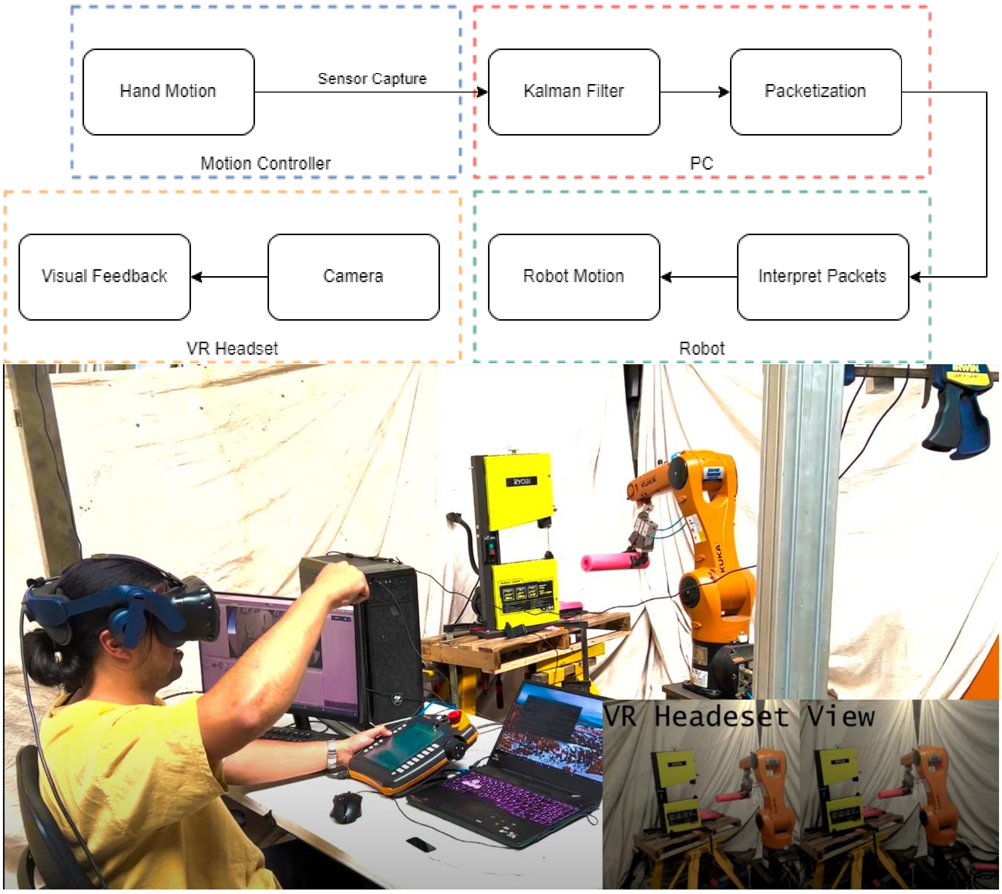

Figure 1 - Flow chart and Implemented System

4.6 Rudimentary Integration of Motion Controller

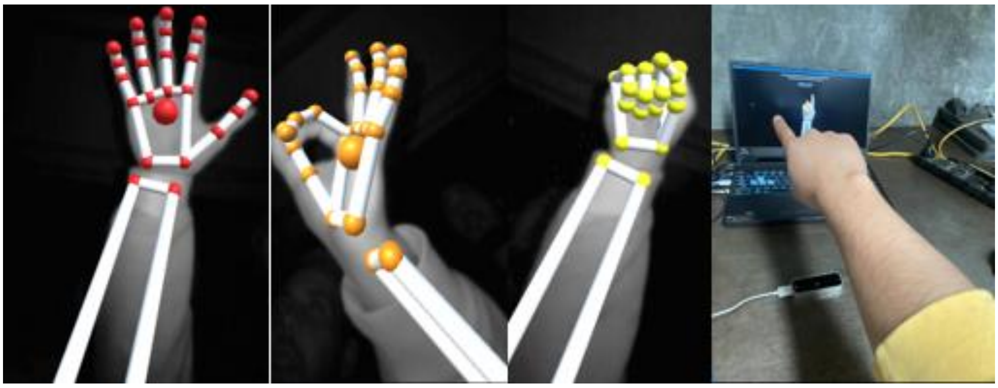

Figure 2 - Hand Gesture Recognition and Hand Tracking

An UltraLeap Leap Motion Controller was acquired (Fig. 3) to commence the rudimentary design and the capabilities of the motion controller was examined via the propriety software and libraries provided by UltraLeap (Fig. 5). Succeeding this, code was developed to track the co-ordinates of a user's hand in a 3D Cartesian coordinate system. The robot workspace was then allocated, set-up and the KUKA RSI software package was acquired. Following this, the configuration of the communication between the two systems begun. The preliminary control of the robot via the LEAP motion controller was introduced to the system proving promising results. The robot was successfully able to mimic, in real-time, the motion of a user's hand within the Leap Motion controller's field of view. The following briefly details some of the software features required to complete the project:

- Kuka RSI software package: KUKA add-on technology package that is used for data exchange between an external PC and the robot controller via UDP protocol. RSI communicates with the robot controller in a loop by sending XML strings through UDP. The current latency of this communication is 12ms per cycle. The RSI requires configurations to determine the control mode. Depending on the control mode, the KUKA RSI will send Cartesian position correction, Cartesian velocity, or joint position correction, or joint velocity commands to a KUKA robot and outputs the robot's current actual Cartesian positions, joint angles and gear torques for each joint.
- User Datagram Protocol (UDP): The UDP is a protocol for transporting data between two systems in a network. UDP is simple and fast, making it ideal for time-sensitive applications. The protocol can often be seen in real-time video streaming or gaming applications.

4.7 Improved Integration of Motion Controller

During the initial tests in Section 4.2, there was a visually and audibly noticeable jitter in the robot's movements, and the overall velocity of the robot was relatively slow. This was due to the sensor providing noisy data and a scaling factor. To overcome this, a Kalman Filter was introduced to the system, similar to Kim et al. (2019). A Kalman Filter is an algorithm that provides estimates of variables given the measurements observed over time. The introduction of the Kalman Filter and some minor changes to the code regarding the robot's movement improved the system, removing the jitter from the robot entirely. A frame was purchased where the LMC was placed inside the frame. Tests were conducted where the operator's hand ran internally along the frame limiting the operator's movements to 50mm on all three axes; the robot's movement was recorded to compare the physical movement of the hand to the physical movement of the robot. Each axis was tested multiple times, where the operator would attempt to move back and forth approx. 50mm. Results are further discussed in Section 5.0.

4.8 Integration of Visual Feedback

The HTC VIVE Pro 2 was utilised as equipment for visual feedback. Two cameras were set-up to create a stereoscopic image in the display of the VR Headset; a detailed example of this can be shown by Lagendijk et al. (2009). The usage of the two cameras was to utilise the depth perception created from stereoscopic images. This allows the operator to view the robot remotely in real-time and perceive the distances between objects. This was created in Unity 3D. The stereo-cameras were placed into different positions and angles to better improve the view of the robot and the movement of the gripper. A third camera was introduced to the cell to attempt to add an additional view that was closer to the items that were being grabbed.

4.9 Testing of Human-Robot Integration

An operator was given the VR headset to test the system's real-life capabilities, with the robot set-up next to a band saw. The operator was tasked to pick up a foam tube and emulate the task of cutting a piece of meat through a bandsaw by cutting the foam tube into small sections on the band saw. An available gripper was attached to the robot, which was used to pick up a foam tube and guide it through a bandsaw. The actuation of the gripper was controlled and communicated in real-time by the user's hand movements. An open hand instructs the gripper to open, while a close fist instructs the gripper to close. Initially, the introduced gripper failed to pick up the pieces consistently. This required a new gripper to be procured, the initial gripper fingers were short, and the actuation stroke of the gripper fingers was 24mm. The new gripper introduced had larger fingers, with an actuation stroke of 300mm. Once the new gripper was introduced, more testing was conducted. Another issue that arose during this testing sequence was that the robot would falsely open or close at different times. Debouncing code was added to mitigate the false state changes; similar code can be seen by Yershov et al. (2019). In short, debounce code cleans up the input data and only triggers an input once instead of multiple times. This is effectively done by adding a timer, and if the input change exceeds a specific time, it triggers the new value. This adds a slight delay to the gripper actuation. This delay has been calculated to be 60ms.

5.0 Project Outcomes

Initially, the motion controller was connected, and hand tracking was tested. It was observed in the provided software that an operator's hands could be detected and tracked, Fig. 5. As mentioned in Section 4.0, the system was initially observed to have noisy data, plus it was observed that the robot would have a more significant movement than the operator's hand. A test was set up where the operator would run their hand along the inside of a box; it was measured that the displacement of the operator's hand was 50mm in one direction. This test was conducted across the three-axes. A gain variable, a Kalman Filter and adjustments to the code were made, which shows in Appendix 1-3 improvements in the robot's movement. Appendix 1-3 compare the data retrieved from the robot's movements before and after the changes were introduced to the system. The data across all three axes shows the removal of the majority of noise and that the robot is moving at approx. 50mm in each direction, proving the robot is moving at a 1:1 ratio of the operator's hand. Initial results showed the robot's movements were out by approximately 1.6-2.1 times the actual operator's motion. The repeatability of the system was approx. ±10mm. Calibration of the sensor was conducted together with modification of the code, which improved the accuracy and the repeatability of the first tests. It should be noted that the following results involve human error, which is included in the repeatability. Looking at the results, the repeatability improved to less than ±5mm with an accuracy within 1mm. The latency of the system was calculated to be 12ms.

When the gripper was introduced to the system, it was noted that the gripper would open sporadically when the operator's hands were closed and would close sporadically when the operator's hands were open. As stated in the previous, a debouncing signal code was introduced to mitigate the false change of state. Tests were conducted over 5-minute periods counting the number of false state changes; this was to determine if the system improved with the newly introduced code. The introduction of the debouncing meant the gripper opening and closing had a 60ms latency compared to its original 12ms. As the opening and closing of the gripper are not regarded as time-critical (sub 500ms), it was deemed that the latency of 60ms was satisfactory. Table 1 shows a significant improvement with the debouncing, improving the grippers stability. Previously the gripper was falsely changing approx. 18 times every 5 minutes. Whereas the introduction of the code eliminated the false state changes. This improvement provides confidence in the gripper handling items without dropping them.

Table 1 - Debouncing Implementation Test

Debouncing Code Implemented (Y/N)	Amount of False State Changes in 5 mins (Test 1)	Amount of False State Changes in 5 mins (Test 2)	Amount of False State Changes in 5 mins (Test 3)	Average False State Changes in 5 mins
No	16	20	19	18.33
Yes	0	0	0	0

Figure 3 - (a) Gripper 1 (b) Gripper 2

When attempting to grip the foam tube with the initial gripper, Fig. 6a. The operator was having difficulties grasping the item. An observation was made by the operator that the fingers of the gripper and the movement between the gripper fingers were minimal compared to the size of the items being grasped. This created difficulty of picking up items. Table 2 shows the improvement in introducing a new gripper with longer fingers and greater movements. The success rate improved by a total of 64%. To validate the development of the remote guided robot, a test was assigned and attempted. This final test was for an operator to guide the robot and attempt to successfully pick up a foam tube and guide it through a bandsaw, Fig 4. The system needed some slight tuning to create better performance, the impact of the tuning and how successful the system is overall is shown in Table 3.

Table 2 - Gripper Test

Gripper	Attempted Picks	Successful Picks	Success Rate (%)
1	50	11	22
2	50	43	86

Table 3 - Human-Robot Interaction Test

Set-Up Version	Attempted Picks	Successful Picks	Succes Rate (%)	Average Time to pick one successfully (s)
1	10	3	30	67.6
2	20	15	75	24.2

6.0 Discussion

Although the above results are promising regarding accuracy and latency. According to operators, it was noted that there are some current limitations:

- Firstly, the system's most significant limitation is the feedback to the operator. Although the visual feedback was able to display a stereoscopic image for the operator to be able to determine the depth. The camera was static, so any head movements on the VR did not change the view of the display. Further work in this would be required to improve the visual feedback, being able to move the operator's head, or even walk around, allowing the operator to view the work cell from any angle to make the operator feels more present in the system.
- Secondly, there is only one type of feedback, visual feedback. Further work in determining the feasibility introducing sound or tactile feedback is necessary to improve the operators experience and interaction with the robot.
- Also, it was noted by operators that the workspace of the motion controller is limited; future work in attaching the motion controller to the VR headset, or adding multiple motion controllers to increase the workspace would allow for the robot to have more space to complete more tasks, and allow the operator more freedom in their movements which could introduce the potential to conduct multiple tasks by one operator.

- It was also observed that the gripper is only capable to picking up limited number of items. Depending on the task required for the robot and operator to conduct, further work would be required to develop a customised gripper.

7.0 Conclusions / Recommendations

In this report, a system consisting of a KUKA 6 DOF robot, UltraLeap Leap Motion Controller and HTC VR headset were integrated. This research explores the combination of the leap motion controller and the VR headset for remote guided operations with realistic hand movement in a robot control scenario. As displayed by the results achieved in this project, the system is accurate and capable of remotely completing tasks given to an operator. The mock task, cutting an item through a band saw, was successfully simulated in this study. With these results, the integrated system that can protect operators' safety and cope with the need for human resources over lockdown. Moreover, the precision of the teleoperated robotic system can be applied to other applications. With further design in a more versatile gripper, systems will have the ability to have more realistic hand movements.

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7.1 Recommended Next Steps

- Further improve the visual feed-back by creating a system that allows the display to be in first person rather than the existing third person set-up. This system will require further research in utilising multiple sensors to create a real-time 3D environment of the work-cell. This will allow the operators to be tele-present within the work-cell and experience controlling the robot in first person. The goal of this step is to improve the operators experience, while simultaneously improving the human-robot performance times. (A similar example of this technology can be seen in the following link: https://www.youtube.com/watch?v=7d59O6cfaM0)
- Optimise the motion control of the robot to improve speeds of human-robot control. This will be achieved by designing and implementing advanced control systems and algorithms into the system. The introduction of these systems will improve the performance of the robot, therefore increasing productivity.
- Test networking and control with system in separate location. This step is to analyse and identify any latency issues. The issues that arise will be addressed and the system will require network design improvements to fix any potential issues. Once these tests are complete the system will be able to be controlled remotely globally where internet is available.
- Design, develop and test a customised gripper for an appropriate task. This step would require discussion with AMPC, interested Meat Processors and Strategic Engineering where a commercial task would be selected. Strategic Engineering to design a custom gripper for selected task and introduce robot to site and remote control of the robot in a factory setting.

It is recommended that the first three steps are to be completed prior to the final step. However, the first three steps can be worked on concurrently. Strategic Engineering believe this is the most effective path-way to introducing remote guided robotics into the industry.

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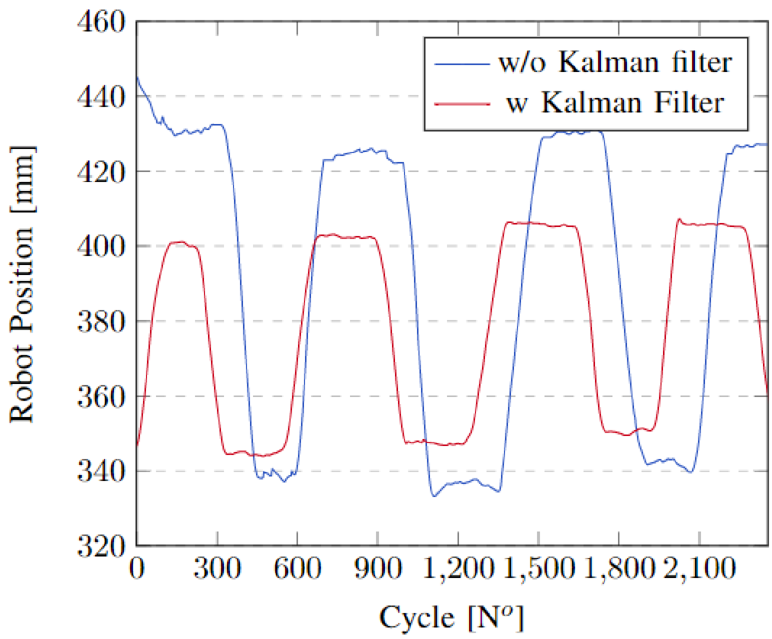
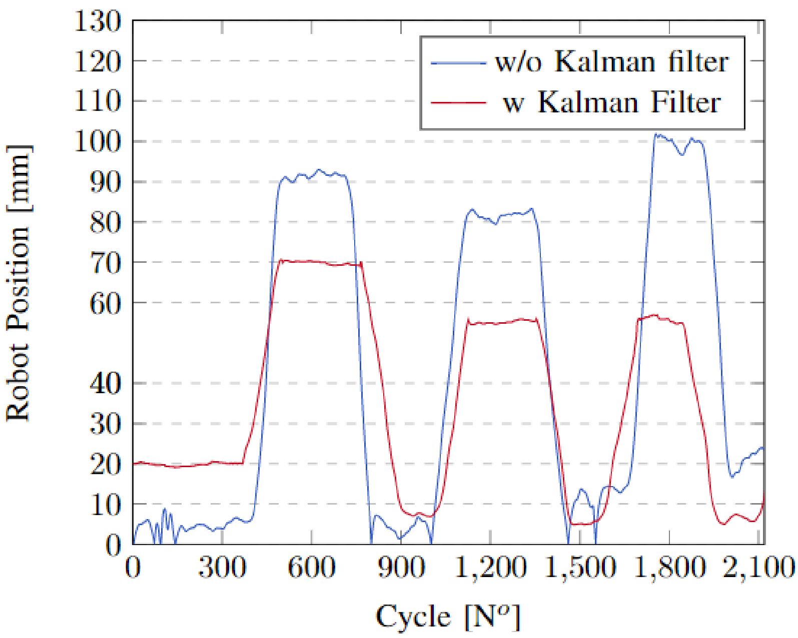
9.0 Appendices

9.1 Appendix 1 – Robot, Motion Controller Calibration – X-Axis



9.2 Appendix 2 – Robot, Motion Controller Calibration – Y-Axis



9.3 Appendix 3 – Robot, Motion Controller Calibration – Z-Axis