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Concept Design & Feasibility Assessment For Picking & Packing Automation Solutions

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Abstract

Meat processing facilities incur significant labour costs and OH&S risks with the manual picking and packing of primal cuts and trims. Primal cut picking and packing is currently a labour intensive and completely manual step in the meat packing process. This step requires operators to transfer cuts of meat from the in-feed conveyor to the appropriate carton for storage or dispatch. This step can involve lifting primal cuts of up to 5kg, placing strain on the operator's body and leading to stress related injuries. The introduction of automated robotic solutions may significantly reduce operators required to perform the picking and packing operation and present significant economic savings.

Strategic Engineering has developed a case study for the implementation of an automated picking and packing system for vacuum sealed primal cuts at Thomas Foods International's Murray Bridge facilities. As vacuum sealed primal cuts make up over 70% of meat output from any particular meat processor, it was evident that this should be the primary area of focus. As part of this study, a number of sensing and gripping technologies were evaluated in order to determine the most appropriate technologies for this task.

The findings of this study present a practical way forward for meat processors to develop and trial autonomous pick and pack solutions. The adoption of such technologies will reduce the labour exerted on the packing end of production line, allowing resources to be redistributed throughout the facility where appropriate.

Executive Summary

Meat processing facilities incur significant labour costs and OH&S risks with the manual picking and packing of primal cuts and trims. Primal cut picking and packing is currently a labour intensive and completely manual step in the primal packing process. This step requires operators to transfer cuts of meat from the in-feed conveyor to the appropriate carton for storage or dispatch. This step can involve lifting primal cuts of up to 5kg, placing strain on the operator's body and leading to stress related injuries. The introduction of automated robotic solutions may significantly reduce operators required to perform the picking and packing operation and present significant economic savings.

Strategic Engineering has developed a case study for the implementation of an automated picking and packing system for vacuum sealed primal cuts at Thomas Foods International's Murray Bridge facilities. As vacuum sealed primal cuts make up over 70% of the processed meats output from TFI's Murray Bridge plant, it was evident that this should be the primary area of focus. As part of this study, a number of sensing and gripping technologies were evaluated in order to determine the most appropriate technologies for this task.

Strategic Engineering's proposed solution relies on the utilisation of a number of complex enabling technologies such as intelligent sensing networks, conveyors, and a team of 6 axis industrial robots to automatically identify, pick and pack primal cuts. The primal cuts will be identified using high definition colour cameras based on the packaging of the primal cut. In the event that generic packaging is used, a QR code labelling system will be introduced. Real time 3D scene information will be captured by a series of Time of Flight cameras. The information gathered by the ToF cameras will be correlated with the vision system data and used to determine the pose and orientation of primal cuts in both the conveyor and cartons in order to inform the picking and packing routines. A 6 axis robotic manipulator equipped with a custom end of arm tool will be used to grasp the primal cuts from the conveyor and transport them to the appropriate cartons.

With the development of the proposed system it is envisaged that staffing levels for the packing station can be reduced significantly. Although the introduction of a single robot cell can yield savings, it is predicted that a team of two or more robotic cells must introduced before significant labour reduction and cost savings can be achieved. Additional robotic cells will be capable of accommodating a greater variation of primal cuts, eliminating the need for manual handling altogether.

The intended outcome of this feasibility study is to inform the meat industry on the practicability of an automated primal cut pick and pack system, the appropriate technologies, and the associate risks involved in the implementation of such a system.

Strategic Engineering believes that the implementation of an autonomous pick and pack system is feasible with existing technologies, although the development of such technologies is required for their adaptation into the red meat industry. Development of the following areas will greatly de-risk this project and assist in the widespread implementation of such technologies:

- The research and development of intelligent sensing algorithms for the Time of Flight and HD industrial camera;
- The development of multiple End of Arm Tool’s to cater for common subsets of primal cuts;
- The development of intelligent tool path generation algorithms and the integration of the End of Arm Tool (EOAT)/intelligent sensing system; and
- The performing of in-depth factory acceptance testing and site acceptance testing workshop and plant trials.

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1. Market Analysis

1.1. Industry Challenge

One of the largest operating costs associated with commercial meat processors stems from the labour requirements of running a boning room. Boning rooms comprise of a sequence of repetitive, manual tasks which includes the bagging and sealing of meats, and then the packaging of cuts in to cardboard cartons for storage or dispatch. Although several packing arrangements exist, the scope of this study will be limited solely to the packing of vacuum sealed primal cuts. This is because vacuum sealed products can account for up to 70% of a meat processers net output, and automating this task will provide the greatest return on investment.

The ability to reduce operating costs of the boning room whilst improving OH&S practices and maintaining productivity is viewed as advantageous to all meat processors around Australia. The major impedance to workflow within the boning room was caused by the packing area. In some facilities, primal cuts are packaged at roughly half the rate than it is produced. Many believe that the key to improving this process lies within the introduction of autonomous robotic cells.

It has been found that 49% of mechanisms for injury in the meat industry have been related to bodily stress[1]. This figure is significant for any industry, and needs to be addressed. The figure is exceeded only by structural and sheet metal product manufacturing. Common injuries are in the form of Repetitive Strain Injury (RSI), heavy lifting and coming into contact with other objects (for examples knives or being hit by a moving object). RSI is a primary cause of injury due to the repetitive lifting of heavy meats. The challenge is to create a safer working environment while increasing the productivity of packing rooms.

Such occupational issues, coupled with the mundane tasks in which they are accompanied, has attributed to the difficulty of employee retention within the meat industry. The constant training of new staff ultimately leads to inefficiencies and loss of quality throughout the production line, resulting in higher overhead costs. To combat this trend, there is has been a steady push by MLA and AMPC for the introduction of automation technologies throughout the meat production cycle.

[1] http://www.redmeatinnovation.com.au/ohs/pdfs/OHS%20Reference%20Guide%20-%20Part1.pdf

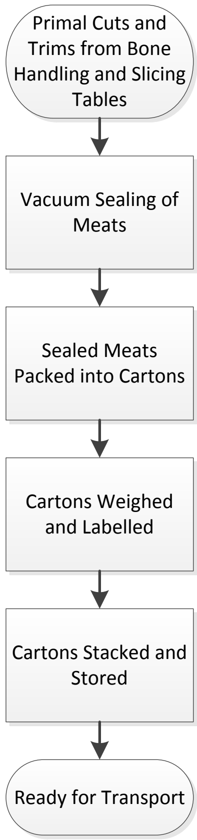
At present there are large opportunities for use of automation technology within the meat industry. Most, if not all, meat processors use some form of automatic assistive technologies, such as conveyor systems to transport primal cuts and trims from the boning stands and slicing tables to the final weighing and labelling stations in preparation for packing[2]. Irrespective of this, the bulk of processes within the meat industry remain manual.

Between the processing and packaging stations, there is a station designated for vacuum bagging, wrapping, weighing and labelling. Technologies exist to automate the bagging processes, although there is no all-encompassing solution to cater for all variations of primal cuts a meat processor may produce. Many of these stations remain semi-automatic, requiring some level of operator intervention. It is perceived that this technology has progressed to the point where further investigation within this feasibility study is not warranted.

Due to the large number of primal cuts (there are over 30 different variants packed regularly at TFI alone) and the inconsistencies between each primal cut profile, there currently exists no solution to automatically identify a given cut, pick it up, and efficiently pack it within a carton. Furthermore, the desired manipulator required to perform such a task must be gentle to the touch, while capable of securely grasping and rapidly transporting cuts of up to 5kg about a robot cell.

[2] http://sicktoolbox.sourceforge.net/docs/sick-lms-technical-description.pdf

1.2. Existing Solutions



Due to the technical complexities involved in this task, there is currently no solution available capable of packing vacuum sealed primal cuts into cartons. The most practical and efficient method of placing primal cuts into cartons is through the use of manual labour. Due to the high amount of variables associated with primal picking and packing, meat processors have been reluctant to adopt an automated approach. The most widely used pick and packing process makes use of multiple operators (dependant on the stock produced, throughput, and plant size) to manually pick and place primal cuts into cartons.

In the first stage of meat processing, carcasses are sent to the '*boning and slicing*' section to 'quarter' the meat. These quarters may later be 'sliced' to the given specification. These stations are typically physically located above and facing towards the slicing tables, allowing boneless meat to fall onto the tables, eliminating unnecessary strain on the operator having to lift or throw the product.

These cuts are then transferred via conveyor to a vacuum sealing section. The cuts are placed individually into a bag, where they are spaced evenly and sent into the vacuum sealing station. Air is then evacuated from the bag prior to sealing via a vacuum process to help increase quality and shelf life of the cuts. Bags that have been incorrectly sealed are rejected at this point and sent back down the production line for reprocessing. It was estimated that cuts required reprocessing between 1 and 2% of the time. Although this figure may sound insignificant, a large meat processor will require the retention of two or more full time staff to constantly cater for this issue.

Sealed cuts are then sent to the picking and packing station via a conveyor system. Here, operators are required to lift cuts and place them into cartons in compliance with the specific order. Specific orders may vary the quality, quantity, and weight of primal cuts, dependant on the market in which the meat will be dispatched. Once all of the required meat has been placed in the carton, an order label is generated and attached. The carton is then conveyed to the appropriate processing area for storage or dispatch.

1.2.1. Robotic Grippers

As previously mentioned, within the red meat industry there has been no application of a gripper being used to pick and pack vacuum sealed primal cuts. In all cases found that involved the autonomous picking and packing of meat, the meat has been of consistent shape and size with little variance. In such systems, the meat enters the robot cell via a belt conveyor, and the vision system is used to determine the location and orientation (usually in two dimensions only) of the meat, allowing the robot to perform the pick and pack routine.

For small cuts such as salami, chicken breasts, ham or turkey the most popular gripper has been the use of a 'scoop' type gripper with an upper clamping mechanism as shown in Figure 1 and Figure 2 below. These grippers are often used in conjunction with an intelligent portion loading (IPL) robot such as ABB's IRB FlexPicker for high speed packing (around 120/minute).

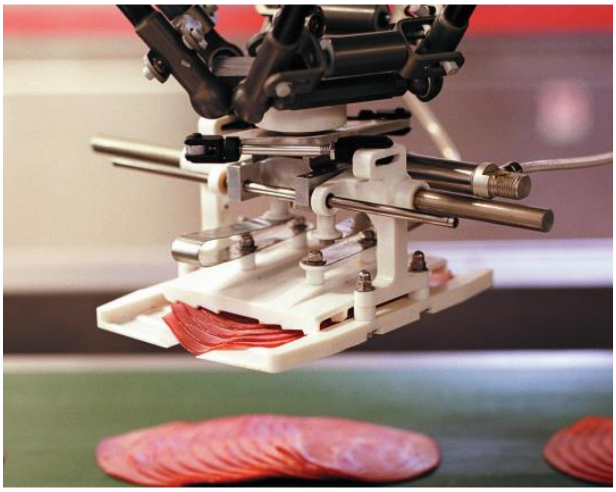


Figure 2 – AEW Delford System's gripper to suit a variety of sliced meats

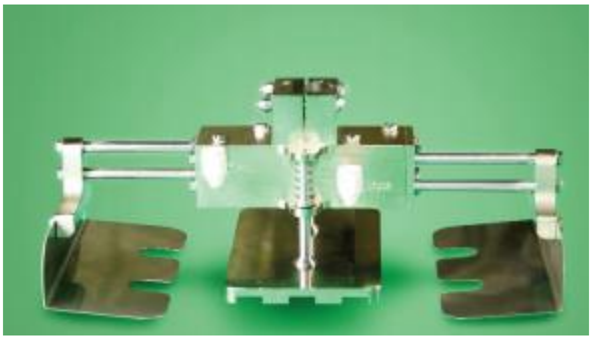


Figure 1 – Applied Robotics' Meat Gripper

While this style of gripper has only been successfully utilised on small cuts with consistent geometric properties, a derivative concept may prove useful for gripping primal cuts. Two key issues are presented with this method when applying it to primal cuts:

a) The width of the gripper may conflict with the carton when the side scoops are extended in order to place the meat within the carton
b) There will be limitations to the primal cut's width and height due to mechanical restrictions in this gripper. Wider cuts may require additional support under the centroid to avoid deformation. As a result the width of the gripper may exceed the carton size making packing difficult.

For sausages, IPL robots have been used in conjunction with two finger grippers. Such grippers firmly grasp the length of the sausage, positively locating the sausage between both fingers as they close. This application does not require the precision and accuracy necessary for a successful primal cut gripper. Gripper assemblies may be configured to contain multiple two finger grippers to improve productivity as shown in Figure 3.

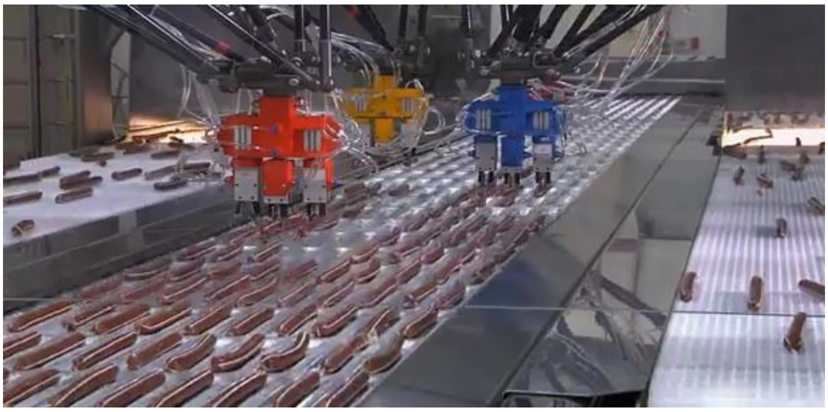


Figure 3 – ABB robots with Robomotion-GmbH's custom gripper picking and packing sausages

For larger and plastic sealed items, the gripper design is largely influenced by the shape and size of the object, however vacuum and clamping style grippers have proven most popular for these applications. For bags of olives, claw shaped grippers have been used to clamp the sides of bags on a conveyor, stacking them into cartons (as shown in Figure 4). The claw shaped gripper is able to slide underneath the bag to provide the necessary support during transport to avoid bag damage. The constant-radius gripper design minimizes interference with the cartons during the packing phase, allowing it to efficiently pack cartons without being limited by the gripper size. Key issues that exist with this method when applied to the primal cuts are:

a) The finger radius will be unable to cater for all primal cuts. It will have trouble picking thinly sliced cuts and may not provide enough under body support for wide cuts. Modification to the shape or curve of the fingers may be needed to cater for a specific range of cuts.
b) There is a fixed distance between the two sets of fingers. If the cut falls short or exceeds this distance, then the cut will not be correctly supported and the meat or plastic seal may become damaged.

Figure 4 – FANUC Robotics Olive Bag Packaging system

Based on our discussion with meat processors and research in the robotics industry, we have been able to derive a list of concerns which may have led to the aversion to robotic technologies in the past. These issues should be considered in depth whilst developing an appropriate gripping solution.

- Extremely high variance in primal cut size and shape – The EOAT must be designed to cater for all cuts. It should be expected that primal cut specifications will differ between boning rooms.
- Limited packing area within the carton – The EOAT must ensure that primal cuts can be tightly packed. Optimal use of space within each carton is essential to ensure the minimum weight requirement is fulfilled without overflowing the carton.
- Manual packing capability is available – The packing line must still be accessible to an operator in the event the robot is offline. Meat processors have tight delivery schedules, and any unplanned downtime can be extremely costly.

1.3. Influencing Factors

There are a number of contributing factors to the red meat industry's acceptance of automation technologies, particularly within a process containing such a large number of variables. Such influencing factors may include technological limitations, market acceptance, financial considerations, quality control, and OH&S concerns. These factors are briefly discussed below.

1.3.1. Technological Limitations

In order for a robotic pick and pack system to be successful, several major technological hurdles must first be overcome. First is the need for an intelligent sensing system and robust algorithms able to correctly identify the position and type of primal cut out of potentially hundreds of different cuts, with a high level of precision and accuracy. The second is the need for an EOAT capable of grasping the identified cut and placing it within the appropriate storage container without damaging the meat.

Although these tasks may seem trivial to an average operator, the technological innovation required for accomplishing such feats is the culmination of years of research and development. For instance, a primal cut viewed at different orientations may result in improper classification.

1.3.2. Financial Considerations

Robot cells are known to have a high upfront investment, with the investment typically paid off over a number of years. As the cost of automation and infrastructure becomes more and more competitive to the cost of human labour in many markets, many industries are beginning to opt towards automation technologies. It is common practice to determine whether introducing a robotic cell is financially viable. This is achieved by determining if the long-term organisational gains outweigh the upfront financial investment.

Labour reduction plays the largest factor in financial savings. The typical salary of a boning room employee was found to be $50,000. The elimination of four operators per shift for an organisation running 2 shifts per day will yield an annual saving of approximately $400,000. Aside from the direct labour savings, other benefits will be realised include improved quality and a reduction in operator error.

The health and safety of employees are also financial considerations to be aware of. Operators will be alleviated of the repetitive movements and heavy lifting associated with the picking and packing process. This may result in the reduction of workers compensation claims, increased productivity and workplace diversity, all leading to financial gain.

There is however on-going costs associated with running robotic cells. As with all mechanical equipment, components are expected to fail after extended use. Preventative and reactive maintenance programs should be enacted which may include the procurement of an initial surplus of spare parts, annual or biannual inspection and servicing programs, additional operator and technician training, and additional energy requirements. Although such systems are designed to last a number of years without failure, any unscheduled downtime could prove costly and therefore many organisations consider the costs worthwhile.

It is estimated that in roughly 14 months a basic system costing $286,100 can be repaid. From this time an annual savings of $200,000 will be obtained. After 5 years, it is expected a $700,000 return will be made. This calculation is taking into account savings in labour costs, reduced rework costs, additional revenue, savings due to reduced stress/strains and injuries, setup costs and ongoing wear costs. This is also generously assuming a reduction of 2 operators per shift, completing 2 shifts per 24 hours. It is possible to reduce the number of operators required by more than 2 operators depending on the size of the processing facility; however for this scenario we will assume 2.

See Appendix A for further details on calculations. It is important to stress that these calculations do not include the investment necessary to develop the robust sensing system algorithms and EOAT design. The pricing included reflects an estimated cost to adapt the algorithms and EOAT to cater for each respective meat processor.

Total System Cost	$286,100	
Total Yearly Savings	$200,000	
ROI	13.6	Months

1.3.3. Quality

In order for the autonomous pick and place strategy to be viable, it is important for the new system to at least meet the specification of the current process. These specifications may include the maintenance or reduction in cycle time, increased accuracy in the identification of cuts, the reliable packing of cuts, appropriate identification and handling of reject cuts, and so forth.

Traceability is also an important facet of meat processing. The ability to rapidly determine the source of suspect produce can aide in the containment of a potential outbreak. Dependant on the requirements of the processing facility, labels are sometimes affixed to individual primal cuts or wholly packed cartons. Although this study will not examine labelling technologies, such technologies are quite accessible and can readily be incorporated into a robotic cell.

The failure to meet one or more of these criteria, however, may be overlooked if the system was able to provide additional benefit to the organisation and its employees. For instance, an increase in the well-being of the plant operators may provide enough justification for a slight increase in cycle time. Furthermore, the ability to negate the effects of high staff turnover by reliably picking and packing a significant portion of primal cuts may also be looked upon favourably.

1.3.4. OH&S

In today's society with the rapid emergence of automation technologies, there is a large emphasis on maintaining the safety of employees. Although the introduction of automation technologies will undoubtedly introduce several workplace hazards, it will also assist in the elimination and/or reduction of existing hazards. Initially robotic cells would target the automated processing of larger, heavier cuts, leading to a reduction in RSI and bodily stress issues. These algorithms will later be expanded to encompass the processer's entire range of primal cuts.

1.3.5. Market Acceptance

Industrial robots have become more prevalent within various industries, particularly manufacturing, over the last 25 years. The ability to perform the most mundane and strenuous tasks with high accuracy and relative ease allows an organisation to maintain high production targets with little concern for OH&S issues. Despite this, some industries have been reluctant to embrace automation solutions.

A robotic cell can be quite complex machinery, and therefore may be quite intimidating to a small / medium business. Coupled with a relatively high procurement cost, a business may be reluctant to bear the burden of operator training, and also preventative / reactive maintenance. Furthermore, if a robotic cell fails, the organisation may be unable to maintain the production required while the fault is rectified, resulting in supply chain issues.

Some sensing systems, particularly machine vision systems, have also attributed to the perception that robotic cells are unreliable. Machine vision was introduced widely in the 1990s as a result of a boom in growth due to the advancement of computer technology. At present, an evident growth in machine vision is still exists. The affordability and availability of camera systems has increased while the accuracy and abilities has also improved dramatically. Reliability has always been an issue in vision based systems, primarily in systems which deal with a wide range of lighting conditions, object shapes, motion, and so forth. Many of these issues can be attributed to the selection of low quality/incorrect hardware, the use of unreliable software algorithms, or simply a lack of testing and refinement.

1.3.6. Hygiene

Hygiene is paramount in food processing. Meat processers are subject to some of the strictest hygiene standards, and any proposed automation solution must first demonstrate its ability to comply with these standards. The cleaning of production lines occurs throughout the entire day; however most of the cleaning is completed at the end of the day. Dry cleaning often occurs throughout the day which assists during the final cleaning phases and reduces water usage. The Australian Standards require:

- Cleaning compounds to be approved for use in meat processing premises
- All chemical residue to be removed from sources likely to contaminate edible products by throughout rinsing with water before the area or equipment is used for handling edible products (unless it is approved for use without a final rinse).

2. Technical Feasibility

2.1. Sensing Systems

The key technological challenge that may impede the delivery of an automated pick and pack system is the sensing system. Primal cuts come in a variety of shapes and sizes, and therefore it is necessary to detect these attributes before attempting to pack them into cartons. Any proposed system must have access to the following information:

- The specifications of the primal cut;
- The size, pose, and orientation of the primal cut; and
- The current configuration of carton in which primal cuts will be packed.

Accurate identification regarding the primal cut's specification is necessary to determine the appropriate carton in which the cut will be packed. Failing to do this correctly will result in additional product handling and/or a displeased client base. Accurate size, position and orientation information will help determine the most appropriate orientation for the EOAT to adequately grasp the cut. Finally, accurate carton configuration data will allow the system to determine the most appropriate location to pack the primal whilst allowing ample room for cuts yet to be packaged.

The following section will detail the information required to solve each problem, examine the solutions applicable to the task, and provide a recommendation in regards to the most suitable technologies.

2.1.1. Cut Identification

Barcodes are a widely used tool to identify a diverse range of products, and is used in a number of industries. A key issue however is ensuring that the barcode is clearly visual to the barcode reader. Issues that may cause the barcode to be unreadable include:

Figure 5 – AusMeat Label Information.

- Barcode partially or wholly occluded;
- Blood, Water or other fluids on the barcode or barcode reader;
- Damaged barcodes; or
- Labelling machine malfunction resulting in the barcode being printed incorrectly.

It is envisaged that for the proposed system, primal cuts not packaged in a uniquely identifiable bag shall be labelled with a unique Quick Response (QR) code prior to picking and packing. A QR code is advantageous over conventional barcode technologies because it allows the primal to be correctly identified from a wider range of viewing angles while damaged or partially occluded. Furthermore, QR codes facilitate a greater storage capacity than other barcode mediums (up to 174 characters for QR v10), allowing information such as cut type, package date, expiration date, weight, fat content, etc. to be depicted on the label.

TFI currently utilise uniquely identifiable packaging for the majority of their primal cuts. There exist cuts reserved for further processing that are not packaged in uniquely identifiable bags. For the purpose of this feasibility study, it is assumed that these primal cuts will be labelled with a QR code. QR codes will be attached immediately preceding the vacuum sealing process to avoid deformation. For the successful implementation of a labelling system, the following considerations must be made:

- How the cut specification is determined – via operator input or sensor array;
- How the label is to be applied – manually or autonomously adhered; and
- What type of label is applied – QR code or a different labelling standard.

Although the use of QR codes is preferable, some meat processors may prefer to use their existing labelling systems. It is therefore important to ensure that the proposed barcode reader has the capability of reading various codes. Although several dedicated barcode readers exist, they often have a limited field of view (FoV) and operating range.

In order for a cut identification system to be considered for this task, it must be capable of readily parsing a vast variety of barcode and bag types. Additionally, the reader must also have a large FoV and able to operate at an overhead height of at least 1.5m in order to avoid collisions with the industrial robot. For these reasons, our conclusion is that this task is best suited towards a high definition industrial camera.

2.1.2. Chemical Lean Status

When packing beef, it is important to ensure the specification of each cut is known. A requirement of a butcher may be to have meats of a certain quality. This is because higher quality cuts will typically reap a higher yield, and the delivery of consistently low quality cuts may result in backlash throughout the supply chain. The quality of cuts can be identified by specifications such as colour and fat content.

Although sensors exist that can accurately determine the chemical lean status of primal cuts, many meat processors, TFI included, perform primal cut grading through visual inspection alone. As it is envisaged that all primal cuts will pass below the HD industrial camera for identification, this camera may also be used to perform the visual grading of cuts as well.

2.1.3. Geometric Profiling

Perhaps the most important section of the picking and packing process is the geometric profiling of primal cuts. Accurate geometric profiles of both the primal cut and the packing carton must be generated in real time. The aim is to determine the overall shape, size, and position of the cut so the system can determine how it will grip the cut and place it within the carton.

Geometric information will assist in the generation of dynamic tool paths, which allows the primal cuts to be grasped in the most efficient manner without collision with other cuts and the environment. This information must be correlated with the primal specification information to determine which carton the cut will be packed in, and then the carton profile to determine the most efficient packing profile.

There exists a range of well-developed technologies which will be able to provide geometric profiling information on cuts. The key technologies that best suit this application include Laser Measuring System (LMS), Time-of-Flight (ToF) cameras, Laser Line Scanner (LLS) and Stereoscopic vision systems.

Laser Measuring Systems

The LMS's operating principle is based on measuring the travel time of laser light pulses. A pulsed laser beam is emitted from the device, and reflected back if it detects an object. The reflection is then registered by the receiver. The time between transmission and reception of the impulse is directly proportional to the distance between the receiver and the object. The contour of an object is determined from the sequence of impulses received. In a radial field of view, a spot impulse is emitted every 0.25-1 degree depending on LMS[3]. As a result the diameter of the laser spot is able to determine the contour shape of that section of the object. Generally LMS's are suited to wide range applications. The Field of View (FoV) can range from 100 degrees all the way to 360 degrees, though this is usually achieved by revolving mirror systems. It is a non-contact, extremely fast, reliable, and repeatable method of determining the 3D profile of objects.

Laser Line Scanners fall under the same category as Laser Measuring Systems. They use the same fundamental principle and components however rather than emitting light in multiple angles, they instead focus the beam to form a line. This line can be passed over the object to determine the 3D characteristics of the object. The advantage of this is that it can scan moving objects far more accurately then standard LMS as it takes into account the velocity of the moving part when forming the image.

Laser measuring systems have been successfully employed in many industries, and relied upon on a daily basis to rapidly provide accurate distance and speed measurements. Such industries include defence, agriculture, sports, manufacturing, construction, and so forth. Such sensors typically produce only a 2D array of values which corresponds to the distance from an object at a particular angle. In order to derive a 3D snapshot of the scene, some LMS must be coupled with an actuator to cyclically tilt the sensor.

As mentioned above, the output of an LMS is typically an array of raw range values. For use within a 'pick and pack' application, the information must be processed in order to provide meaningful information. The raw data must first be correlated and aligned with preceding readings to develop an accurate 3D point cloud of the scene. From the point cloud, an algorithm can then be applied to remove the background information (i.e. the conveyor) and identify the primal cut of interest. A 'fitting' algorithm may be used to compare the sensed object with a database of 3D profiles to determine its orientation.

Before any robot manipulation can occur, the sensing system must first transform the co-ordinate system of the vision system to one co-ordinate system used by the industrial robot. Discrepancies

[3] http://sicktoolbox.sourceforge.net/docs/sick-lms-technical-description.pdf

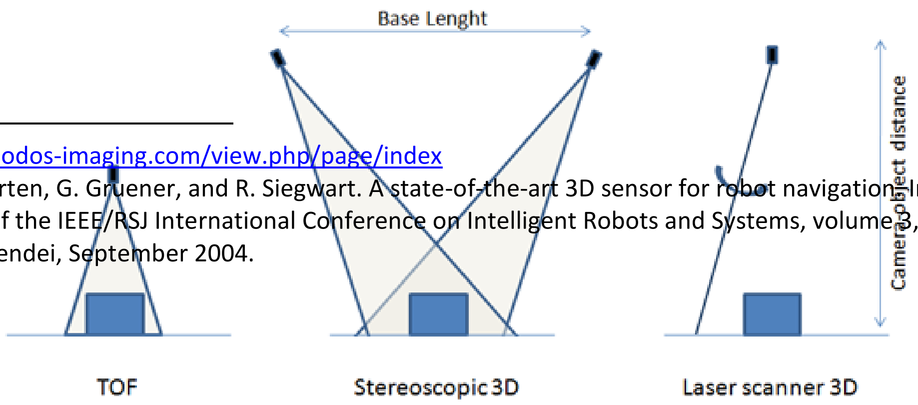
between these two co-ordinate systems may result in robot collisions with the environment. A high precision sensing device will minimise variances between calculated and actual tool paths.

Time-of-Flight

Time of Flight Cameras (ToF) utilise a similar principle to LMS, however in addition to a laser emitter and receiver, it features the components of a camera. This allows the ToF Camera to operate very quickly, providing up to 100 images per second[4] with a larger vertical field of view then 3D LMS[5] which is achievable without any moving parts.

A ToF camera is a camera system that captures vision of a scene and creates distance data using pulses of infra-red light. A pulse of infra-red light illuminates the scene, and light is reflected by the objects. The camera lens gathers the reflected light and images it onto the sensor plane. Depending on the distance to objects in the scene, the incoming light experiences a delay. This delay is measured and distance data is calculated. As the distance data is provided natively by the ToF camera, no additional computation is required to post-process the captured data to provide distance measurement. As the entire scene is captured and distance data calculated at the one time, precise real-time tracking of the primal cut or trim is possible at the full frame rate of the selected camera.

Strategic Engineering has implemented a system which was capable of locating and tracking the rear hocks of beef cattle in 3 dimensional space while lying in a cradle shortly after stunning. It was found that the ToF camera was able to produce predictable and repeatable results for extended periods of time which is paramount to ensuring successful identification and 3D profiling of primal cuts. A similar product is easily adapted to aid a robotic manipulator to pick and place vacuum sealed products.



[4] http://www.odos-imaging.com/view.php/page/index

[5] J.W. Weingarten, G. Gruener, and R. Siegwart. A state-of-the-art 3D sensor for robot navigation. In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, volume 3, pages 2155–2160, Sendei, September 2004.

Figure 6 – Difference between Sensing Solutions

There are two ideal candidates for ToF cameras currently on the market. These include the PMDTec CamCube3 and the MESA Swissranger SR4000.

Figure 8 – PMDTec CamCube3

Figure 7 –MESA Swissranger SR4000

While it can be found that the SR4000 has a larger range than the CamCube3 (10m compared to 7.5m), the maximum sensor resolution of the CamCube3 is 200x200 pixels compared to Swissranger's 176x144. This is the highest resolution of all phase shift ToF cameras on the market and is a key feature when image accuracy is an important requirement. The declared distance measurement repeatability is similar for both devices (0.003m for the CamCube3 and 0.004m for the SR4000)[6]. While the maximum native image capture speed for the SR4000 is 54 FPS (frames per second) compared to the CamCube3's 40 FPS, the "crop utility" offered by PMD allows cropping of pixel columns and rows to reduce image size and increase FPS, making it possible to achieve up to 60

[6] http://www.mdpi.com/2072-4292/4/4/1069

FPS. Based on these findings, it can be determined that PMD's CamCube3 offers a greater level of accuracy (<3mm at 1σ) than the SR4000 and has a higher protection rating (IP67) than the SR4000 and Baumer (IP65) alternatives making it the most suitable candidate.

ToF vision has also been successfully used in a number of industries, particularly in the industrial (vehicle guidance, presence sensing, and object detection) and entertainment (interactive gaming, e.g. the XBOX Kinect) industries. Contrary to LMS sensors, ToF vision sensors will directly output 3D distance data. This alleviates the need for an additional actuator to pan / tilt the device, or to correlate and align multiple sensor readings. Background subtraction and fitting algorithms must still be employed to remove unnecessary features and determine the orientation of the cut.

Stereoscopic Systems

Stereoscopic 3D measuring systems utilise two slightly offset cameras looking at the same scene. By analysing the minor differences between the images seen by each camera, it is possible to determine the relative distance at each point in the images. Stereoscopic vision attempts to compute the third dimension in the similar way to the human brain as shown in Figure 9.

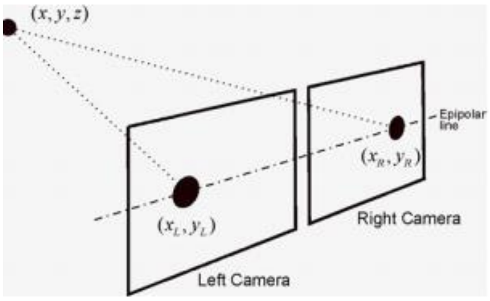


Figure 9 – Stereo Vision Principle

The main process in stereoscopic vision is the stereo relation between two images which is used to approximate the difference between image locations of an object recorded by two cameras[7]. In robotic applications which require multidimensional part localization in 3D space stereo is considered an older technology[8] [9]. The main advantage of Stereoscopic is that it is a relatively cheap and cost effective solution. It does not however achieve the accuracy and repeatability attainable with other intelligent sensing systems, it may require pre-calibration, and is subjected to interference related to dynamic lighting conditions (shadow, glare, etc.).

2.1.4. Sensing System Development and Adaptability

[7] Calin, G. & Roda, V.O. (2007) Real-time disparity map extraction in a dual head stereo vision system, Latin American Applied Research, v.37 n.1, Jan-Mar 2007, ISSN 0327-0793
[8] W. (2008). 3D Vision Guided Robotics: When Scanning Just WonâA˘Zt Do, ´ Machine Vision Online. Retrieved from https://www.machinevisiononline.org/public/articles/archivedetails.cfm?id=3507
[9] Iversen, W. (2006). Vision-guided Robotics: In Search of the Holy Grail, Automation World. Retrieved from http://www.automationworld.com/feature-1878

There are various factors that must be considered to ensure that the intelligent sensing system is capable of performing at an acceptable level. These factors will exist in every meat processor, however their significance may vary. These development strategies include:

- Information Exchange requirements

It is important to ensure all sensing peripherals are able to exchange information via standard mediums (i.e. Ethernet, USB, serial, digital IO, etc.) using standard communications protocols. Although custom interfaces can be developed, such implementation can be costly and offer no significant benefit to the end user. It is also important that all sensing information may be amalgamated within a master control system. The system must therefore contain hardware and software architecture to efficiently support these information exchange requirements.

Furthermore, it may be necessary for the master control system to communicate with legacy infrastructure to optimise the flow of the production line. For instance, it may prove beneficial to allow the master control system to speed up and slow down the in-feed and out-feed conveyors to ease congestion on the production line.

- Algorithms Selection

There exists a plethora of academic and industrial literature to review in order to select the most appropriate algorithm/s for a particular application. As technologies mature, innovative and creative algorithms and operating techniques will be developed. At times a combination of multiple algorithms may prove the best solution to a complex problem. It is also important to determine any software packages and/or toolkits available that may assist in the rapid prototype and/or evaluation of the algorithms.

- Test apparatus

It is envisaged that the design and construction of test apparatus may be necessary to support the test and evaluation of various sensing and control algorithms. This may include the framework for mounting the sensing unit, a lighting solution that will mimic conditions within a standard packing room, and an in-feed conveyor transporting primal cuts at speeds expected within a commercial meat processor.

The option exists for footage of primal cuts passing through a packing room to be captured and recorded for processing off-site, offsetting some procurement and fabrication costs. Though this option may be more cost effective, it inhibits our ability to readily alter testing conditions and parameters, and strenuously validate our experiments.

- Test and evaluation plan

This involves the development of evaluation criteria to ensure the performance of the sensing system complies with the minimum operating criteria dictated by the meat processor (i.e. minimum acceptable values for repeatability, accuracy, detection time, etc.). Test and evaluation plans will be created in collaboration with the partnering meat processing facility, and strenuously conducted to ensure the solution produces the desired results in a range of operating conditions.

Furthermore, it is important to ensure that the profiles generated from the algorithms align with the actual distances and geometric properties of the physical meat cuts. Variances in these values may lead to inaccuracies while picking and packing, which must be overcome in a commercially viable system.

- Rejection Handling

In the event that a handling failure occurs (i.e. the vacuum sealed packaging is punctured or the product is not compliant with specification), a rejection routine must be instigated to cater for the failure condition.

The sensing system will attempt to provide adequate information regarding the cut type, size, position, and orientation. However, if a primal cut cannot be identified, or is not compliant with the current packing specification, it will be ignored. As more primal cuts are added to the conveyor, congestion may occur. This will make it increasingly difficult to track, pick, and place desirable products off of the conveyor.

To address these scenarios, an operator may be positioned further downstream the carousel conveyor to manually handle the primal cuts on the production line. The operator can assist in manually packing cartons as well as reorientating meats that the sensing system was unable to identify. Rejection will be a rare occurrence; however a robust system must be implemented to account or anything that may occur within the robot cell.

- Adaptation

Precautions must be made when moving from controlled to production environment. Variations in cut sizes and orientations may differ significantly from those observed within the controlled environment, and should be expected. Although this exercise may be costly, it is beneficial to conduct trials with a substantial sample size to adequately reduce the risk of complications.

Similarly, lighting conditions may vary throughout the day also, and must be catered for. Lighting has a large effect on vision systems and can alter the way an object is perceived. Packing rooms with an abundance of natural light may require alteration to ensure the sensing system can perform reliably, regardless of the time of day.

2.2. Gripping Mechanisms

The robotic end of arm tool (EOAT) is the gripping mechanism used to pick and place primal cuts. The EOAT is to be connected to a 6 axis robotic manipulator that allows the gripper to interact with the surrounding environment. It will be used to pick primal cuts from an in-feed conveyor and efficiently pack them into cartons. Data containing approach angles, velocities and gripper output states will be obtained based on feedback from the sensing system.

2.2.1. Design Factors

The design of the EOAT allows room for innovation. For a specific task it is possible to customise the tool in order to achieve the best possible performance. When designing the tool it is important to consider all external factors that may influence the gripping functionality. To design a gripper that is suitable for this application, several key considerations have been identified:

- Tool material
- Cut variety
- Tool size
- Tool weight
- Tool Strength
- Gripping surface type
- Ensuring secure grip of primal cuts
- Primal cut alignment
- Picking and packing failure and collision avoidance
- Tool changeability
- Tool maintenance

Tool Material

Selection of the EOAT's material is generally governed by operating characteristics the tool will experience. It is beneficial to keep the weight of the gripper as low as possible, while maintaining high rigidity and strength. The majority of components within the gripper will be constructed out of aluminium due to its excellent strength to weight ratio, durability, ease in fabrication, and great corrosion resistant properties. Mild steel and stainless steel may also be an option, however considering weight is a major factor, and with the steel being far denser than aluminium (7850 kg/m^3 compared to 2800 kg/m^3), aluminium may be the better choice for this application.

Cut Variation

As previously stated, there will be significant variation between primal cuts. TFI in particular supports the picking and packing of roughly 30 different primal cuts, each with their own unique attributes. The weight of each of these cuts varies from between a few hundred grams to up to five kilograms. Additionally, the dimensions of each cut will vary drastically. For instance, the long slender tenderloin differs greatly from the large, bulky brisket; requiring completely different mechanical requirements to perform a pick and pack routine. Though it may be impossible for a single EOAT to accommodate all these variations, the EOAT must be able to cater for a reasonable subset in order to be financially viable.

Tool Size

The dimensions of a typical packing carton at *TFI* are approximately 400 x 700 x 200 (mm). As a result, there is limited space for insertion of primal cuts and the EOAT. The size of the EOAT needs to be optimised so it is able to place meat into a carton while not conflicting with its surroundings. Some cartons require very compact packing as shown below in Figure 10. Furthermore the tool size needs to cater for the variances in cut size as discussed in the previous section. A gripper too small will be unable to cater for large cuts and a gripper too large may be unable to accurately pack the smaller cuts.

Figure 10 – Cassino Packing Station

Tool Weight

The weight of the EOAT will directly influence the size and specification of the industrial robot selected. Industrial robots are limited to a specific static and dynamic payload it can reliably handle. Loads that are applied beyond this specification are not covered by vendor and manufacturer warranty and may produce unpredictable results, damaging the robot and harming personnel in the process. Furthermore, an unnecessarily heavy EOAT may incur additional costs due to the procurement of an unnecessarily larger robot, tool materials and fabrication costs, miscellaneous additional peripherals and so forth. These additional costs can easily exceed tens of thousands of dollars.

Tool Strength

Ensuring that the EOAT is capable of performing all of the required operations whilst withstanding all applicable forces without impeding functionality is an obvious consideration. Tool strength is generally based on tool frame and structural configuration. For large tools, gussets or supporting beams may be required to spread out load stress over the frame. Theoretical load calculations and Finite Element Analysis (FEA) should be completed to ensure that the stresses applied on the tool are at an acceptable level, and that deformation will not occur.

Gripping Surface Type

All meats which enter the picking and packing cell are enclosed in vacuum sealed packaging. Air is evacuated from the packaging prior to sealing (Example of Cassino Packing Station shown in Figure 11). The reduced atmospheric oxygen limits the growth of aerobic bacteria and fungi, increasing the shelf life of the meat. The gripper needs to be designed so it is able to pick and pack meats consistently without puncturing this packaging. If the packaging is punctured it will significantly decrease the quality and shelf life of the product. This may also lead to a variety of issues for the meat processor and its customers throughout the supply chain.

It is believed the most ideal EOAT would be capable of supporting the meat from the bottom surface. This base support will result in less stress being applied to the plastic packaging, reducing the potential of damage. Another concern associated with gripping the meat is the centrifugal force it may experience during transition from the conveyor to the carton at high speeds. Dependant on the gripping mechanism, it is envisaged that this process may place further stresses on the plastic packaging. Eliminating this effect may negatively impact the cycle time, as the speed of the robot will need to be limited should damage occur. Regardless of the gripping mechanism, strenuous testing must be conducted to ensure no damage is done to the meat or packaging.

Figure 11 – Cassino Vacuum Sealing of Cuts

Ensuring Secure Grip of Primal Cuts

As primal cuts are transported from the conveyor to the carton, they will experience additional dynamic forces. These forces need to be counteracted to avoid movement during transit. If the primal cut shifts significantly during transit, it may not be accurately placed in the carton. This type of failure mode is often difficult to identify due to the dynamic trajectories associated with the pick and place routines affecting the systems path repeatability.

While it is ideal to wholly secure the primal cut, often this may not be practical. A better solution may be to implement a gripping mechanism that follows the contours of the object being gripped. This will distribute the gripping forces over a large surface area and minimise deformation. Due to the large variation in cut shapes and sizes, this gripping technique is not practical. Irrespective of the gripping mechanism selected, it is important to ensure that the primal cut has sufficient support to minimise movement during transit between the conveyor and packing station.

Gripper Alignment

The ability to positively align primal cuts to a known datum is highly beneficial. Such mechanisms will improve system reliability by ensuring the location of the primal cut is known relative to the gripper throughout the pick and pack phases. This is vital as the position of the primal cut within the gripper will influence the robots trajectory during operation.

Picking and Packing Failure and Collision Avoidance

The ability to autonomously detect and resolve picking and packing failures will drastically reduce production downtime incurred by the operating facility. It is acknowledged that all issues cannot be rectified autonomously; however reducing the number of incidences in which operator intervention is required will be greatly beneficial. In the event that an incident does occur that requires operator intervention, the operator should be signalled using audible and visual mediums.

A method of detecting picking and packing failure is required to alert operators, should failure occur. This can be done by assessing or implementing the following:

- Photoelectric sensor mounted within the gripper to detect the presence of the cut throughout the '*pick and place'* sequence.
- Reed switches on any moving components to ensure they have been successfully actuated.
- Robot load analysis to monitor the load on the EOAT. The robot will halt the routine and sound an alarm should the current load exceed the maximum permissible load.

Robotic collisions can be a hazardous event in the automation industry. Safety regulations must be enforced to ensure that no persons are permitted within the robot's area of operation during operation. To ensure operator safety, safety guarding must also be utilised. This guarding will surround the working area of the robot to ensure operators remain at a safe distance while the robot is running. Furthermore, it is possible to also introduce mechanical and software limits to the cell to restrict the allowable work envelope if required. This will cause the robot's safety circuit to alarm should the robot attempt to move outside the assigned working area.

Tool Changeability

There are over 30 different types of primal cuts. Many of these will vary in size, weight, bone density and shape. Although it may be possible to design a gripper that is able to accommodate all 300 different variants of cuts, it may be more practical to design a gripper that is easily interchangeable and will provide the meat processor the ability to efficiently change the tooling to cater for the particular types of primal cuts to be packed that day. This will result in a higher level of modularity for the robot cell, and will allow the meat processor to change the gripper for their robot cell/s depending on their production requirements.

The EOAT must be able to simply bolt on and off the flange of the robot. Any electrical and pneumatic connections will be terminated in the junction box mounted on the shoulder of the robot. The junction box must contain push-in and bayonet style connectors for rapid exchange. This will allow the technician to simply unplug/plug pneumatic and electrical components to the junction box when changing the tool. An option on the HMI must be toggled to notify the robot controller what specific EOAT is being used. This selection will ultimately dictate the type of primal cuts can be successfully picked and placed. It is envisaged an EOAT could be swapped in less than 30 minutes, minimising disruptions to production.

Alternatively, a robot team can be employed and programmed to operate in unison. Each robot would be equipped with a unique EOAT to cater for a specific subset of meat to be packaged. This will provide the robot team far greater flexibility than a single robot cell, with the ability to collectively cater for a larger variety of primal cuts.

Tool Maintenance

Like all machinery, the EOAT will need to be regularly maintained in order to preserve life and functionality. The period between maintenance will be more frequent than robot maintenance, and may often be done with the robot maintenance to minimise down time. Tool maintenance will generally involve:

- Lubrication of actuating components,
- Ensure that fasteners are done up to the required torque specification, and

- Visual inspection of wiring or componentry for damage.

2.2.2. Gripping Options

There are a variety of gripping styles which are currently used in the automation industry. However, due to the unique application, there isn't a standard gripping style which is best suited to the picking and packing of primal cuts. It is possible to use a combination of tools or tool sections to assist in the picking and packing of primal cuts. There are four general categories for robot grippers:

- Ingressive – Grippers that physically penetrate the surface of the object for example pins, needles or hackles
- Astrictive- Forces applied to the objects surface through vacuum, magnetic or electro-adhesion.
- Impactive – Clamping style grippers which physically grasp the object by direct impact
- Contigutive – requires direct contact for adhesion to occur, for example glue, freezing or surface tension.

From these categories, the most viable gripping methods for picking and packing of primal cuts are impactive and astrictive type grippers as they avoid damaging the product.

Vacuum Grippers

Vacuum grippers often comprise of an array of suction cups coupled with one or more vacuum generators. Air can be sent or removed from the vacuum cups, allowing the cups to latch onto the desired object by forming an airtight seal. Suction cups are generally made from polyurethane or rubber and can operate at temperatures between -50 and 200 degrees Celsius. Different methods of vacuum grippers have been recently introduced which provide easier integration, higher suction force and the ability to grip non-uniform surfaces. A prime example is Romheld's UniGripper as shown in Figure 12. The UniGripper utilises a foam suction pad that deforms to the contours of the target object, increasing the gripper surface area. The gripper detects and occludes unused suction ports to ensure the maximum allowable pressure is used to grasp the object.

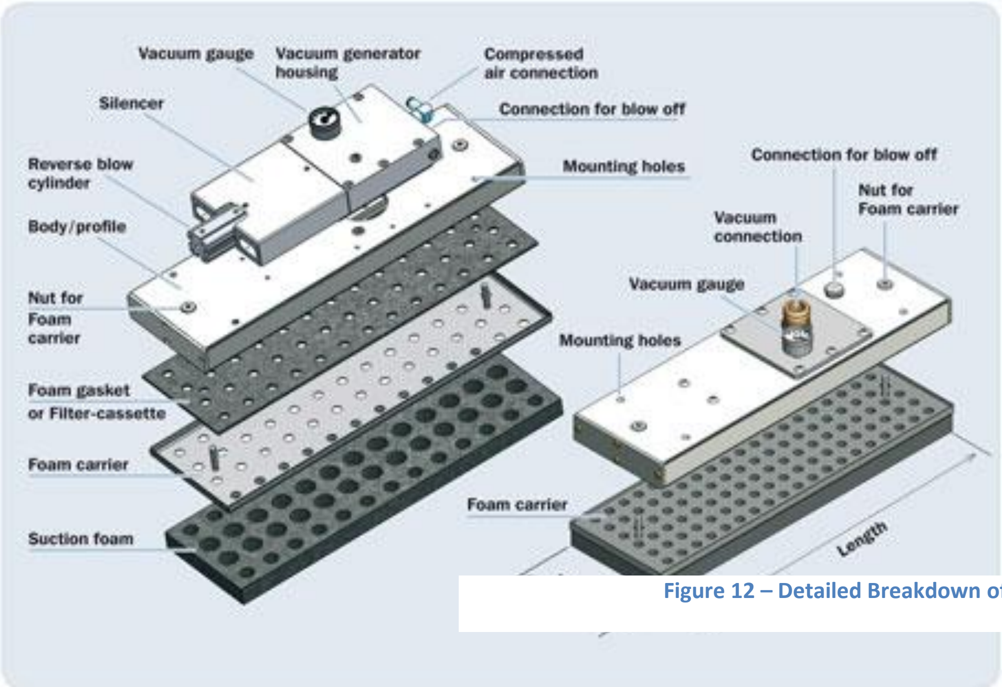


Figure 12 – Detailed Breakdown of a UniGripper

Vacuum grippers often have difficulty dealing with porous materials, discontinuities, and objects with rough surfaces. The smooth plastic packaging of vacuum sealed meats makes an excellent surface to grip. Considerations must be made in the selection and placement of suction cups to ensure the appropriate lifting forces are generated and maintained. It has been found that lifting cuts solely by the top surface only may result in damage to the packaging. Operators are taught to support the base of the meat while handling sealed cuts to ensure the plastic packaging does not tear. While this practice may also apply to vacuum grippers, no conclusive testing or evaluation has been completed to confirm this theory. Dependant on the packaging used and whether the vacuum forces are distributed over a large enough surface area, the resultant shear forces may reside in an acceptable level.

As there are large variations in the size, shape and weight of primal cuts, this may make it difficult for vacuum grippers to be used. Fortunately, there are easily accessible tools on the market that can increase the suitability of suction cups in this application. These tools include:

- Ball Swivel Connectors – provides up to 45 degree swivel, useful for picking up random or curved surfaces

- Level compensator – maintains the suction cup level when it comes into contact with an item
- Mounting brackets – to assist in the positioning and easy adjustment of suction cup location

Clamping Grippers

Clamping style grippers grasp an object by applying pressure externally or internally to more than one of the objects surfaces. Generally this gripper is driven by pneumatics or hydraulics, depending on the weight of the payload. For smaller objects the pneumatic method is preferred, whereas for heavy objects where large forces are required, the hydraulic method is ideal. The pneumatic method is more common because of the ease of use, low price and low weight[10].

Two and Three finger grippers are the most commonly used clamping grippers. Depending on the size and shape of the object to be grasped, finger tooling can be appropriately designed to ensure accurate and secure clamping. Three finger grippers are generally used to handle more complex geometries, or to provide a larger clamping force if required. Three finger grippers are slightly more complex to operate than the two fingered variants, and are also slightly more expensive.

A '*scoop'* style clamping gripper may be one viable option for this application. This gripper will utilise a static lower 'scoop' that will align with the conveyor and use its motion to allow primal cuts to slide onto it. Once the primal cut is located securely on the scoop, the robot will reorient the tool to allow the primal cut to align to a known datum. Simultaneously, the upper lip will extend, lightly clamping the primal cut in the scoop. This method will minimise damage to the meat, provide a slim tool that is able to fit with the carton, and is able to cater for a large variety of primal cuts. Two concerns associated with this option include:

a) The lower scoop must make contact with the conveyor for each pick and place sequence to ensure that the meat does not catch between the gripper and the conveyor. This may reduce the life of the gripper considerably.
b) The clamping force applied to the primal must be limited to prevent deformation in the lower scoop, resulting in insufficient force. During transport from the conveyor to the carton, the meat may shift, resulting in an orientation differing to what was observed by the sensing system.

[10] D.T. Pham, S. H. Yeo. Grippex: A hybrid expert system for selecting robot gripper types, (1990), 349-352.

Flexible Grippers

Flexible grippers consist of various joints on several fingers as shown in Figure 13. Each joint can be controlled individually giving high precision and flexibility. Generally with these form of grippers they lack the strength to handle large objects, are expensive, unreliable and require intensive maintenance. However due to the large amount of joints they are able to simulate the shape of the object being gripped which is ideal for picking and packing of cuts. These disadvantages of flexible grippers do not make this type a viable option for the picking and packing of primal cuts.

Figure 13 – Examples of Flexible Grippers, Adapted from [12]

Stop/Pusher Method

While this method is not a “gripping” type method, it should be considered as it is a method that has been used to align items in boxes in the past. Generally it consists of a stopper that stops the item on a conveyor, and a pusher which is used to push the item off the conveyor into another system (whether it is packaging or another conveyor). Cryovac uses this method to transfer large cuts from a belt conveyor into an automated bag loading machine, and then again to push the meat into a bag for vacuum sealing (as seen in Figure 14).

Figure 14 – Cryovac's Automatic Bag Loader

This method may only be suitable if a single size primal cut is in production as it is unable to account for a large size variance, which is a rare occurrence. Other disadvantages may include primal cut damage from pushing of the conveyor and lack of aligning accuracy within the carton.

3. System Design

The following section details the design and functionality of all major aspects required for the successful implementation of a robotic pick and pack system.

3.1. Control System

The control system is the 'brains' behind the robotic cell that controls the operation of each individual component. The control system shall comprise of a number of different control devices, all performing a particular task, to contribute to solving the larger, complex issue. An indicative control system architecture can be seen in Figure 15 below.

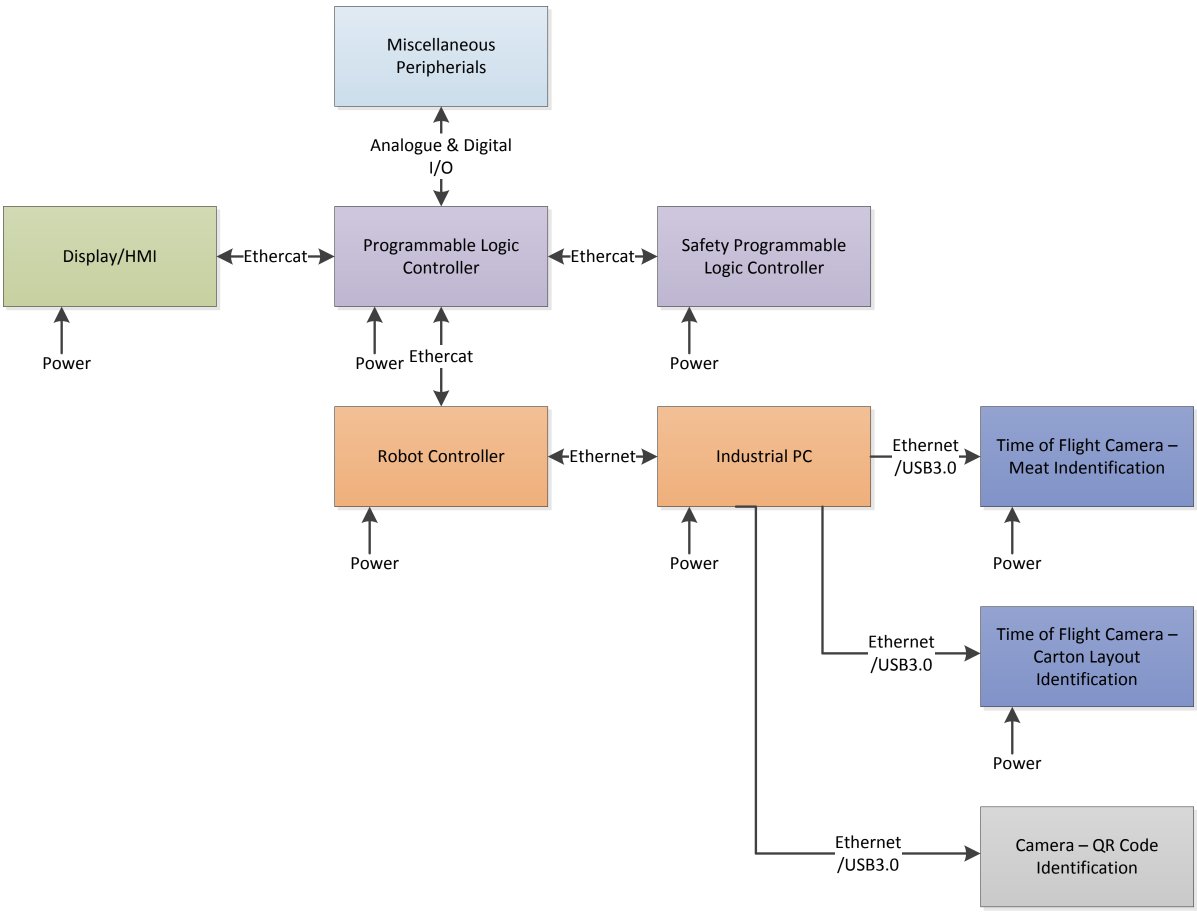


Figure 15 – Control System Hardware Diagram

3.1.1. Programmable Logic Controllers

Primary decision making will be performed via the Programmable Logic Controller (PLC). This PLC may be a software PLC embedded within the robot controller or an external standalone device. The PLC will determine the tasks to be performed by the industrial robot, dependant on feedback from the Industrial PC and the state of miscellaneous inputs and outputs. Some of the tasks the PLC will be responsible for include:

- Determining which primal cut the robot should pick up,
- Determining which carton the robot should pack into,
- Indexing and out-feeding cartons through the cell, and
- Monitoring and manipulating of inputs and outputs.

Cell safety will be monitored and controlled via a Safety Programmable Logic Controller. This controller contains safety rated inputs and outputs for the control and monitoring of safety critical componentry such as the safety interlocks and conveyors. This controller will restrict access to the robotic cell whilst the robot is operational. Furthermore, it will also inhibit the actuation of peripherals while an operator is within the cell.

3.1.2. Human-Machine Interface

A standard touch panel HMI will be employed to handle the interactions between the robot cell and the operator. The HMI will clearly depict the system state and information critical to the operation of the robot.

Some of the tasks the HMI will be responsible for:

- Start, stop, and reset the cell as required,
- Alter the current operating modes (i.e. between manual and autonomous packing),
- Manual manipulation and monitoring of all inputs and outputs,
- Input packing descriptions schedule for the shift,
- Monitor and track packing schedule, and
- Notifying the operator when a fault occurs.

3.1.3. Industrial PC

An industrial PC will be employed to perform the bulk of the image processing algorithms. The industrial PC will be responsible for the processing of raw point clouds and image data. It must also correlate each primal cut with a corresponding QR code. In the event that the QR code cannot be read, the geometric profile of the primal cut will not be calculated and no attempt will be made to pack the cut. Similarly, the Industrial PC is also responsible for the processing of images captured by the ToF camera above the cardboard cartons. Based on the current packing profile, and what cuts are yet to be packed within the carton, the software algorithms must determine the most optimal position to pack the next cut.

The industrial PC will parse the geometric profile, cut specifications, and optimal packing location to the robot controller either via either Ethernet or serial communication. Once the robot controller has completed the necessary sequence of events, it will request the information necessary to pack the next primal cut.

3.1.4. Robot Controller and Industrial Robot

The robot controller will retrieve the cut specifications and compare it to the packing list of the cartons currently being packed. If the cut exists on the packing list, the robot controller will generate two tool paths. The first tool path will guide the EOAT from its overhead position to a location where it can comfortably grasp the intended primal cut. This tool path will be based on the geometric profile of the cut generated by the Industrial PC. The second tool path will guide the EOAT to deposit the primal cut neatly within the carton. This tool path will be based on the optimal packing location provided by the Industrial PC.

The industrial robot must be resistant to the harsh cleaning chemical used within boning rooms to ensure the strict hygiene standards in place can be maintained. The industrial robot must also be capable of repeatedly and accurately manipulating loads of up to 5kg. In order to meet these requirements, the KR16-2 CR was selected. This robot has a special coating that allows it to operate in clean room environments. Its paint is resistant to harsh cleaning chemicals that make it suitable for the given environment. Although it is only rated to IP65, it is envisaged that the greater ingress protection is not required for a robot cell in a picking and packing line.

3.1.5. Communications Protocols

The system will consist of two primary fieldbus protocols. For the parsing of control and automation information, an Ethercat (Ethernet for Control Automation Technologies) topology will be used. Gigabit Ethernet (Gig-E) or USB3.0 will be used to transfer the raw camera data from the cameras to the industrial pc for processing.

3.2. Sensing System

3.2.1. QR Code Reader – HD Industrial Camera

As no commercial off-the-shelf reader was able to provide the range and viewing angle required for this task, it was decided that a HD industrial colour camera was deemed best suited for this task. A standard industrial camera features a large FoV and may readily capture high resolution images of a scene in excess of 50 fps.

The industrial camera will be interfaced directly with the Industrial PC via either Gigabit Ethernet or USB, and programmed on a case-by-case basis to complement the packaging / barcode system that is employed by the meat processor. Should the need arise, there exists the opportunity to utilise additional cameras to increase the FoV of the vision system.

3.2.2. Geometric Profiling System - Time of Flight Camera

It was decided that the Time of Flight (ToF) camera provided the solution that best met the requirements of the project, primarily because it is capable of capturing an entire scene at once. The absence of such ability is a major drawback of technologies such as Laser Measurement Systems and Stereoscopic vision. Distance computation and correction for lens distortion are both performed on-board the camera and provided in real time with each frame. This results in superior spatial capturing of objects and allows rapid and accurate detection of objects' dimensions and positions. For these reasons, the Time of Flight camera was chosen.

A ToF camera is a camera system that captures vision of a scene and creates distance data using pulses of infra-red light. A pulse of infra-red light illuminates the scene and is reflected by the objects. The camera lens gathers the reflected light and images it onto the sensor plane. Depending on the distance to objects in the scene, the incoming light experiences a delay. This delay is measured and distance data is calculated.

As the distance data is provided natively by the ToF camera, no additional computation is required to post-process the captured data to provide distance measurement. As the entire scene is captured and distance data calculated at the one time, precise real-time tracking of the primal cut is possible at the full frame rate of the selected camera.

The implementation of a ToF camera to generate a 3D display of the scene is very compact, being an all-in-one system. As the lighting is built into the camera housing, the system is not reliant on any external parts. Additionally, unlike Stereoscopic Vision, only one camera is necessary to acquire a three-dimensional scene. This minimises the footprint of the system on site, maximises reliability, and reduces the number of components and resulting maintenance burden.

3.3. Conveyor Systems

3.3.1. Carton In-feed Conveyor

The carton in-feed conveyor system will be used to autonomously in-feed empty cartons onto the packing conveyor for packing. Cartons may be erected using an automatic carton erector or manually via a human operator. Dependent on its length, the carton in-feed conveyor system will comprise of several roller conveyor sections controlled via variable speed drives. It is envisaged that the carton in-feed conveyor will run below the existing primal cut in-feed conveyor in order to conserve space.

A single carton in-feed conveyor is capable of supplying a steady stream of cartons to two robotic cells. A feed-off conveyor section will be required for the introduction of each additional set of robotic cells. The feed off section contains a segment that can lower or rise at will to align with both the carton in-feed and carton packing conveyors, and run left or right to insert a carton into the appropriate cell.

3.3.2. Carton Packing Conveyor

A carton packing conveyor system will be used to autonomously align and eject cartons being packed by the robotic cell. This shall be a simple roller conveyor and will replace the existing ledge that cartons are currently packed on. As cartons are filled and ejected, the packing conveyor will index, shifting all remaining cartons along in the process. The carton in-feed conveyor can then insert an empty carton to fill the void and the packing routine will continue.

This conveyor will accommodate a number of load cells in its chassis. As primal cuts are placed into cartons, the load cells will determine the net weight differential, allowing the PLC to monitor the mass of each carton in real time.

3.3.3. Carton Out feed Conveyor

The existing carton out-feed conveyor shall be reutilised to export cartons from the robotic cell to be strapped and labelled further down the production line. The height of this conveyor may require adjustment in order to align with the carton packing conveyor.

3.3.4. Primal Cut In-feed Conveyor

The existing primal cut in-feed conveyor may be reutilised to in-feed primal cuts to be packaged into cartons. The height of this conveyor may require adjustment in order to provide clearance for the carton in-feed conveyor.

Ideally, the primal cut in-feed conveyer will be replaced with a carousel conveyor, allowing primal cuts not picked by the robot manipulator for whatever reason to loop back through the system for re-evaluation. However due to space constraints within TFI's existing boning room, the commissioning of such a conveyor may not be practical.

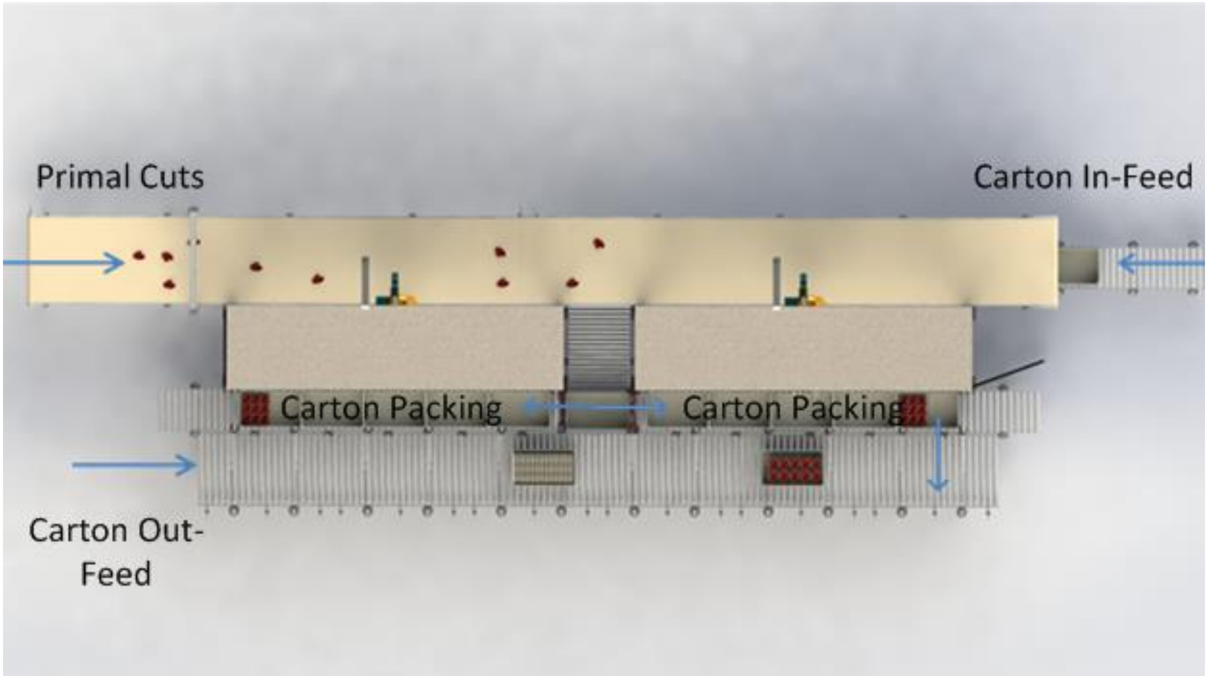


Figure 16: Carton In-feed Conveyor System

3.4. Gripping Tool

The proposed gripping tool shall utilise both vacuum and clamping mechanisms. A purpose built UniGripper vacuum pad has been selected to perform the gripping functionality for this task. This gripper allows the EOAT to deform to the contours of the primal cut whilst gripping to achieve a more refined grasp on the product. First, the UniGripper will suck on the primal cut and raise it off of the conveyor. Once at a suitable height, the clamping mechanism shall activate, securely grasping the primal cut, providing enough support for the robot to transport the cut at full speed to the desired carton.

The EOAT will be actuated solely by pneumatics. Several electronic reed switches shall be required to signify the state in which the EOAT is presently operating. This permits only extra low voltage to be run directly to the EOAT.

Figure 17 below presents an indicative illustration of the EOAT suited for larger primal cuts such as the sirloin. For smaller primal cuts, a similar gripper is envisaged, utilising a smaller vacuum pad and clamping mechanisms.

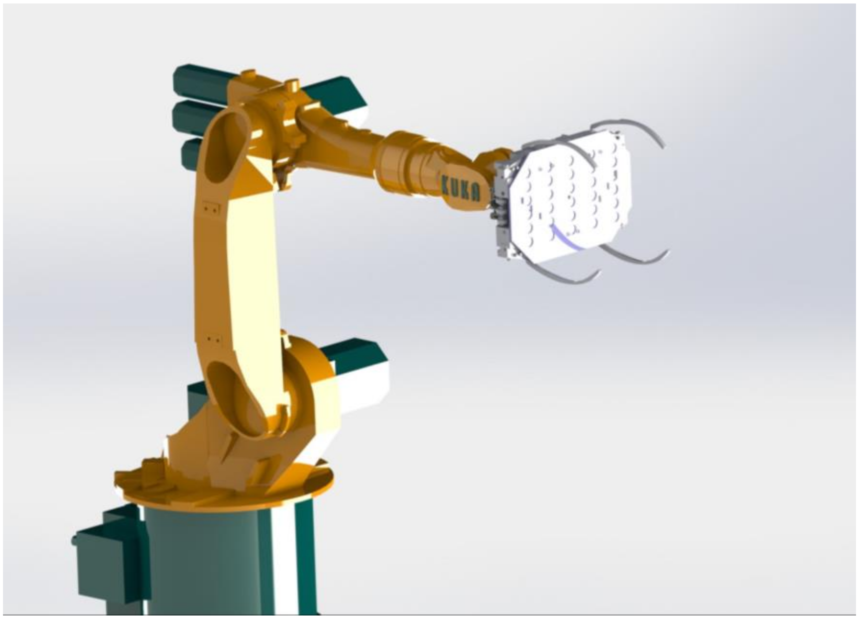


Figure 17: Concept Robotic Gripper for larger Primal Cuts

4. Case Study – Thomas Foods International

Thomas Foods International (TFI) is the subject of the case study for this report. TFI is the largest 100% family-owned meat processing company in Australia, with annual revenue well in excess of $1 billion[11]. This portion of the report will examine the requirements necessary to automate the picking and packing of vacuum sealed primal cuts within TFI's Murray Bridge plant.

4.1. Boning Room Layout

The Boning room is likely the most highly productive and dense room within a meat processing facility. The boning room encompasses deboning and slicing tables, bagging and sealing stations, and pick and pack stations. The essence of the boning room involves breaking a carcass down into many individual cuts for packaging. All such operations are performed in highly constrained spaces.

Once a carcass enters a boning room, particular cuts are removed from the carcass by the 'boners'. These cuts are placed on the slicing table and further broken down into primal cuts and trims by the 'slicers'. As the carcass reaches the end of the boning room, all meat will be removed from the carcass.

Once the meat has been separated into the specified cuts, they are either bagged into individual wrapping for vacuum sealing or collated as trims. Bagged meat are individually aligned and fed into the vacuum sealing machine for sealing. One operator is typically dedicated to bag alignment per vacuum sealing station. Upon sealing, they are conveyed to the packing station to be packed into cartons and dispatched for chilling or storage. An indicative layout to this process can be seen in Figure 18 below. It is our understanding that the structures of many boning rooms throughout Australia generally follow this layout. This provides the benefit of being able to readily retrofit a number of packing lines with minimal alterations to the host facility and cell layout.

[11] www.tandrpastoral.com.au visited 08/08/13

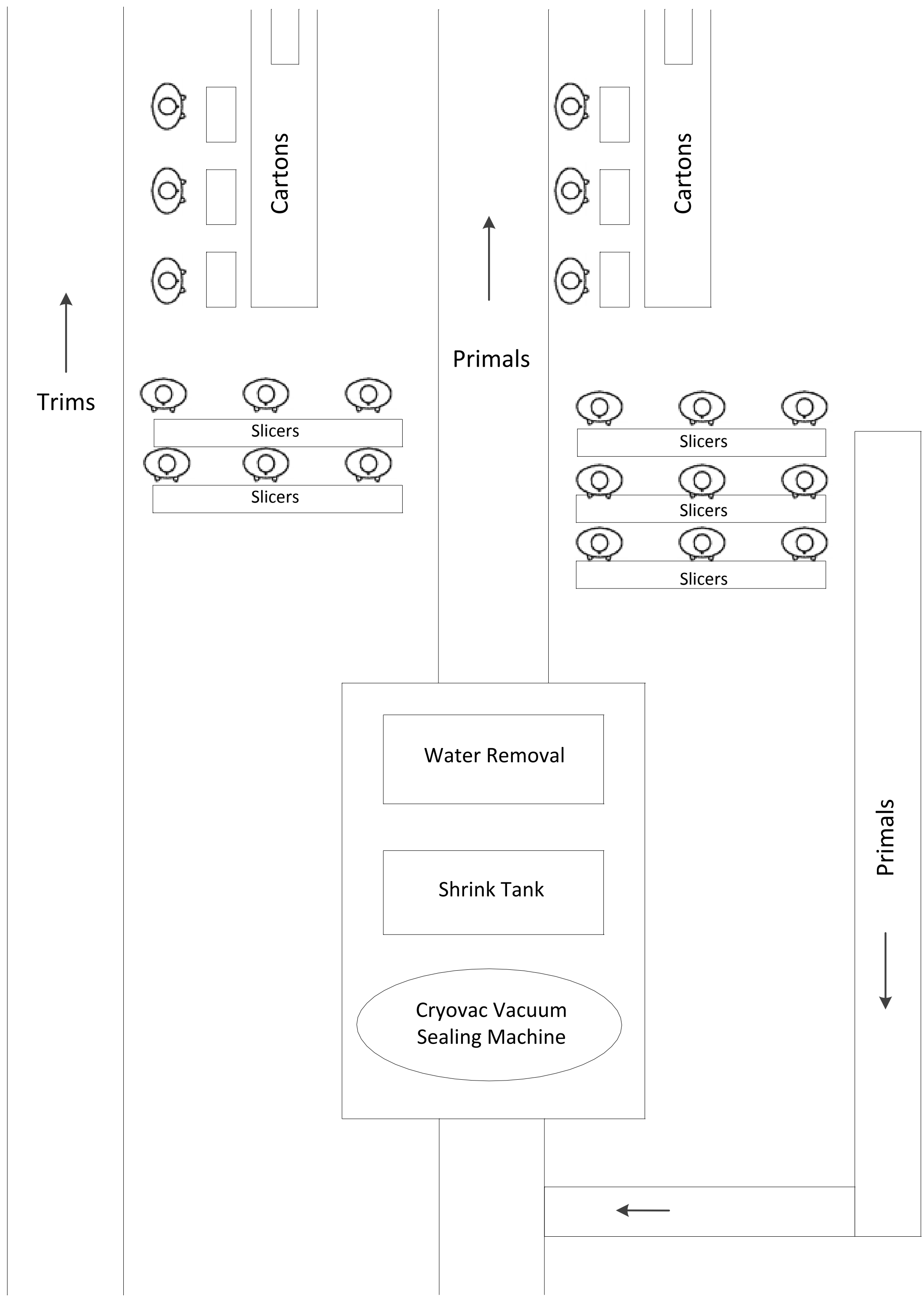


Figure 18 - TFI Boning Room Layout

4.2. Proposed Robot Solution

The proposed robot cell consists of a ceiling mounted KUKA KR16-2 CR industrial robot. Each robot cell shall be capable of packing up to 5 cartons simultaneously. The products each robot is capable of packing shall be restricted by the type of EOAT currently utilised by the robot. One or more robot cells may be commissioned side by side to work in unison, with the ability to cater for a larger variety of primal cuts. Figure 19 and 18 depicts a proposed layout for two robots operating side by side.

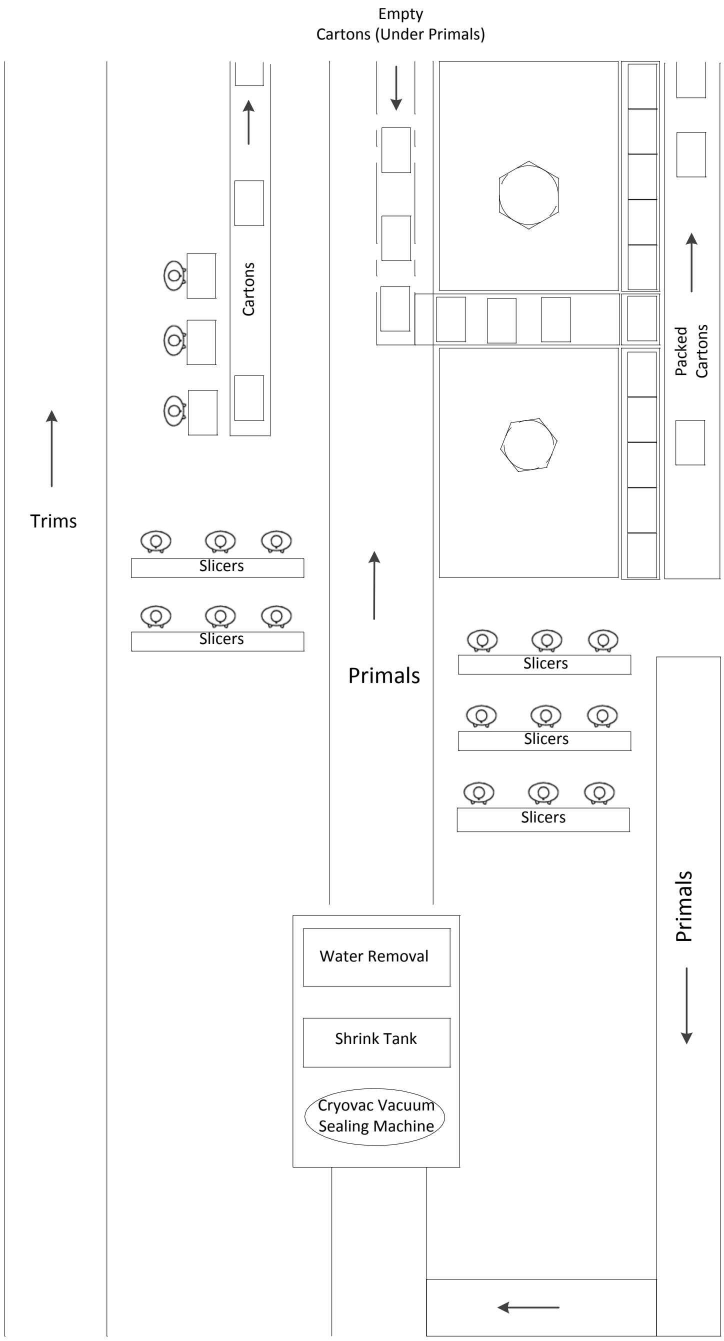


Figure 19 - Proposed Robot Cell Layout

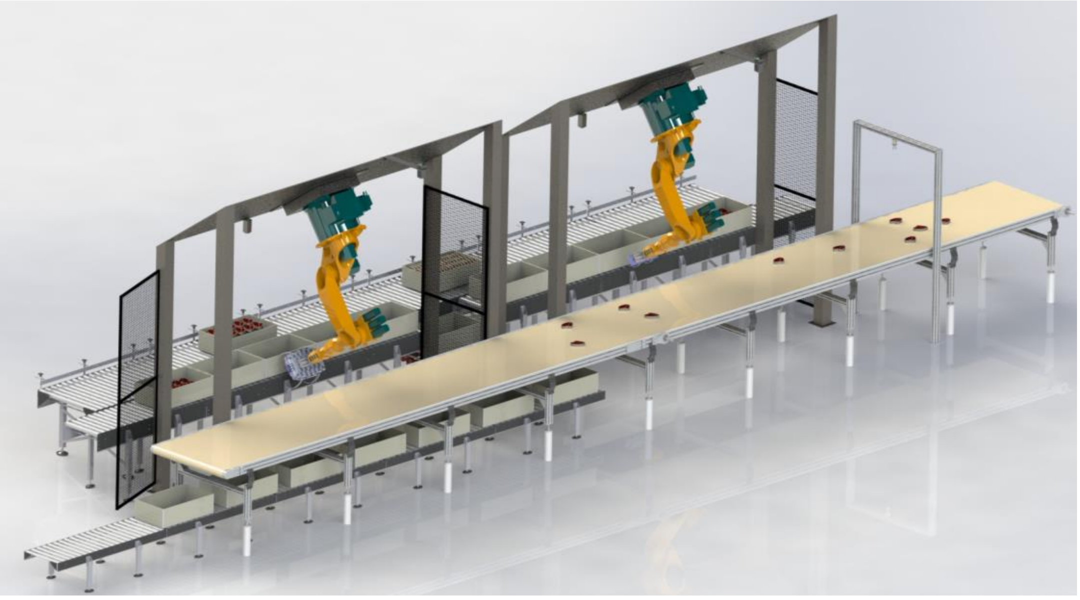


Figure 20 – Proposed Robot Cell Model

The cell was designed with the intention of causing minimal disruption to the existing packing line. The industrial robots are ceiling mounted to allow an operator to enter the cell and comfortably pack primal cuts in the event that the robot must be taken offline. Each robot is enclosed in its own guarding, providing the option for one packing station to run autonomously while the other is undergoing maintenance or manned by an operator.

Empty cartons with plastic lining inserts will be fed into the packing area via a carton in-feed conveyor as shown in Figure 21. A carton erection machine may be introduced to perform this task; however for the purpose of this study this process has remained manual. A single carton in-feed conveyor will be capable of supplying empty cartons to adjacent robot cells. This is performed by the use of a bidirectional lift conveyor located at the intersection of the carton conveyor and the packing conveyor as shown below in Figure 22.

Figure 21 – Carton In-feed Conveyor

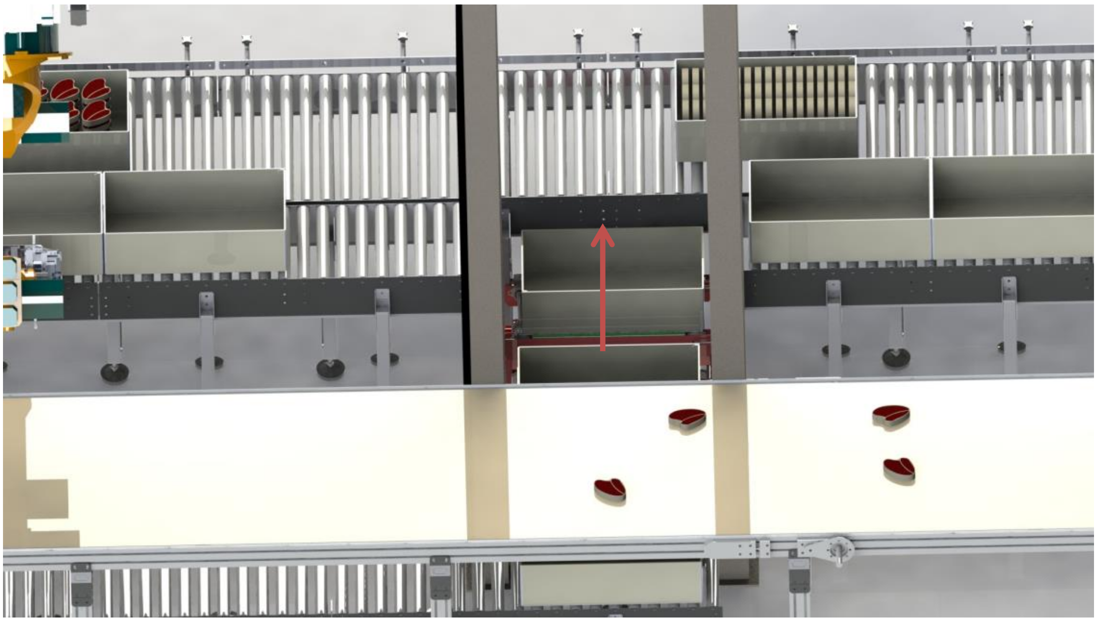


Figure 22 - Bidirectional Conveyor

The HD industrial camera will be mounted above the primal cut in-feed conveyor and be utilised to identify the particular primal cut based solely on the product's packaging or QR code (in the event that the meat is in generic packaging). Tracking will be maintained on successfully identified products as it travels down the in-feed conveyor and correlated with geometric profiles generated from the ToF cameras. The geometric profile shall also be used to estimate the weight of the primal cut. This will allow the robot cell to select the appropriate cut for packing, and pack cartons as close as possible to the specified target weight.

As the primal cut comes within range of the industrial robot with the appropriate EOAT, the industrial robot shall generate a suitable tool path and pack the primal cut in the appropriate carton. Tool paths for both the pick and place sequence will be based on geometric profile of the primal cut and destination carton of the primal cut. It is envisaged that due to limitations in the FoV of the ToF camera, multiple cameras may be required to observe all five packing locations simultaneously.

As primal cuts are packed into cartons, the robotic cell will determine the net gain in weight from the addition of the last primal cut. This will be achieved via load sensors mounted within the supports of the packing conveyor. This information will help inform the system of the average weight of the remaining primal cuts. The system shall also be able to accurately determine whether a carton is within its desired weight range.

Once a carton has been fully packed, an ejection mechanism will be energised to push the carton from the packing conveyor to the out-feed conveyor. Once the carton has been ejected, the packing conveyor will index, filling the gap created by the ejected carton. An empty carton will then be indexed into the appropriate cell via the bidirectional conveyor and packing routine shall resume. This process is shown in Figure 23.

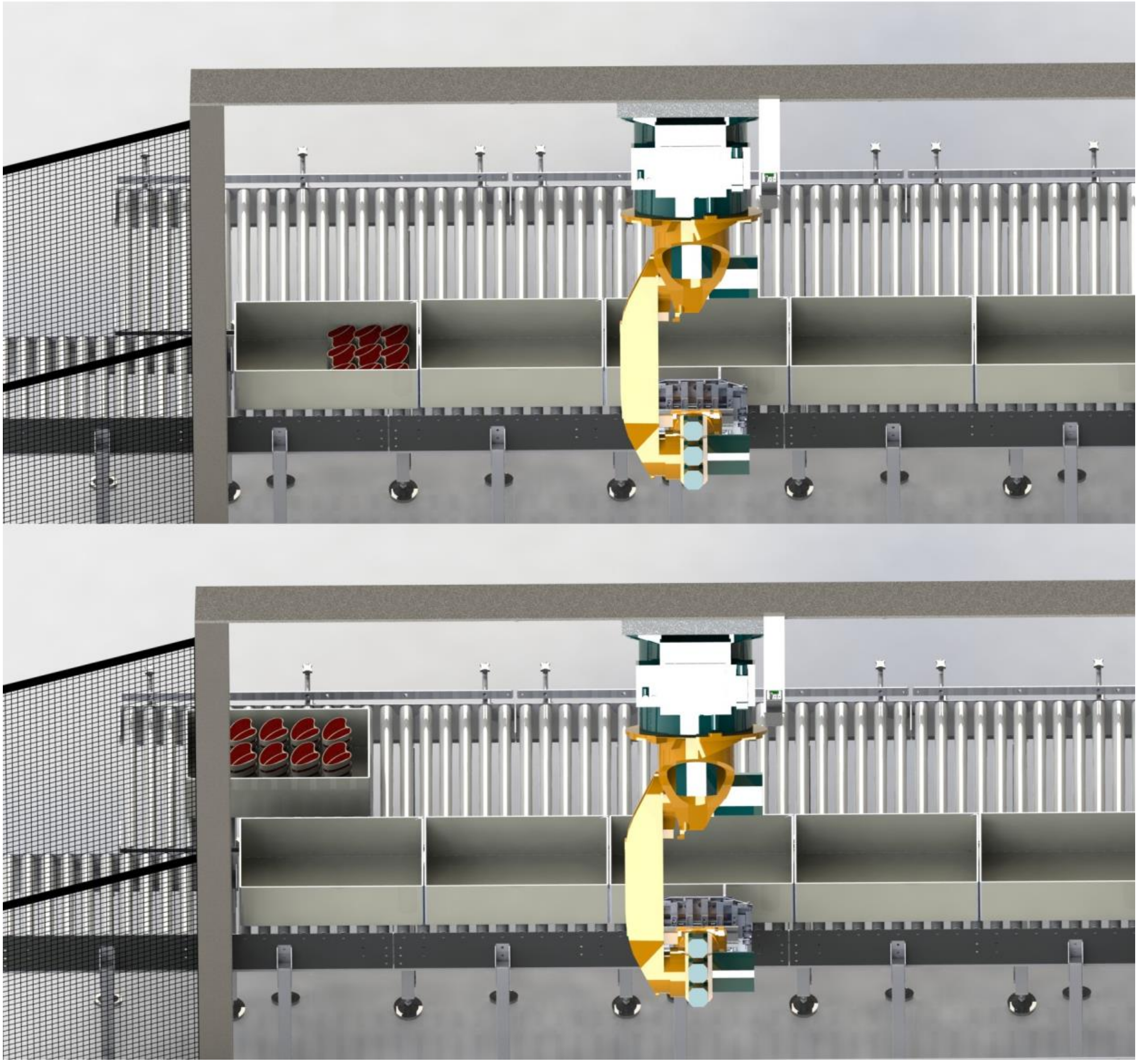


Figure 23 - Carton Ejection and Indexing

4.3. Infrastructure Alternations and Integration Considerations

Although a turnkey solution with minimal alterations to the existing boning room is most desirable, some layout redesign should be expected. It is envisaged that both TFI's facilities and the robotic cell must be designed in collaboration to accommodate the introduction of a robotic cell. TFI has limited space along the picking and packing area, and this constraint has been considered in the design of the robotic solution. In depth planning and consideration needs to be performed before infrastructure alternations take place.

The robot cell has been designed to be as space conscience as possible. Based on the indicative layout supplied in Figure 20, it is expected that the total area required for the installation of a single robotic cell will be approximately 6 m^2 including out feed conveyors. Additional space away from the packing line will also be required to house the control system and associated peripherals. It is vital to communicate with the abattoir to ensure it is possible to obtain the required floor space for system implementation.

Based on the current layout of TFI's packing station, key areas of consideration include:

- **Robot Cell** – The cell must be designed and integrated within the existing infrastructure to economically house all of the primary components that encompass the robotic system. The cell must also safely guard operators from the potential hazards within the cell.
  The robot cell must also be designed in such a way to support manual actuation of conveyors and peripherals to support the manual packing of cartons as necessary.
- **Carton In-feed Conveyor –** A carton in-feed conveyor must be introduced and integrated within the existing infrastructure to handle the autonomous insertion of cartons onto the packing conveyor.
- **Carton Packing Conveyor –** A carton packing conveyor system must be introduced and integrated with the existing infrastructure to replace the existing ledge that cartons are currently packed on. This conveyor system will facilitate the alignment and insertion of unpacked cartons and the ejection of packed cartons.
- **Carton Out-feed Conveyor** – The existing carton out-feed conveyor shall be reutilised to expel cartons from the robotic cell to be strapped and labelled further down the production

line. The height of this conveyor may require adjustment in order to align with the carton packing conveyor.

- **Primal Cut In-feed Conveyor** – The existing primal cut in-feed conveyor may be reutilised to in-feed primal cuts to be packaged into cartons. The height of this conveyor may require adjustment in order to provide clearance for the carton in-feed conveyor.

  Ideally, the primal cut in-feed conveyer will be replaced with a carousel conveyor, allowing primal cuts not picked by the robot manipulator for whatever reason to loop back through the system for re-evaluation. However due to space constraints within TFI's existing boning room, the commissioning of such a conveyor may not be practical.
- **Power Supply** – Each robot cell shall require a constant power supply of 415V @ 32A. Such power is quite common in an industrial setting and required for many other devices. An electrician may be required to provide a power outlet close to the robotic cell to fulfil this requirement.
- **Compressed Air Supply** – The EOAT shall require a constant supply of dry air rated at 6 bars. An air supply may also be required to actuate the various cylinders, grippers and stoppers utilised to manipulate cartons on various conveyors.
- **Meat Rejection** – It is envisaged that 'leakers' will be detected and reprocessed using existing practices and procedures. Reprocessing must be completed before the packaged meat reaches the robotic packing station. In the event that a leaker is fed into the robotic cell, the system will pack the product as per usual.

4.4. Current vs. Proposed Processing Practises

4.4.1. Product alterations

It is envisaged that no alterations will be required for the bulk of existing primal cut packaging. At present, TFI packages each primal cut in a uniquely identifiable packaging. This packaging will negate the requirement for a uniquely identifiable QR code and allows the HD industrial camera to determine the type of cut based on packaging alone.

There exists a small portion of plain packaged primal cuts which require identification based on size and shape alone. These cuts are designated for further processing off-site and therefore do not require unique packaging. It is envisaged that a unique QR code may be necessary to accommodate the packing of these products. Labelling will most likely occur preceding the vacuum sealing process to ensure it remains legible by the vision system.

4.4.2. Labour Requirements

It is estimated that the labour requirement of the picking and packing process will be reduced. The labour requirements for picking and packing at TFI varies daily dependant on factors including the required throughput and destination markets for the various orders. There may be in excess of 10 operators dedicated solely to picking and packing at any one time.

The implementation of a single robot solution is not expected to reduce the number of operators required significantly, as a sole gripper is unable to accommodate the entire range of primal cuts. Although the layout provided (see Figure 19 above) depicts a cell utilising two robots, it is envisaged that as confidence in the technology grows, additional robots will be integrated to increase throughput. It is our belief that four robot cells will be sufficient to cater for all variations of primal cuts at TFI.

With the introduction of four industrial robots, it is estimated that the picking and packing process can be performed with two per shift. These operators are required to perform basic tasks such as input the packing schedule for the robots on the HMI, reorient primal cuts that cannot be correctly identified by the sensing system and insert additional cartons into the carton erecting machine.

4.4.3. Training

Operator training is an essential facet for introducing new hardware in the worksite. In order to effectively utilise the system, operators must first gain familiarity with its functions and capabilities. Training will be provided in the form of both practical demonstrations and literature for operators and on-site engineers. The goal of this is to illustrate system interfaces, general operation procedures, and basic troubleshooting techniques. Training is typically supplied as a once-off activity performed over a number of days. Once an operator is competent, they may then train additional operators.

Detailed technical information will also be provided and tailored specifically to on-site engineers. This documentation will outline detailed technical specifics such as process information, mechanical, electrical and pneumatic drawings, and detailed troubleshooting procedures. This will minimise downtime in the event of system failure.

Training in respect to EOAT and robot upkeep shall also be provided. Detailed instructions regarding cleaning instructions for both the industrial robot and EOAT are essential to ensure the strict hygiene practices undertaken by TFI are adhered to and maintained.

4.4.4. OH&S

The introduction of a robotic cell will raise a number of OH&S concerns, whilst also alleviating many others. The robotic cell will be compliant with Australia’s machine safety standards (AS4024.1-2006), and therefore have many of these concerns addressed during the system design phase. This is typically done via the use of safety specific equipment such as safety guarding, interlocks on operator access gates, light curtains, safety PLC’s, and emergency stop buttons.

5. Recommendations

This study has emphasised primarily on the picking and packing of vacuum sealed beef products. This is due to vacuum packaged products account for approximately 70% of all beef produced by many meat processors, and therefore the automation of this process would reap the greatest return on investment across the industry.

Strategic Engineering believes that the implementation of an autonomous pick and pack system is feasible with existing technologies, although the development of such technologies is required for their adaptation into the red meat industry. Implementation of such a system will greatly assist to alleviate the bottleneck currently experienced by many processors within their packing station. Further development of the following areas of will greatly de-risk this project and assist in the widespread implementation of such technologies:

- The research and development of intelligent sensing algorithms for the Time of Flight and HD industrial camera – for the identification, classification, and localisation of primal cuts from a known database, as well as quality control for visually identifiable defects;
- The development of multiple End of Arm Tool’s to cater for common subsets of primal cuts;
- The development of intelligent tool path generation algorithms and the integration of the End of Arm Tool (EOAT)/intelligent sensing system; and
- The performing of in-depth factory acceptance testing and site acceptance testing workshop and plant trials.

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Appendix A – Financial Costs

Main Component Acquisitions – Single Robot System	**Cost**
Industrial Robot	$55,200
Single Robot EOAT	$20,000
Carton In-feed Conveyor	$15,000
Carton In-feed Conveyor Motor and Drives	$6,000
Carton Packing Conveyor	$10,000
Carton Packing Conveyor Motor and Drives	$6,000
Primal Cut In-feed Conveyor modifications	$3,000
Carton Out-feed Conveyor modifications	$3,000
HD Industrial Camera	$1,500
Time of Flight Camera x 3	$30,000
Touch Panel HMI	$3,000
Programmable Logic Controller	$2,000
Safety Programmable Logic Controller	$1,500
Industrial PC	$1,000
Electrical Control Cabinets	$2,000
Electronic Design and Wiring	$8,000
Miscellaneous Electrical Componentry	$10,000
Pneumatic Design and Plumbing	$6,000
Miscellaneous Pneumatic Componentry	$10,000
Miscellaneous Mechanical Componentry	$5,000
Mechanical framework – Industrial Robot	$10,000
Mechanical Framework – Cell Guarding	$10,000
Mechanical Framework – Industrial Camera	$3,500
Mechanical Framework – Time of Flight Cameras	$3,500
Robot Dressing	$3,000
Sensing Algorithm Tuning for 3D profiling	$4,500
Primal Cut Identification Algorithm Tuning	$8,900
Robotic Pick and Pack Algorithm Tuning	$6,000
HMI Programming	$6,500
Installation	$12,000
Commissioning and Integration Labour	$18,000
2 Day Course for 4 Operators	$2,000
Total:	$286,100

Direct Cost Savings - Direct Costs Saved		
Reduced # of Operators Per Shift	2	
# of Shifts Per 24 hours	2	
Operator Cost (including benefits)	$50,000	per year
Direct Labour Savings	$200,000	per year
Estimated Reduced Scrap/Rework Costs	$5,000	per year

Additional Revenue - Is the value-add process bottlenecked?		
Additional Revenue	$30,000	per year

Ergonomic Savings - Stress, Strains, Injuries		
Average cost due to stress/strains/injuries	$22,500	per year
Total Yearly Savings	***$207,500***	***per year***

Typical Single Robot System Cost	
Total System Cost	$286,100
Initial Spare Parts	$10,000
Total System Cost	***$296,100***

Return-On-Investment (ROI)	**1.1**	**Years**
Return-On-Investment (ROI)	**13.2**	**Months**
Internal Rate of Return (IRR)	**91.2%**	

System Cash-Flow					
Year	**Total Savings**	**Initial Purchase**	**Spare Parts and Wear Items**	**Maintenance /Service**	**Cash Position**
1	$207,500	-$286,100	-$10,000	-$3,500	-$92,100
2	$207,500	$0	-$5,000	-$3,500	$106,900
3	$207,500	$0	-$5,000	-$3,500	$305,900
4	$207,500	$0	-$5,000	-$3,500	$504,900
5	$207,500	$0	-$5,000	-$3,500	$703,900
6	$207,500	$0	-$5,000	-$3,500	$902,900
7	$207,500	$0	-$5,000	-$3,500	$1,101,900
8	$207,500	$0	-$5,000	-$3,500	$1,300,900
9	$207,500	$0	-$5,000	-$3,500	$1,499,900
10	$207,500	$0	-$5,000	-$3,500	$1,698,900