Final report

RoboDock – Automated Load-out Logistics – RoboDock-L (carton fed) Technical Trials

Project code:	P.PSH.2055
Prepared by:	Todd Enfield, Jonathan Cook, Kristian Guard Intelligent Robotics
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Meat and Livestock Australia Limited
PO Box 1961
NORTH SYDNEY NSW 2059

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Abstract

In the Red Meat industry, there are a large range of costs that are associated with loading containers, including:

- Damaged cartons from manual handling
- Labour
- WHS costs due to injury from repetitive tasks and proximity to heavy forklift traffic
- Rejection of products and possible loss of market access due to incorrect orders and/or damaged product

RoboDock is an automated logistics system proposed by Intelligent Robotics to automate the load-out process and address these areas of concern to unlock value to processors. This project targeted the highest technical risk components of this proposed system.

Within this project, a range of activities occurred to mitigate the major risks identified within the Automated Container Loading Process, for the RoboLoader system. The identified risks included:

1) Vehicle Navigation within a Reefer Container.
2) Wireless network robustness.
3) Vehicle driving cycle time.
4) Layer building cycle time for processor adoption.
5) Risk of carton damage during the loading process.
6) Mechanical failure of vehicle due to large stresses.

As a result of these identified risks, a range of developments and simulations were designed and actioned in order to mitigate these particular risks. This included:

1) Design and build of a prototype AGV and trialling a newly developed Container Loading Navigation algorithm.
2) High level design of the actual RoboLoader Vehicle to allow for simulation.
3) Performing simulations and motion analysis to ensure the cycle times could be made by current technologies, at forces that will not cause damage.
4) Performing simulations and analysis to reduce risk of mechanical failure.
5) Perform accuracy analysis on the Prototype AGV to ensure that the accuracies allow for collision free navigation within Reefer Containers.

At the end of the trials performed in this project, it was confirmed that the AGV was able to navigate within the required accuracies. In addition, the cycle time requirements were met, with the measured cycle time resulting in a 9% decrease in actual cycle time to the originally modelled times.

As a result, it was confirmed that the vehicle could navigate within the required bounds, at the speeds required to allow the RoboLoader-L development to continue. Based on the information received, the vehicle's performance will allow for the product to be adopted within industry.

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1. Background

1.1 Project background

This project will address the high technical-risk components of the RoboDock technology without investment by processors. This drastically reduces the risk to processors and industry investment in future development projects and will enable more accurate costing information for the cost-benefit analysis.

The project has developed from the industry drive to become more efficient with available labour and prioritise supply chain traceability and biosecurity measures. The project provides a unique opportunity to directly address the objectives related to reducing labour cost, improving efficiency, and mitigating WHS issues in an expensive portion of the supply chain. Doing so will make Australian red meat more globally competitive. The benefits of this program of works are underpinned by the Red Meat 2030 vision as Our Consumers, Customers and Community, Our Markets and Our Systems.

With respect to exports going into the US, industry has invested in developing the Meat Messaging Portal. By integrating this into the load-out logistics automation, uptake of this tool across industry can also be accelerated in a manner which is seamless for processors while also providing efficiency benefits relating to handling of export-related documentation.

Currently all exported chilled product is loaded out in 25-30kg cartons that are manually stacked in the refrigerated containers. Pallets are not used as they take up valuable shipping space and weight, would represent a significant running cost, and would possibly require fumigating for entry to the destination countries. To get an understanding of the magnitude of materials handling, each 40ft container has ~1300 cartons loaded. The major plants are loading 10-20 containers per day, so this means 13,000 – 26,000 cartons need to be manually loaded daily for such sites. The people completing this loading need to lift the 20-30kg cartons off a conveyor or pallet and place the carton anywhere from the floor as the first layer to a height of 2200mm in the top layer. This reach distance and resulting twisting movement causes significant exposure to injury. The manual nature of this task also means risk of carton damage is high, particularly as operators begin to tire.

There have been several previous attempts (~$1m) to automate the loading process but none that are commercially available due to reliability, loading speed & functionality issues. Intelligent Robotics have addressed this in the following manner. For chilled export cartons Intelligent Robotics have now a completely revised solution that uses a multi axis servo controlled high payload robotic arm for the positioning and placement of the cartons in the container. This eliminates the damage to the cartons.

The proposed engineering concept has been reviewed by management, engineering, and logistics personnel at several meat processing plants as well as several meat Industry suppliers with very positive feedback that this concept addresses the needs of the industry and is also practical to make functional. MLA have conducted a discovery sprint which partially validated the value propositions with partner companies, brand owners, research providers, and others. Concept drawings and mock trials have been completed to test the base functionality of the automated container loading system with good success.

The high technical risk components from the project have been isolated and separated out into a separate partnership project between MLA and Intelligent Robotics. This work will be pivotal in defining the design of the system and will provide valuable input into the ex-ante cost benefit analysis process within this project. It also enables the processor to be shielded from investment into the highest technical risk components of developing the technology.

2. Project objectives

2.1 Project purpose

The RoboDock projects seek to develop and integrate enabling platforms to protect high value market access for Australian Red Meat Industry processors. This program of work will also maximise impact in the areas of lifetime traceability, labour and WHS risk reduction, which are related issues to loading and managing inventory and consistency of supply.

This particular project will tackle the high technical risk areas for this technology by testing assumptions regarding: sensing requirements for automated navigation into, within, and out of reflective shipping containers of varying internal dimensions (variations between 2246mm and 2294mm internal width were found when examining the datasheets of 12 different refrigerated containers); controls and navigation algorithms required to perform this navigation; the speeds and accuracies achievable with the current electrical and mechanical machine concept; and the ability to wirelessly communicate controls and safety signals within a reflective shipping container.

The broader RoboDock suite of projects will achieve these goals by automating the logistics of load-out area for meat processors, including the marshalling, and loading of cartons into refrigerated containers. Product damage is minimised, resulting in economic benefits due to claims, as well as maintaining industry brand integrity to Australia’s export customers.

This proposal will separate the high technical risk aspects of the RoboDock-L (carton fed) system into a partnership project between Intelligent Robotics and MLA. The benefits in taking this approach are:

1. lowering of risks from potential sites – the most significant technical risks are evaluated without financial commitment by any processor; and
2. better informed data for cost-benefit analysis activities.

According to the Red Meat 2030 report, one of the six priorities outlined is “Our Systems”, under which the initiatives provided include: “Ensuring end-to-end integrity traceability and provenance”, “Enabling supply chain data integration and efficiency”, “Embracing automation and Agtech”. The RoboDock automated load-out logistics system aligns strongly with these initiatives.

Similarly, MLA’s objectives in the Strategic Plan 2025 are to help double the value of Australian red meat sales, and to become the trusted source of highest quality protein. A core component underpinning this is the drive for better data and traceability across the supply chain to drive value back to producers. Load-out logistics automation provides a key opportunity to address these objectives, specifically:

1. “Prioritis[ing] investments that allow for the seamless transfer of information through a national data platform”;
2. “Invest[ing] in the strengthening of our integrity systems”; and
3. “Extending our systems - Our industry’s current traceability systems do not extend into international markets. Being able to demonstrate our world-leading animal health, welfare and sustainability attributes through traceability and objective measurement would deliver consumer trust and help achieve greater premiums. It could also help mitigate risks which have potential to impact on market access.”

This is echoed in the MLA Annual Investment Plan for 2020-21, which lists “high-impact activities, including supply chain logistics projects in areas such as … load-out automation” as a core activity.

Eliminating claims from the incorrect product being shipped and minimising the claims from damaged goods being claimed due to incorrect loading presents a significant opportunity for processors. For one large Australian processor, the cost of incorrectly port-marked product for their US exports alone was approximately AU$65,000 in 2017 (P.PIP.0523), not factoring in other export customers or claims due to carton damage. “Cost to industry for the application of, and “missing or incorrect” port marks to the US is estimated at $14.5 million per year as reported in June 2013 by D.N Harris & Associates on the technical barriers to trade for Australian red meat prepared for MLA and AMIC.” (P.PIP.0523).

The load out area is critical to all plants as it is the interface between the processor and the client who has purchased the product. By its nature, the labour in this role completes a very challenging and heavy lifting task. As they get tired the quality of the loading can deteriorate and this can lead to mistakes in loading the incorrect cartons in the wrong container as well as increasing risk of injury.

2.2 Project objective overview

The primary outcome of this project is to automate the load-out logistics in meat processing sites and to define what value capture can be achieved along the supply chain from this innovation. Through this innovation, the aim is to create new value that can support producers, processors, red meat brand owners and importers with highly efficient loadout and traceability system.

In doing so the following objectives will be accomplished:

- Assessment of sensing required for navigation in reflective, low-clearance container environment – what sensors are required? What accuracy should be achievable?
- Application evaluation for navigation of AGV tasks based on the outcomes of the sensing trials – how should the navigation system be structured?
- What accuracies and speeds are achievable with the proposed navigation in conjunction with AGV hardware (steering and traction wheels, drives, encoders, etc).
- Trialling for wireless network connectivity within the container – is safe wireless communications within a container possible? What does this framework look like?
- Assess maximum achievable cycle times and forces induced onto cartons for layer forming process – are there any issues with the proposed concept? What is the potential for carton damage?
- Assess mechanical limitations of design operating at required speeds – are there any mechanical issues with the assumptions made on the concept design?

3. Methodology

The envisioned methodology for the project is as follows:

- Perform detailed design of the trials to be conducted within the project.
- Review the project via a Go/No Go decision point to take into consideration any learnings which may have arisen through the trial design process.
- Perform sensing trials emulating container environment to assess what will be required for autonomous navigation of the RoboLoader vehicle.
- Assess outcomes of sensing trials to design AGV theory of operations and develop design for integration of mechanical, electrical, and sensing components. Map out and prototype navigation software.
- Create a prototype vehicle with required sensing, navigation software, steer and traction wheels, encoders, motor drives.
- Perform driving trials with prototype moving into, within, and out of a container or environmental reconstruction.
- Perform trials of wireless network hardware within container environments to test performance and reliability.
- Perform high-level design and simulation work for carton handling and layer forming.
- Perform high-level design and simulation work to assess mechanical limitations of design operating at required speeds.

This methodology will allow Intelligent Robotics to tackle the key areas of technical risk for the RoboDock technology in a logical order, facilitating a “fail fast” approach to the R&D process.

3.1 Risk Identification

3.1.1 Identified Risks- Navigation

There are a range of major navigational risks that were identified during the Technical Risk assessment portion of the Pre-Engineering Design. These risks are dictated in the sections below.

3.1.1.1 Total Accuracy Required

Red meat industry processors run very tight tolerances between the overall width of the cartons versus the internal width of the reefers. This is to ensure products do not move significantly during transport, which would risk product damage. As a result, the RoboLoader has been designed to load cartons substantially across the internal width of the container, with its widest part (the placement table) spanning 2100mm in width.

Coupled with this is the fact that while refrigerated shipping containers have external dimensions as dictated by international standards, the internal dimensions vary across manufacturer due to variations in refrigeration and insulation panelling. Table 1 below shows the internal dimensions for four different models each of 20ft and 40ft refrigerated containers. While the average width is 2280-2290mm, they can be as low as 2200mm.

	Reefer								
	20ft	**20ft**	**20ft**	**20ft**	**20ft**	**40ft**	**40ft**	**40ft**	**40ft**
Internal									
Length	5449	5449	5440	5535	5340	11560	11679	11563	11690
Width	2290	2286	2290	2284	2200	2280	2286	2294	2250
Height	2244	2122	2270	2224	2250	2250	2211	2161	2247

Table 1 - Variations in refrigerated container internal dimensions for four different container models

In its transport position, the RoboLoader is approximately 5000mm long and 2150mm wide. In the smallest width container, this would give the RoboLoader 50mm clearance either side to the walls, if perfectly centred and aligned. Coping with Reflective Surfaces

3.1.1.2 Reflective Walls

A critical component of the total accuracy is the accuracy with which we can sense within the environment. When travelling down a container with reflective surfaces, at different angles of incidence laser scanners tend to get results that begin to “curve” at angles of incidence away from 90 degrees (see Fig. 1).

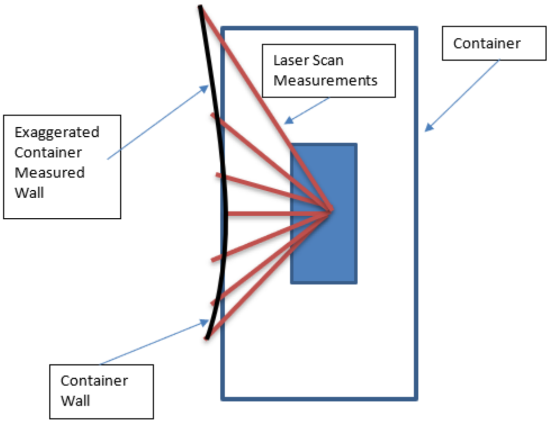


Fig. 1 - Laser scan measurement on reflective surfaces

Due to these laser scan measurements, navigation algorithms may calculate curved walls rather than the straight walls that are present within the physical container.

3.1.1.3 Driving on Ramps

Moving up and down ramps is another risk, due to the way that measurements are taken by a laser scanner. This is a risk both when entering the container, and when attempting to load while on the dock ramp. Performing this task accurately is critical for optimal alignment once inside the container.

The laser scanner measurements will have some parallax errors that are likely to cause the measurements to be further away (due to the angle on the vehicle). This could reduce the consistency of stopping positions on the ramp, and lateral positioning while navigating inside a container doorway. Fig. 2 below illustrates this possibility.

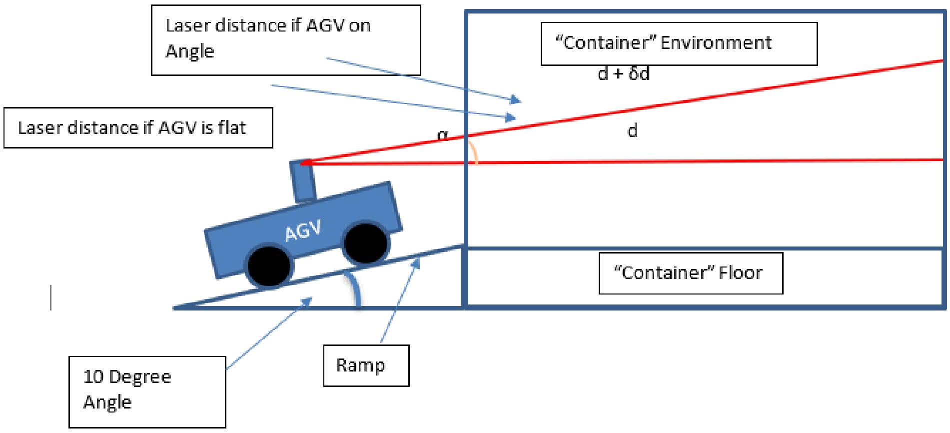


Fig. 2 - Parallax errors on laser scan measurements

Based on the risks of navigations on ramps described, tests also need to be performed on stopping on the ramp. A range of tests were performed, validating the accuracy and reliability of the positioning of the AGV on a ramp, using a container.

How the navigation system corrects for any such geometrical errors, as well as the quality of data provided by the sensing is crucial for ensuring accuracy during this stage of the driving cycle.

Fig. 3 - Reefer Container Internals

The accuracy with which the prescribed sensing can determine the position of the walls to the vehicle is therefore of key importance, as well as how the navigation system corrects for any abnormalities in data.

3.1.2 Identified Risks - Communications

An unassuming but quite critical risk to the RoboLoader lies with the communications hardware used. To facilitate its ability to move between different docks, the RoboLoader will rely on wireless communications to the PLC in the dock area. This will be used to relay control signals, as well as

CCTV footage between the dock PLC and HMI, and the RoboLoader. Most critically however, it will also be used to communicate safety information between the dock and the RoboLoader.

To ensure the integrity of the wireless connection for the safety signalling, bi-directional heartbeats will be utilised between the RoboLoader and the dock. If the connection drops out, then the cell and RoboLoader will be safety stopped. The quality of this connection is therefore critical to the reliable operation of the RoboLoader. Constant safety stoppages would be deemed a critical flaw in the system and severely limit market uptake of the technology.

The main challenge to ensuring high-quality, continuous wireless connection is the environment of the container itself. Due to the reflective walls, the container effectively acts as a “mirror box” to the wireless signals. To ensure success of the project, it is therefore critical that the correct hardware be selected and set up properly to ensure it can function reliably in this environment.

3.1.3 Identified Risks - Electromechanical

To ensure uptake by the Australian red meat industry, the machine must be able to operate within cycle times of current loading rates.

All the electrical and mechanical components within the cycle must individually meet cycle time restrictions and be sized appropriately to ensure robustness. Further, the interplay of these components must be assessed along a common timeline to understand the true process cycle time, as well as gain an accurate image of how cartons are progressed through the system.

3.1.3.1 Motion component selection unable to make cycle time

Due to the extremely limited space available in the machine, it is imperative that the motion hardware selected for the system is capable of making the required cycle times. If a piece of hardware is undersized, it will be extremely difficult and costing to change once the machine has been fully designed and built.

Furthermore, safety factors must be incorporated to cope with unknowns regarding how the machine will operate as a whole, in real-world conditions. These safety factors cannot be too generous however given the aforementioned space limitations.

If the machine is not able to meet the required cycle times due to incorrect motion equipment selection and sizing, this will severely limit its marketability as a product to the Australian red meat industry.

3.1.3.2 Mechanical failures of RoboLoader

In a similar vein, a number of key mechanical items are put through significant stresses and strains throughout the cycle. Due to space and weight limitations, it is not possible to simply ‘overkill’ the design in all the components, and the static and dynamic forces placed upon critical components must be understood in detail first to be able to apply the required safety factors to ensure the machine is capable of meeting cycle time restrictions whilst also being robust and reliable.

Similarly, to change the design of mechanical members once the manufacture of the machine has been completed would be an extremely time- and cost-intensive exercise given the space and weight limitations of the machine, as well as the interplay between a large number of components.

3.1.3.3 Inducing carton damage

One of the key value drivers in the RoboLoader technology is the reduction in carton damage. This must be weighed up with the requirement to achieve fast cycle times. During design, the likelihood of inducing carton damage during cycle, particularly of high-speed movements, must be assessed to ensure the RoboLoader is truly fit-for-purpose.

If the RoboLoader is not able to load containers automatically without inducing carton damage, this would be a critical impediment to commercial uptake of the machine.

3.2 Detailed Design for Trials

Once the primary risks were identified in the range of areas- the detailed design of each trial had to be determined. This allowed the understanding of whether the project was to go ahead, allowing a Go/No Go decision point based on the applicability of the trials required.

The detailed design of each trial is shown below.

3.2.1 Navigation Risk Mitigation Activities

Having confirmed the direction for the sensing and navigation algorithms, this milestone will bring these components together with the wheels and tyres to perform extensive trialling to assess how accurately the RoboLoader will be able to drive at what speeds, and how this fits into the industry's needs.

Trial: Perform driving trials with test vehicle into, within, and out of a refrigerated container.

Objective: Identify accuracy with which the RoboLoader vehicle can be driven, and at what speeds.

Methodology:

Scenario tests will include, but not necessarily limited to:

- *Navigation into Container Trials* - Navigate into a pre-defined container environment. Navigate the vehicle in auto through the container doors to level.
- *Navigation within Container Trials* - Drive the vehicle in the container and perform the "move back" sequence of RoboLoader L.
- *External Scan of Container Trials* - Use the vehicle to scan the container from the entry, find the container location and enter the container.
- *Navigation on Dock Trials* - Do a scan of an environment of the vehicle and measure accuracy and repeatability of position when pulling up to stations.
- *Stopping on Ramp Trials* - Drive the vehicle to a defined position on the dock ramp. This includes in the direction travelling up the ramp, and down the ramp. Measure the accuracy of the stop location.
- *Testing of adjustment inside container* - Put AGV in location inside container. Move AGV required location and see how it moves/adjusts laterally.

3.2.2 Communication Risk Mitigation Activities

Trial: Performance and reliability trialling of wireless network hardware.

Objective: Select required hardware and optimal setup to ensure reliable performance.

Methodology:

- Procure wireless network hardware
- Setup hardware and organise access for a refrigerated container
- Perform a number of trials with various locations of Wi-Fi transceivers external to and within the containers, with varying setup parameters to identify the most optimal
    - Perform bandwidth and dropped packet testing to monitor performance

Repeat with alternative suppliers if necessary

3.2.3 Electromechanical Risk Mitigation Activities

Cycle Time Analysis

Task: Construct a detailed cycle time analysis of the entire process.

Objective: Understand the requirements of each aspect of the electrical and mechanical motion hardware, as well as the forces induced onto cartons during the cycle.

Methodology:

- Map out process in detail (note, this may be split across multiple levels for different sub-systems as well the complete process as a whole)
- Analyse and optimise timings for each operation
- Analyse and calculate forces induced into cartons through the cycle. Identify and incorporate additional measures to reduce risk to carton damage where needed

Forces Induced on Cartons

Task: Assess forces induced onto cartons based on detailed cycle time analysis and adjust as needed.

Objective: Select and size motion hardware to meet cycle time and reliability targets.

Methodology:

- Calculate forces, etc induced into the carton for the different steps based on results of cycle time analysis.
- Adjust timings as necessary.
- Identify and incorporate any other design or control measures, as necessary.

Motor, Gearbox and Hydraulic Sizing Selection

Task: Size and select motors, gearboxes, and hydraulics based on detailed cycle time analysis.

Objective: Select and size motion hardware to meet cycle time and reliability targets.

Methodology:

- Calculate forces, torques, speeds, etc for the different motion components as required based on results of cycle time analysis.

- Apply appropriate safety factors and select hardware and appropriately incorporate into mechanical design of the machine.

Mechanical Stress Analysis

Task: Perform detailed stress analyses on critical mechanical components.

Objective: Identify and address areas of concern early in design to ensure robust and reliable machine.

Methodology:

- Complete 3D modelling of all machine components.
- Perform FEAs to model different the loading situations to be encountered.
- Perform modifications to mechanical design as required and validate by re-performing FEA.

3.3 Initial Vehicle Design

3.3.1 Electrical Design

The electrical design was also carried out during this milestone, to put together the power distribution and controls of the already chosen navigation components. Power distribution and control of the drives, Navigation PC, navigation sensors and wheels were designed for the trial frame during this phase.

3.3.2 Mechanical Design

The frame of the trial vehicle was designed, and FEA analysis was completed to ensure that the vehicle could handle the forces on it without breaking.

The positioning of the wheels relative to each other was kept consistent with how they would be mounted on the final RoboLoader machine. The mounting points for the wheels were designed to allow actual wheels which are to be used with the final RoboLoader to be mounted. The electrical components will be mounted onto the plate above.

The frame of the trial vehicle was designed with sufficient strength to enable to test it at various speeds and under varying loads (e.g., on ramps)and designed to withstand up to 50% of RoboLoader's total weight.

3.4 Performance of Navigation Pre-Engineering

The key risks identified within Milestone 1 were related to the accuracy with which the vehicle is required to navigate within the container. This is due to the required width of the RoboLoader-L, given the low clearance to the container walls. As the main conduit of navigation information, it is imperative for risk mitigation that the proposed sensor is trialled for its accuracy within such environments.

3.4.1 Preliminary Sensing Trials

The preliminary sensor trials were performed at a Third-Party Logistics provider within Sydney, where both a 20ft container and a 20ft refrigerated truck trailer were made available for sensor testing. While the focus of the project is on refrigerated container loading, the trailer data allowed a good baseline to compare against regarding the effect of the reflective nature of the internal walls of the container. It also gives insight into the performance difference for future RoboDock systems where trailer loading may be considered.

Least square fitting methods were used to set walls from an individual scan in order to get an estimate of how accurate the raw data of the container sizing is, by comparisons of wall measurements in reality to the calculated results.

A range of trials were performed to determine if the vehicle development could be carried on to the next stage.

From the trials performed there was enough data and data that was accurate enough (based on side wall perpendicular measurements) to allow navigation within this environment with bespoke programming.

The next stage was carried out, with a small AGV navigating inside a reefer container.

3.4.2 Further Trials on Small AGV

Following the initial sensing trials, IR consulted heavily with their navigation partner, who then analysed the data themselves. The conclusion was that, while the results for the container were not as accurate as the trailer, this was to be expected given the reflective environment. Furthermore, the data from close to, and within, the container itself was very good.

However, it was still deemed wise to perform an additional trial on the sensing. These trials would be held near the navigation partner’s facility and using a modified version of a test AGV.

A container at a test facility was rented to be able to perform the trials, which would involve driving the test AGV up a ramp and into the container, to confirm the suitability of the laser and what programming would be required to accurately track the centreline of the container.

A ramp was prepared out of wood and it was made sure that the ramp was strong enough to support demo Omni AGV’s weight of about 12 kg. A scanner was installed on the test AGV, and its programming modified to allow logging of all relevant data, including raw scanner data, throughout each trial.

In light of the outcomes of the performed tests, it can be deduced that the selected laser will suffice the needs for determining the centre line between the reefer side walls.

3.5 Initial Wireless Trials

For the RoboLoader system, the wireless network performance is going to be imperative for the overall performance of the system. Due to the use of the wireless network as part of the safety system, a slow and unstable wireless network will result in a decrease in uptime due to nuisance tripping in the safety circuit. Such performance impacts would greatly reduce the commercial viability for RoboDock as a product. As a result, it is important to perform trials on the network and wireless hardware to de-risk the nuisance tripping that would cause a decline of the system's throughput.

There are a range of network performance metrics that can allow the analysis of the network performance. These are:

1) Network Latency

The network latency is the difference in time between the sent and received packets on the network. Sources of Network Latency include the physical distance between the WIFI hardware, delays which may have been caused by hardware and software processing time, and lost packets. A perfect system will have near zero latency, and this speed is integral to the safety chain and the stopping distance of the RoboLoader. To ensure nuisance tripping is minimal, and the stopping time of the hardware within the safety cell is as small as possible, the network latency needs to be minimal.

2) Packet Loss

Packet loss refers to the number of packets sent from one point in a network, and not received in another. This packet loss means that the sent data was lost and needs to be sent again which in turn increases the network latency. This means setting up a test to count the sent and received packets from two points in the network.

3) Bandwidth and Throughput

Bandwidth refers to the amount of data that is able to be transmitted from one point to another in a network, within a given time. Throughput is the realised actual data transmitted in the allotted time. If the throughput is significantly lower than the bandwidth, it means that the network is performing poorly, and could negatively impact the RoboLoader system.

A test was required to determine the three WIFI performance factors within the Wireless system. As a result, a network was set up to allow for the testing of these performance metrics. Running the software iPerf3 on the PC allowed the determination of these key metrics in a range of different setups.

Initially it was anticipated the trials would be performed in a shipping container. Through conversations with the supplier, and based on the principles of the technology, it was agreed that a more stressful simulation would be something provided on a smaller scale due to the more intense interference which would be encountered. Assuming the modified trials were not over the top in inhibiting the performance, it was decided that this would be a sensible way to progress. By trialling a "worst-case scenario" there would be more confidence that the hardware would stand up to the variations experienced in differing shipping containers.

Throughout the trialling of the performance of the WIFI network, it is evident that there is a minimal change in network performance due to the reflective environment. There was a small decrease of bandwidth of most configurations of the receiver within the reflective environment, but not enough to cause significant impact within the RoboLoader system. This is likely due to the MIMO technology used in these WIFI receivers.

The average results of the measured bandwidth, latencies, and lost packets for the box with and without foil can be seen below in Table *2*.

Table 2- Network Testing Results Averages

Setup	TCP Bandwidth	UDP Bandwidth	Lost Packets	Latency Max (ms)	Latency Min (ms)	Latency Average (ms)
No Foil	21.2	1.06	0	8	4	5
Foil	21.32	1.06	0	11.2	3.8	4.6
Percentage Change	+0.5%	0%	0%	+140%	-5.3%	-8%

There were extremely small changes in the network performance parameters between the reflective, and non-reflective environment, as can be seen above in **Table 2.** The only larger increase was in the max latency, which was negligible - a small increase of only 3.2 ms in absolute terms.

As a result, it was determined that this WIFI network was applicable to be used for further trials of the RoboLoader prototype.

3.6 Cycle Time Analysis

To increase adoption of the RoboLoader system across the Red Meat Industry, the system must be able to complete the container loading sequence within a time that allows it to be commercially viable. As a result, cycle time analysis was undertaken to mitigate the risk of building a machine that would not perform to the standards of the industry.

The goals of the cycle time analysis within this part of the project, is to assist in providing a motion specification for sizing of any motors, and to make sure that our machine can operate at the speeds required. Industrial expertise was leveraged to choose the correct speeds for the motors so that cartons would not bounce around on conveyors and be pushed too far.

An excel spreadsheet was developed with timings to determine the time of the whole system per carton. Timing spreadsheets were developed with the start and stop time of each function of the machine so that the full cycle of a whole container could be modelled.

Initially, the timings for the creation of a layer of cartons was modelled. Where certain processes within a cycle, or between other cycles, are overlapping, this is also accounted for to enable an accurate demonstration of the total cycle time, as well as demonstrating which items are occurring in parallel.

Actuator parameters such as acceleration and decelerations, speeds, distances, etc have been modelled at the top to enable times of operations to be adjusted through various mechanisms such as changing the speeds of operations, the distances involved in an actuation, etc. By linking the times of each operation mathematically to these parameters, the ultimate impact of each adjustment was able to be understand in the context of the full cycle. For instance, it made no sense increasing the speed of some operations which were not a limiting factor in the cycle time (i.e., the cycle time was limited by a parallel operation) – speeding these operations up made no benefit meaning that given actuator is much better off being run at a slower speed for reliability, or potentially reduced in size.

The mechanical contractors working on the system design were engaged to perform the calculations and worked closely with IR when modelling changes in timings of operations, to ensure an accurate result reflective of the way in which the machine had been designed.

Through the development of these timing models, there were two primary achievements. Firstly, IR de-risked adoption shortcomings by confirming that the cycle times we are required to be met can be by the current design.

3.7 Mechanical Simulations for Carton Handling and RoboLoader Mechanical Design

The next component of the RoboLoader that had to have its risk mitigated was the electro-mechanical components and the physical mechanical design of the frame and the various mechanical components.

3.7.1 Carton Handling Simulations

Based on the cycle time analysis, motion studies and analysis had to be carried out. Once the time required for each linear axis movement had been determined, correct hardware had to be determined and simulated to confirm the movement times could be achieved.

Working with our motor supplier, the motion specifications built through the cycle time analysis were used as a basis to determine the physical properties of the drive units. Each axis was placed through simulation software to determine the forces, timings, and jerk of each axis to ensure they met specifications.

For each of the following axes, the start and end velocity combined with the time required to move a specified distance, and the forces required based on the load being pushed, allowed for a large range of calculations. These calculations allow the selection of a suitable motor and gearbox. If there was not a motor and gearbox combination that allowed the required motion profile, then a redesign would have to occur to reach the required cycle time.

For each axis, the motion profile was split up into a range of different times, such as accelerations, constant speeds, decelerations, and dwell times. For each required acceleration time, the various forces were calculated, including the sharp braking time required for an Estop. These resulted in the minimum and maximum values of the motor and gearbox which allowed their selection.

In addition, it is important to include the modelling of torque when the cartons are contacted by the various axes. Acceleration and deceleration curves are used to ensure that the cartons are not jerked too hard on contact with pushers. In addition to this, the ability to control the torque of the motors allows for cartons to not be crushed and damaged during the loading process.

As with the previous work, the mechanical contractors working on the system design were engaged to perform the calculations required and work closely with IR and the servo provider to ensure the modelling and equipment selections continued to align with the design intent of the vehicle, the loadings provided were accurate, and that no mechanical detail had been missed.

Intelligent Robotics worked closely with the motion solution supplier in producing and optimising these models and aligning them with the most appropriate gearbox, motor, and drive combinations given the specific cycle limitations set out in the cycle time analysis.

Based on the simulations performed, motor and gear units were selected based on the motion specifications. This indicates that hardware exists to perform the required motions to hit the RoboLoader's cycle time requirements. With the electromechanical and cycle time simulations complete, the carton formation has been significantly de-risked to the point where building the carton handling system is the next step.

3.7.2 Mechanical Simulations

Due to the unique nature of the vehicle design, it is imperative that stress analysis is performed to ensure that the vehicle can handle the stresses associated with the actions to be performed.

IR need to design the system so that each component can take the maximum force that can be exerted onto it, as well as to test the strength when the components hit the roof and the floor of the container with the full force.

During the design phase of the machine, loading calculations were performed using first principles. The 3D CAD models of the machine were loaded into software and the forces were applied under multiple conditions. A Finite Element Analysis was then performed for each scenario to assess the stress concentrations, and displacement, experienced by each component under load.

The mechanical design contractors used for the machine design for engaged to perform this simulation work, working closely with IR to oversee the results and direct the process-driven aspects of any decisions made from the outcomes of the analysis.

In all scenarios tested, the stresses were deemed to be well below the yield stress of each component. This was achieved while maintaining an acceptable weight, however more optimisation in design is reviewed to further minimise weight of the vehicle. Similarly, the displacements experienced are well within the design parameters for the machine. The fundamental design of these machine components are fit-for-purpose though. The next phase will be to do more work to optimise the weight while maintaining a good safety factor.

3.8 Prototype AGV Built

For the testing of the navigation algorithms, the AGV prototype had to first be built. This prototype design was based on the developments of the prototype over the last few milestones. As a result, the first part of this milestone involved the physical building of the vehicle such that it could be tested.

The build occurred in a few stages, based off lead times of components and time required to commission certain parts of the vehicle. The Control panel was the first part to be built, due to the time required to commission the communications and the various parts of the control system. This way, the panel could be commissioned in parallel with the building of the vehicle frame.

The vehicle was successfully built, and all components were wired up.

During this phase, the various components of the control system, and the required software was commissioned and written. These included:

1) Vehicle Navigation IPC
2) Vehicle communications networks
3) Each wheel steer and traction drive
4) Sensors for information logging
5) PLC Code for network communication control and sensor information collation
6) Software for communications with the Vehicle Navigation IPC
7) Logging software for vehicle navigation analysis

This allowed for the next stage of calibration of the vehicle.

3.9 Prototype AGV Calibration

After the vehicle build and commissioning of the various components, the next important part is the vehicle calibration. This consists of the calibration of the encoders (steer and traction), the laser scanner position, PID parameters and a range of other parameters. This part of the process is integral as any errors introduced into the system will decrease accuracy when it comes to the container navigation algorithms. As a result, time was taken to assure that the vehicle was calibrated within the required bounds to allow for the best opportunity for the algorithms to work correctly.

Once calibrated, it is important to perform repeatability testing to ensure that the vehicle repeatably arrives to the same position, therefore indicating reliability and accuracy.

Two positions were chosen within the given environment to test the repeatability of the Vehicle arriving at the same location, from a range of different locations.

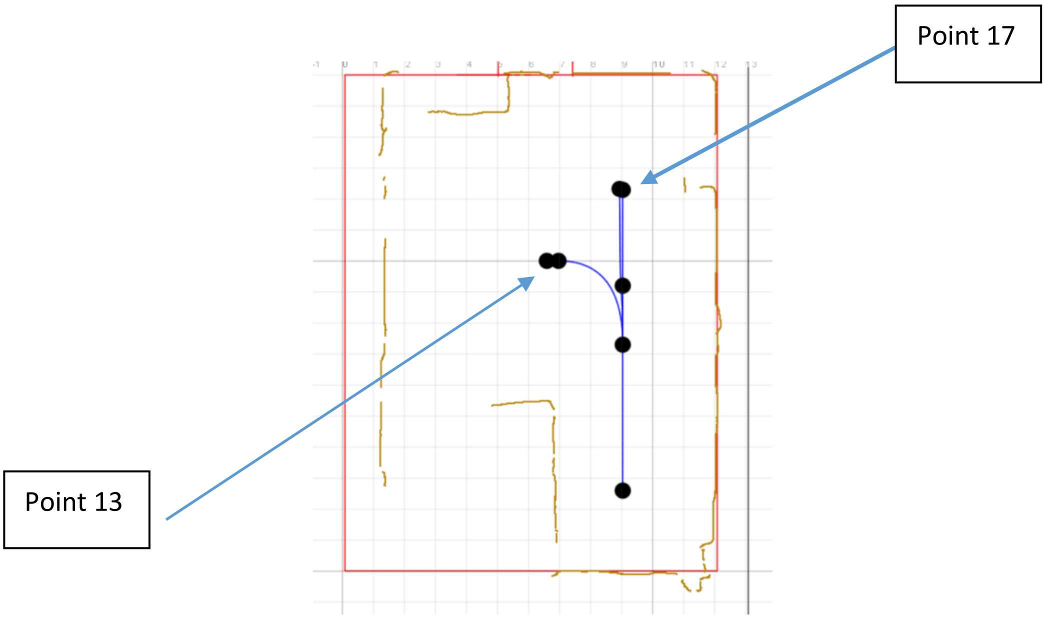


Fig. 4- Chosen Repeatability Locations

The AGV was directed to these points from a range of different locations to ensure that the AGV was not just following the same path each time. A self-levelling laser was used as a reference point.

Once arriving to a location, the cross was used as the marking point on a piece of paper to measure the spread of different results. The test was carried out on both locations 10 times which proved the accuracy and reliability of the vehicle and its calibration.

3.10 Prototype AGV Navigation Algorithm Development

With the vehicle built, commissioned, and calibrated, the next important step was the testing of the container navigation algorithm to determine if the vehicle can stay within the required accuracy limits within the container. This process was an iterative process, testing the algorithms and updating parameters and code when required to improve the performance of the navigation.

3.10.1 Initial Setup

The first step was to create the environment in which the vehicle was to navigate in. As a result, hoarding was used to create artificial walls around the vehicle, and a reefer container was delivered and placed in a location to complete the environment.

Fig. 5- Initial Environment Setup

Once completed, a navigation map was created using the same method used previously within the calibration process.

Trial 1: Initial Algorithm and Parameters

The first day of testing involved trialling the initial algorithm with small tweaks to parameters to attempt to get the vehicle to navigate down the centre line of the container. The navigation in this circumstance allowed the vehicle to enter the container, get over the lip of the ramp, but then attempt to turn into the right wall.

This result required some minor changes to the parameters within the algorithms. These changes were made prior to trial 2.

Trial 2: Initial Algorithm and New Parameters

After small changes to parameters and the underlying code, a new trial was performed. The vehicle managed to drive further into the container, without hitting any of the container walls.

This same trial was performed again, but with different results. In the second test, the vehicle turned into the wall.

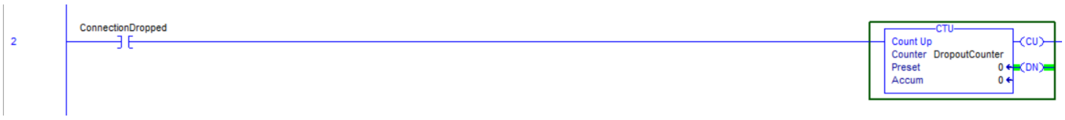
This driving of the vehicle into the wall was due to large correction amounts in the vehicle position. These large correction amounts are largely due to a bug introduced into the code. The map is constantly changing position based on the vehicle detecting that it is now in a new position. This causes large fluctuations in the calculated path, causing issues like attempting to turn into walls. This bug had to be fixed prior to continuing the container loading navigation process.

Trial 3: Full Container Loading Sequence

After changes to the code, the bug was eliminated, and more commissioning allowed for the full cycle to be completed. During trial 3, the test was performed to confirm that the container could be traversed into, and out of.

Through Trial 3, it was confirmed that the AGV could reliably scan, and navigate inside a reefer container reliably and accurately enough for use in a loading dock. The approach position was changed in multiple trials to ensure that the vehicle was able to cope with a range of different container positions.

In addition, the dropout counter written into the code was utilised and analysed to ensure the reliability of the wireless network. Throughout the whole process the dropout counter stayed at 0- confirming the reliability of the chosen hardware within the reflective environment.



Counter DropoutCounter
Preset 0
Accum 0

Fig. 6- Trial 3 Dropout Counter

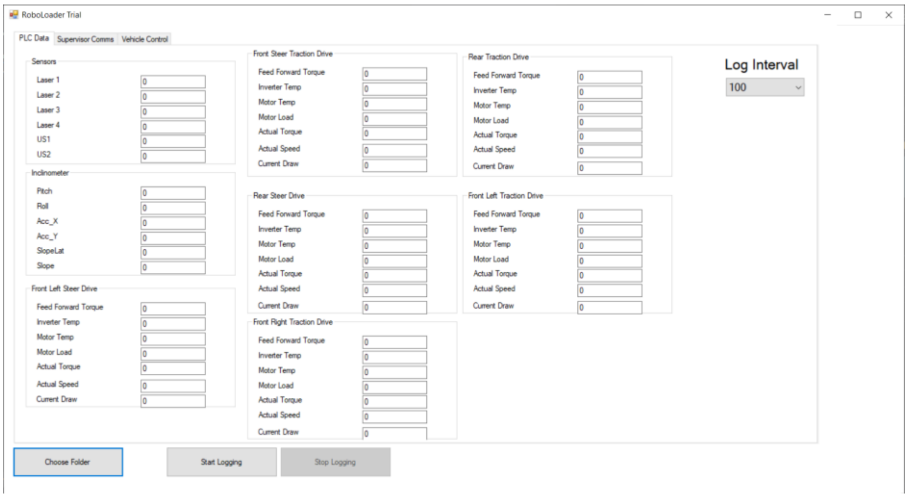
Based on the results within this trial, the accuracy data was taken next to analyse the accuracy and repeatability of the system.

3.11 AGV Accuracy and Container Loading Trials

The assessment of the navigational accuracy within a reefer container was the primary risk-mitigation activity of this project. If the AGV is not able to enter the container accurately, attempting to build layers of cartons becomes a fruitless activity.

As a result of finishing of the commissioning of the navigation algorithm, data was taken and processed to determine the vehicle accuracy.

Using the Vehicle Logger code, the logger is started and the vehicle is sent into the container.



Sensors
Laser 1: 0
Laser 2: 0
Laser 3: 0
Laser 4: 0
US1: 0
US2: 0

Inclinometer
Pitch: 0
Roll: 0
Acc_X: 0
Acc_Y: 0
SlopeLat: 0
Slope: 0

Front Left Steer Drive
Feed Forward Torque: 0
Inverter Temp: 0
Motor Temp: 0
Motor Load: 0
Actual Torque: 0
Actual Speed: 0
Current Draw: 0

Front Steer Traction Drive
Feed Forward Torque: 0
Inverter Temp: 0
Motor Temp: 0
Motor Load: 0
Actual Torque: 0
Actual Speed: 0
Current Draw: 0

Rear Steer Drive
Feed Forward Torque: 0
Inverter Temp: 0
Motor Temp: 0
Motor Load: 0
Actual Torque: 0
Actual Speed: 0
Current Draw: 0

Front Right Traction Drive
Feed Forward Torque: 0
Inverter Temp: 0
Motor Temp: 0
Motor Load: 0
Actual Torque: 0
Actual Speed: 0
Current Draw: 0

Rear Traction Drive
Feed Forward Torque: 0
Inverter Temp: 0
Motor Temp: 0
Motor Load: 0
Actual Torque: 0
Actual Speed: 0
Current Draw: 0

Front Left Traction Drive
Feed Forward Torque: 0
Inverter Temp: 0
Motor Temp: 0
Motor Load: 0
Actual Torque: 0
Actual Speed: 0
Current Draw: 0

Log Interval: 100

Fig. 7- Vehicle Logger GUI

Once the vehicle exits the container, the stop logging button can be pressed. This exports a csv file containing all of the data received from the sensors and various components on the vehicle.

This data can then be parsed to plot the laser sensors looking at the wall, to see how much the vehicle deviates from the centre to understand the overall accuracy in the vehicle driving down the centre line of the container. This in turn can be compared with the information from the Navigation Visualisation software to determine the reliability and accuracy. This test of driving in and out of the container needs to be done a multitude of times in order to ensure reliability.

3.12 AGV Cycle Time Trials

For the RoboLoader-L to be a feasible product in the red meat industry which allows for adoption, the system must load containers at a speed comparable to current loading speeds. As a result, it is important to analyse the cycle time of the navigation system to ensure that the timing is consistent with previously modelled cycle times.

Throughout the trialling of the vehicle navigation system, the cycle times of each process was taken down in order to find some typical values for the timings of each part of the process. The process timings were taken off the visualisation software provided by the Navigation partner.

3.13 Wireless Network Testing

Another component of the system that had to be tested is the reliability of the wireless network. If the wireless system is not robust, the vehicle will stop intermittently causing cycle time issues. As a result, the trials performed previously in the makeshift container environment were tested again in the container.

The vehicle was driven into the container, and the wireless nodes were placed in locations that would be replicated on a range of different sites. Running the software iPerf3 on a PC allowed the determination of the key metrics, as well as using the command line to determine network latency.

The trials performed were carried out the same way as they were in section 3.5 Initial Wireless Trials.

4. Results

Throughout this project, each previous stage culminates to the primary risk-mitigation activities: the cycle time and the Container Navigation Accuracy results. By writing the bespoke container navigation algorithm and testing the accuracy, it can be proven that the algorithms enable the rest of the RoboLoader to be developed.

4.1 Vehicle Container Loading Accuracy Results

Trial: Preferable Starting Position

For the first trial to analyse the accuracy results, the AGV was started off in a good position relative to the container position. This means that the AGV was relatively straight to the container, and towards the middle.

This position had the vehicle 76mm to the right of the container, with an angle of 2 degrees relative to the container back wall. During this navigational sequence, data was logged to determine the accuracy results.

The data was taken over the whole sequence, including the entering of the container.

During the time the vehicle was travelling down the length of the container the accuracy was calculated by finding the difference of the laser distance values on each side of the vehicle.

The data taken over these trials shows that the vehicle is most definitely accurate enough to navigate within the container. The position the AGV was placed in before starting the navigation trial was on par with the sort of positioning that will be provided by truck drivers in real-life scenarios.

Trial: Starting from Another Position

Trials were also performed at different start positions to assess the ability of the vehicle to correct.

This trial was performed to see the way in which the vehicle can correct in a short period of time to get into the container.

The results dictated that a different starting position still results in acceptable accuracies that allow the vehicle to navigate within the container without hitting any of the side walls.

Trial: Starting Further Back

Next, a trial was performed to start the container navigation algorithm as far back as the algorithm allowed to look at the accuracy when the vehicle has more time to correct before entering the container doors. This ended up being 750mm back from the initial position, with this configuration of the algorithm.

This position ended up being offset from the container entry by about 70mm, with an angle of around 2 degrees.

In this scenario, the accuracy is still within required bounds when travelling down the length of the container, at a position further back than initially trialled. This means that the vehicle is still able to navigate accurately within the container when starting further back- meaning that the algorithm is not completely dependent on start position. In addition to this, it means the start position can be moved backwards to ensure that there is more time to correct the vehicle’s position.

4.1.1 Conclusions

After a multitude of different trials were carried out, it was evident that the development of the Container Loading Navigation Algorithm was a success. For each trial performed, the AGV was able to navigate within the required limits.

As a result, the development was considered a success, and this confirms the risk mitigation of the navigational risk that was previously identified at the beginning of the project.

4.2 Vehicle Cycle Time Analysis

The results for the typical timing values can be seen in the table below. These are compared with the originally modelled values.

Throughout the cycle time analysis, it was found that the time measured for each of the processes, is on par with, or lower than the initially modelled timings. With further commissioning, the measured timings could also be reduced further.

4.3 Wireless Network Testing

Tests were performed with iPerf3, and the results are tabulated below.

Table 3- Results of Wireless Network Testing

Setup	TCP Bandwidth	UDP Bandwidth	Lost Packets	Latency Max (ms)	Latency Min (ms)	Latency Average (ms)
In Container	20.9	1.02	0	22	7	13

Based on the results, it could be concluded that using MIMO WIFI units for the WIFI network allowed a robust and fast network. The connection speeds were a little slower than expected based on tests from previous milestones, but the latency and bandwidths were well within acceptable limits for a robust system.

5. Conclusions/recommendations

This Project has been completed successfully and the work has resulted in a significant reduction in some of the key risks of the RoboDock technology development, including:

1. Vehicle Navigation within a Reefer Container.
2. Wireless network robustness.
3. Vehicle driving cycle time.
4. Layer building cycle time for processor adoption.
5. Risk of carton damage during the loading process.
6. Mechanical failure of vehicle due to large stresses.

The primary identified risk - the ability to navigate accurately within Reefer containers autonomously without pre-mapping - was mitigated throughout this project. This mitigation was performed through the development of new technology and algorithms that work together to allow navigation in such a difficult environment.

At the end of the trials performed in this project, it was confirmed that the AGV was able to navigate within the required accuracies. In addition, the cycle time requirements were met, with the measured cycle time resulting in a 9% decrease in actual cycle time to the originally modelled times.

As a result, it was confirmed that the vehicle could navigate within the required bounds, at the speeds required to allow the RoboLoader development to continue. Based on the information received, the vehicle’s performance will allow for the product to be adopted within industry.

6.1 Key Findings/Developments

There were a range of key findings within this project, but based on this being a technological project, there were also some developments. These included:

1. Development of a Container Loading Navigation Algorithm that allows a vehicle to navigate inside a reefer container autonomously, without any manual intervention to map the walls.
2. Further development of the RoboLoader machine design, both mechanically and electrically, to the point where detailed design is ready to be completed.
3. An AGV platform, that when coupled with the developed navigation algorithms, is able to navigate in a reefer container.
4. A mechanical and electrical design of a RoboLoader that allows for container loading of a 20ft container in required cycle times to be on par with industry.

6.2 Benefits to Industry

Based on the results of this project, there are a large range of benefits to the red meat industry that have been developed.

The main risk mitigation activity in this project included the development of a Container Loading AGV, which is able to navigate in and out of reefer containers to a high degree of accuracy. In addition, throughout this project, the RoboLoader's high level electrical and mechanical design was extended in order to minimise the risk for processors as the next stages of this product development is undertaken. The full development of the product will result in a large range of benefits to the industry, including:

1. The removal of manual labour from the container loading process
2. The removal of workers from high-risk areas, such as in the back of containers or on busy loading docks
3. A decrease in the risk of incorrect product going into a container for export
4. An enabler for quality assurance of cartons before they go into a container for export.

7. Future Research and Recommendations

As is depicted in the section above, there is a large range of benefits the Automated Container Loading System can deliver processors within the Red Meat industry. Now that the major risks within this project have been reduced, the next phase is to begin the process of building a full RoboLoader system. This will include stages of how the cartons are handled, and the technology is to be developed into a fully functional system. Securing an industry partner to customise this solution in partnership with MLA is now recommended.

References

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