Development of a Vision-Guided Robotic System for Automated Sugarcane Train Carriage Decoupling

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Statement of the Contribution of Others

eople contributed in these ways

Abstract

Abstracty abstract

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List of Abbreviations

ARD	–	Autonomous Robotic Decoupler
MSF	–	Maryborough Sugar Factory
MSM	–	Mulgrave Sugar Mill
PSM	–	Proserpine Sugar Mill

Chapter 1

Introduction

1.1 Design Problem

This paper documents the development of a vision-guided robotic system for automated sugarcane train carriage decoupling.

At the Mulgrave Sugar Mill (MSM), cane train carriages are still manually decoupled and coupled by a labourer. Apart from being a rather boring task, the labourer is exposed to risks of fatigue, collision with the carriage, and physical strain from performing repetitive tasks; and stress on the body due to exposure to rain, sun, and high temperatures. These risks can be eliminated by installing an autonomous robotic decoupler (ARD) that uses computer vision to allow automatic decoupling of the carriages.

1.2 Mulgrave Sugar Mill

MSM, located in Gordonvale 25 km south of Cairns, Australia, has been in operation since 1896. It is owned by MSF (Maryborough Sugar Factory), which is itself part of the Thai-based Mitr Phol Group [1]. Because of its age and layout, as well as cost restrictions, redesigning the plant to use the latest automated decoupling system is not feasible. Similarly, installing newer buffers on approximately 2000 carriages is not an option due to high costs. There is a balance to be struck between altering existing mechanisms (i.e. costs) and reducing ARD complexity (i.e. points of failure). This means to increase simplicity and reliability of the ARD, the existing buffers and possibly railway network require extensive upgrades. Conversely, minimising such upgrades necessitates a more complex ARD. After speaking with the MSM electrical engineering superintendent, altering a smaller component of the buffer such as the pin is acceptable, as doing so on approximately 2000 carriages will not be as exorbitant as replacing the each entire buffer. This is an example of striking a balance.

1.2.1 Carriage Dimensions

There are two sizes of carriages used at the mill:

- Approximately 800 10-tonne types, 5810 mm long × 2284 mm high × 2410 mm wide. With buffers, the length extends to a maximum of 6360 mm.
- Approximately 1200 6-tonne types, 3759 mm long × 2415 mm high × 2442 mm wide. With buffers, the length extends to a maximum of 4323 mm.

These dimensions were obtained from the scaled CAD drawings provided by the MSM electrical engineering superintendent. These drawings are in Appendix A .

Heights are defined as the measurement from the top of the railway to the extreme top of the carriage.

1.2.2 Carriage Journey

Cane is loaded into cane carriages on farms in the area surrounding MSM. These carriages, once loaded, begin their journey to the MSM. They eventually reach the site, where they first pass through a tunnel with a 2750 mm clearance above the top of the railway. At this point, any overloaded carriages will have the top of their load skimmed to a maximum height of 2750 mm. After the tunnel, the carriages enter the receivals area, where they are systematically decoupled. The receivals area contains position sensors, actuators, and a button that the labourer presses to allow carriages to be moved ahead one at a time.

After a carriage moves forward, it comes to rest temporarily, allowing the labourer to decouple the next carriage. The labourer then presses a button when the decoupling is complete, allowing the carriage to be moved forward. Due to the setup on site, the carriages are not tightly butted against each other, so they can move along the length of the railway. Consequently, there is a variation in the y-location (distance parallel to the railway) of the pin of ± 150 mm when understood from a stationary point of reference on the nearby wall (See Fig. 1.1 for a visual representation of x-, y-, and z-positions).

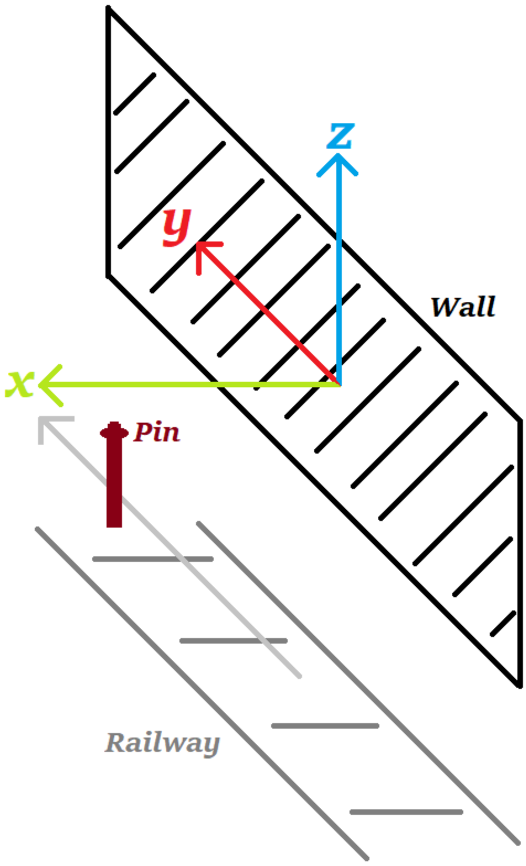

Fig. 1.1 Reference coordinate system.

There is a much smaller variation in the x-location (distance perpendicular to the railway) of the pin of $\pm$X mm, because the carriage cannot move (has negligible movement) in the direction perpendicular to the length of the railway tracks. The variation in the z-location (height above railway) of the pin within the same carriage type is also small at $\pm$Z mm, because there is minimal variance in the height above the ground of the coupling mechanism. Be that as it may, there are 2000 carriages — provisions should be made for anomalous cases where the buffer is not positioned correctly (therefore causing the pin to be located outside its expected position).

At any given time in the tippler, two 6-tonne carriages are tipped at once, or only one 10-tonne carriage is tipped. This means the point in space (y-position) at which the carriages are decoupled changes depending on the carriage size. Assuming the same stopping point of all carriages is at their forward-most set of railway wheels, the difference in the y-position of the pin between the 10-tonne and 6-tonne carriages is 2294 mm. ASSUMING THE SAME STOPPING POINT OF ALL CARRIAGES IS AT THE FORWARD-MOST POINT OF THE FRONT BUFFER, THE DIFFERENCE IN THE Y-POSITION OF THE PIN BETWEEN THE 10-TONNE AND 6-TONNE CARRIAGES IS 2364 mm.

According to the scaled drawing, the z-position of the pin (the height of its head above the railway) is different for each carriage type:

- 10-tonne type: 547 mm
- 6-tonne type: 510 mm

The variation in pin z-position between carriage types is 37 mm. Within the same carriage type, this variation is expected to be smaller.

According to the scaled drawings, the x-position of the pin (between and within carriage types) remains the same as it is always centred between the railways.

However, due to manufacturing tolerances, wear through use, and repairs, a variance in all these dimensions of ± 30 mm is normal and should be accounted for by the ARD.

In summary, the variation (±) in three dimensions of a pin's position within the same carriage type are:

- x: $\leq$ 30 mm
- y: $\leq$ 150 mm
- z: $\leq$ 30 mm

1.2.3 Link and Pin Coupling Mechanism

All carriages are fitted with the same link and pin coupling mechanism (shown in Fig. 1.2). Due to buffers' being replaced or repaired, there are naturally some slight variations in dimensions of each coupling mechanism. However, the layout remains the same and so do the locations of the links and pins (approximately), which are the chief points of interest in this thesis.

Fig. 1.2 Link and pin coupling mechanism currently in use on all carriages at MSM.

To the head of the pin is welded an inverted u-shaped rod. This is the point at which one end of the chain is tethered.

1.2.4 Current Decoupling Method

Currently, a manual labourer uses a long pole (approximately 1.5 m in length) ending with a v-shaped fork to lift the pin by the chain to which it is tethered. The pin is then placed aside, and the labourer pushes the oval-shaped link away from the buffer so that no fouling occurs as the now-uncoupled leading carriage moves forward. This entire process is shown in Fig. 1.3

Fig. 1.3 Example of manual decoupling process currently in use at MSM. Left to right: pin through link, lifted pin, link pushed aside.

On occasion, the pin will require a lot of force to be removed due to being jammed. Jamming occurs due to the pin itself being bent, debris becoming wedged between the pin and the hole, or because the link is still pulling on the pin. In these instances, extra force is required to remove the pin, or repeated blows to the chain to rattle the pin free are required to perform the decoupling process.

1.2.5 Existing Infrastructure

SCADA, PLCs. Digital signals - train carriage is ready to move forward Clearances. Wall to wall of carriage. 2.75 m tunnel height etc.

1.2.6 Practical Considerations

Cairns is hot, humid, and experiences great rainfall during the wet season (with which the cane-crushing period partly coincides). The mechanical and electrical components of the ARD must operate unaffected by these extremes.

A small amount of cane is always lost from the carriage. As it falls, some cane will cover surfaces or fill cavities. As well as cane, dirt and mud will inevitably coat surfaces and obstruct the ARD. This is important to consider when designing the object detection method and lifting mechanism.

Apart from environmental obstructions, abnormalities will occur. Important cases to consider are:

- There is no tethering chain attached to the pin (raise alarm, place pin aside)
- the pin is jammed so tightly that the robot cannot perform decoupling (raise alarm)
- the pin is outside the expected location (move arm)
- there is debris atop the pin head (compressed air?)
- the link cannot be pushed aside (raise alarm)
-

Missing chain can be detected by extra weight on load cell AFTER pin is removed. It can also be detected by a camera and object detection. What method is more reliable?...

Because of this harsh work environment, the ARD needs to:

- have minimal points of potential failure;
- be robust;

- have high reliability;
- be simple to maintain;

These general requirements will direct the theoretical research taken. E.g. a complicated robotic arm with multiple degrees of freedom controlled by an advanced object detection algorithm will not be suitable due to the surrounding environment being too dusty, dirty, and damaging. Something more simple like a half gantry with a vertical actuator and electromagnetic attractor would be more appropriate.

(Compressed air)

1.3 Research Problems

1.4 Research Objectives

The objective of this research is to find a simple, reliable, and effective way to automatically decouple cane train carriages.

1.5 Scope

This paper will document the process, from research to physical design, sample collection, testing, and recommendations, of an automated *decoupling* robot that uses computer vision. Though it may mention, it will not cover the following in the same depth:

- Automatic recoupling
- Research into the best coupling mechanism for cane trains

Chapter 2

Literature Review

2.1 Introduction

It is important to consider where similar problems have been encountered and what measures were taken to solve them. This information will help to inform the design process and improve methodologies.

In this chapter, similar problems and their solutions will be discussed. Then, a variety of computer "vision" methods, potentially appropriate for use in the ARD, will be discussed. In this context, vision is defined as a way the ARD can "see" the carriage and its coupling mechanism.

Literature will be selected if it answers yes to any of the following questions:

- Is it related to link and pin couplings of the same type used at MSM?
- Is it a type of vision that will likely survive in a dirty and harsh environment?

2.2 Similar Problems and Their Solutions

There are multiple coupling types used on cane trains, such as but not limited to hook and chain, link and pin, ball and socket, and automatic Willison [2]. Though link and pin couplings are old, primitive technology, they are tried and true, and cheap to fabricate due to their simplicity. However, determining the best coupling type for use at MSM is out of the scope of this paper, and would be a futile exercise anyway, as MSM will not replace couplings on approximately 2000 bins due to prohibitive costs.

2.2.1 Proserpine Sugar Mill

In 2006, Proserpine Sugar Mill (PSM) received a $112,000 Sugar Industry Innovation Fund (SIIF) grant from the QLD State Government to aid in developing a robot to locate and remove the coupling pins between cane carriages before being weighed at the mill [3, 4]. At the time, the Proserpine Cooperative Sugar Milling Association believed it was to be the first out of all the world's sugar industries to implement a robotic pin remover. Their justifications for implementing this robot were to increase safety; reduce intense labour; reduce down time (by 5%); and increase throughput (by 10 tonnes per hour).

Compared to that at MSM, the PSM link and pin mechanism features an additional component — called a "locking latch" or "cockatoo" (due to its appearance) — that prevents the pin from riding up during transport. Their robot was required to locate the pin, push down the latch, pull the pin up, and finally drop it clear of the coupling (pushing the link was not required due to a then future change to the tippler that would prevent link fouling). Their design criteria were: 99.9% pin removal accuracy; no greater failure rate than 1 per 24 hours; 24-7 continuous operation on tight pins (20 kg pulling effort required as per testing) for 6 or 7 weeks (after which an 8-hour maintenance window occurred); perform as normal in high dust, humidity, and temperature situations despite being under cover; determine pin position despite variations of up to 100 mm in all axes of the theoretical correct pin location; maximum 15 second pin removal time; seamless interfacing with existing control systems (and additional non-third party equipment was unacceptable); maintenance costs no greater than 10% of the initial cost per year; reasonable software upgrade costs; continued technical support from the original supplier; on-site support within 24 hours; acceptable lifting capacity; and SIL3/Category 4 level of safety at all times.

A KUKA robot with a 140 kg lifting capacity was selected for trials. Marand Precision Engineering of Moorabin, Victoria, designed the bespoke gripper and latch operator, and programmed the robot.

Despite trials yielding positive results [5], it is not clear whether the robotic arm was ever installed for a significant period of time — if at all — after the trials were concluded.

In 2016, an upgrade was performed at PSM to eliminate manual decoupling and coupling by replacing the link and pin system with a variant of the Willison system. This upgrade was a success, and many risks were eliminated [6]. However, there was no mention of a robotic arm being in use in the 2016 paper. This implies that the arm was never permanently installed.

From 1993 – 1997, an early variant of the Willison system was in use but was replaced with the link and pin system after several dangerous uncoupling occurrences during service. Therefore, from 1997 – 2016, the pin and link system was in use before being switched back to a newer variant of the Willison system. This return to the Willison system — now newer and enabling complete automation of the decoupling and coupling processes — was done due to the requirement to reduce the risk to workers in the feeding station [6].

2.2.2 Marian Sugar Mill

Reference [7, p. 6] writes Marian Sugar Mill has

> ...link and pin connected bins...[that] were handled automatically within the mill...

However, further research did not yield any information on this claimed automatic handling of link-and-pin-coupled carriages in Marian Sugar Mill.

2.2.3 Cattle Creek Mill

According to [5], Cattle Creek Mill uses a "pin popper" to perform the decoupling process. Further research on this mechanism yielded no results — it is not known whether the pin popper is fully automatic or requires human input.

2.3 Varieties of Vision

2.3.1 RGB Camera

2.3.2 Stereocamera

2.3.3 Structured Light 3D Scanner

https://www.e-consystems.com/blog/camera/technology/how-time-of-flight-tof-compares-with-other-3d-depth-mapping-technologies/

2.3.4 Time of Flight Camera

Time of Flight (ToF) cameras capture a 2D array of depth points. These depth points can be translated into a pseudo-colour image, where blue represents far-away objects, and red close objects.

2.3.5 Ultrasonic

2.3.6 mmWave

2.3.7 LiDAR

2.3.8 Kinect

2.4 Object Detection

If the pin is the highest point in the buffer, a ToF camera would provide a good starting point for object detection. Perhaps a better starting point than an RGB camera, because the colour of the pin is similar to the rest of the coupling mechanism, and because RGB cameras do not sense depth.

The head of the pin is a simple shape — a circle. This would be easy to detect. https://pmc.ncbi.nlm.nih.gov/articles/PMC9572816/ https://www.mdpi.com/1424-8220/19/7/1539 https://www.mdpi.com/1424-8220/23/22/9030

2.4.1 Salient Object Detection (SOD)

2.4.2 Detecting Circles with a ToF Camera

2.5 Main Arm Mechanism Types

A type of arm or gantry is required to extend from the wall and support the pin lifter and link pusher mechanism. It has to be strong enough to support linear reaction forces and moments about its fixing point due to its own weight, the weight of the pin lifter, and the weight of the load it is lifting.

2.5.1 3-DOF Robotic Arm

2.5.2 Half Gantry and Actuator

2.5.3 Horizontal Scissor Arm

2.6 Pin Lifter and Link Pushing Mechanisms

There are multiple mechanisms that can be used to lift the pin and push the link.

2.6.1 Claw

A 3-pronged gripping claw could grip a pin that has had a ball welded to its top.

A 2-pronged gripping claw could grip the existing pin through the u-shaped chain tethering point. However, this would require pin orientation detection to allow the prongs to pass through the u-shape. This would increase complexity, decrease reliability.

Similar to a 2-pronged gripping claw would be an actuator that passes a pin through the u-shaped chain tethering point.

2.6.2 Vacuum

A vacuum would draw in dust and debris, and would require a clean and sealable surface. The site is not conducive to such requirements. A vacuum is therefore not suitable.

2.6.3 Electromagnet

An electromagnetic attractor would require modification to the pin, as outlined in section 3.4.1.

2.7 Control Methods

2.7.1 Inverse Kinematics

If a robotic arm with rotating points is used, complex but well-understood trigonometric kinematic methods must be used to control it.

If the arm has no rotating points, but only actuators that move linearly, much simpler linear kinematic methods must be used.

2.7.2 AI

Due to an easily-accessible pin, and only simple x-, y-, and z-translational positioning of the arm being required, with no rotations necessary, an AI-algorithm would be superfluous to requirements. It also requires training and may behave unexpectedly in unusual scenarios presented by the coupling mechanism. Its algorithm complexity would increase operating costs should it fail. Overall, it is not a good choice when simpler and more reliable choices are available, such as inverse kinematics.

2.8 Conclusion

Chapter 3

Methodology

3.1 Introduction

This chapter discusses the research design, how data will be collected, experimental design, data analysis, and associated limitations. Specifically, a high-level overview will first presented, visually depicting everything from the research design to the conclusion. Second, the sensor setups will be laid out as well as the data collection and processing methods. Third the pin position estimation and object detection methods will be explained. Fourth, the pin lifter and link pusher mechanism types will be compared. Fifth, main arm mechanisms will be compared. Finally, the limitations of the hardware and software of the research design will be critically analysed before a conclusion is presented.

3.2 Research Design

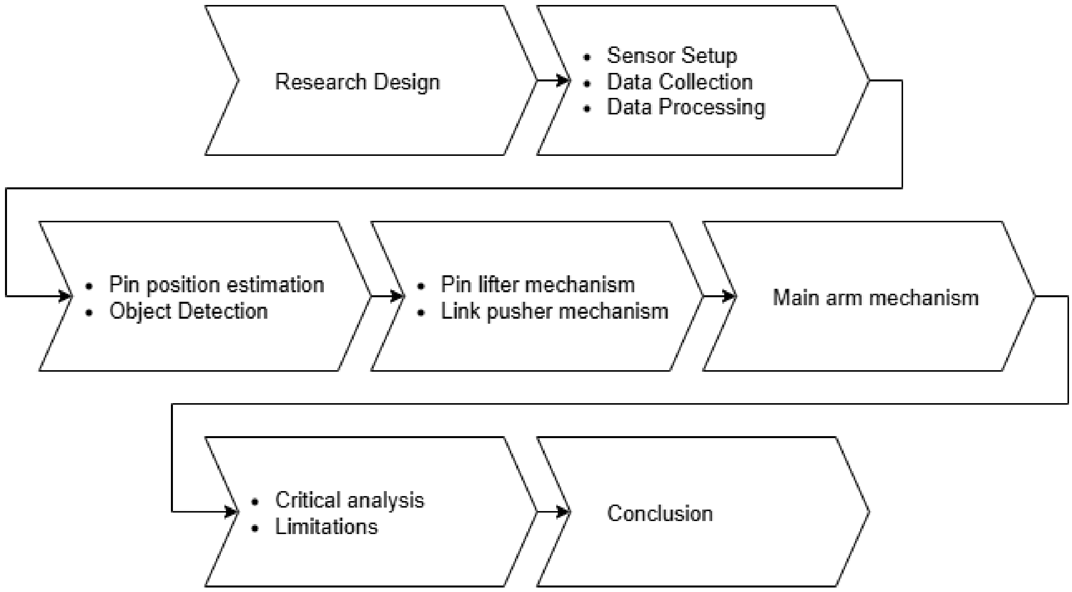

Fig. 3.1 Research design flowchart showing the sequential layout of the methodology chapter.

3.3 Instrumentation and Data Collection

Several instruments will be used to collect preliminary data at MSM. They are described in Table I.

TABLE I
INSTRUMENT LIST

Instrument	**Purpose**	**Cost (AUD)**	**Procurement Status**
Raspberry Pi 4 Model B - 4GB	Collect RGB camera imagery and ultrasonic sensor data	$98.69	On hand
Raspberry Pi 3 Model B Plus	Collect ToF camera imagery	$60.54	On hand
RGB Camera Module	Capture RGB images of the coupling from above	$48.50	On hand
Ultrasonic Sensor	Detect presence of carriage and find leading edge of carriage	$62.80	On hand
ToF Camera Module	Collect depth images of coupling from above	$86.85	Purchased Week 8
Active Cable Extension Kit for Camera Modules	Power and data link between ToF camera and Pi for.	$87.40	Purchased Week 8

Two Raspberry Pis will be used due to each having only one camera port. The RGB camera will be connected to the Pi 4, and the ToF camera will be connected to the Pi 3.

3.3.1 RGB Camera Module

The RGB camera module will capture images of the coupling mechanism from above. These images will serve as the ground truth for use in object detection. 1000 images will be captured

3.3.2 Ultrasonic Sensor

The ultrasonic sensor will be used to determine the presence of a carriage. Then it will sweep sideways until the leading edge of the carriage is detected (known from a sudden change in depth). This will allow the approximate pin location to be determined. Then the main arm can then move to this location, where precise pin location estimation begins, with the use of the ToF camera module.

3.3.3 ToF Camera Module

The ToF camera that will be used has the following specifications:

TABLE II

Arducam ToF Camera Specifications

Parameter	**Value**
Number of Effective Pixels	240×180
Image Size	1/6”
Max. Frame Rate (Sensor)	120fps
Max. Depth Frame Rate (Raspberry Pi)	30fps, 4-phase
Raspberry Pi OS	Bullseye (32-bit/64-bit), 01/28/22 or later releases
TDP	3.5W (Power supply for Pi should be at least 5V/4A)
Supported Platforms	Pi 2/3/CM3/4B, Zero W/Zero 2 W/CM4
Modulation Frequency	75MHz/37.5MHz
Viewing Angle	70° Diagonal
Measurement Distance	Far Mode: 4m Near Mode: 2m
Light Source	940nm VCSEL illuminator
Board Size	38mm x 38mm
Interface	MIPI (2-Lane)
Output Formats	4-phases RAW Frame, Depth Frame, Grayscale Amplitude Frame

3.4 Experimental Design/s

3.4.1 Pin Lifter

The attractor design will require pin modification. Specifically, an extra washer will have to be welded beneath the existing washer, with some clearance between the two. Then the chain must be relocated to between the two washers. Finally, the u-shaped chain tethering point must be completely removed. The extra washer beneath the existing one will raise the height of the seated pin relative to the rest of the coupling mechanism, allowing the electromagnetic attractor unobstructed access to the flat head of the pin. Compared to the small point of contact the u-shaped chain tethering point affords, the flat head will allow a greater pulling force before the attractor breaks away. Fig. 3.2 shows the new design.

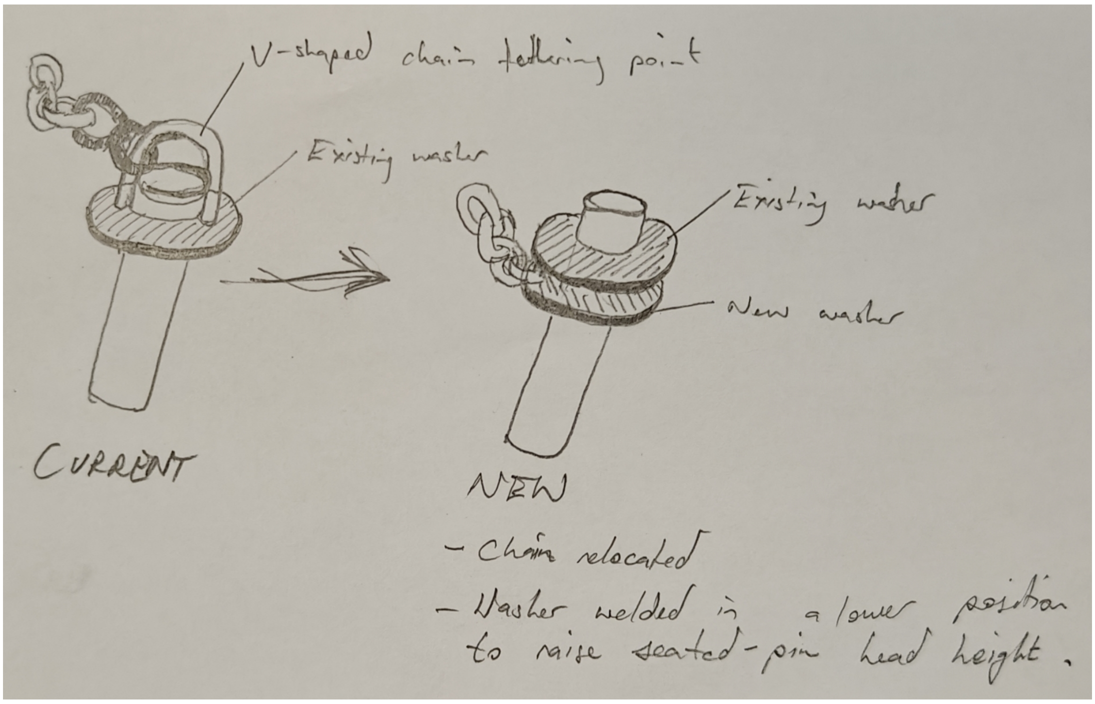

Fig. 3.2 Pin redesign

A potential consequence of such a modification is that the pin could work its way up and out of the link now that the tail is effectively shorter [[5]]. If this consequence manifests during trials, it could possibly be ameliorated by lengthening the tail of the pin.

Whatever the physical modification may be, care should be taken to minimise its extent and to simplify any countermeasures required to quell new issues it may engender. This will ensure system reliability is maintained.

3.4.2 Link Pusher

When on the straight section of railway in the receivals area, the link will always be collinear with the pin. In addition, and allowable due to the topology of the coupling mechanism, a winged and tapered-point "locator" could be lowered simultaneously with the pin lifter once the pin head has been detected. This locator would be guided by its tapered point to the centre of the link. Its wings would act as a stopper on the link, allowing vertical support to the attractor as it is pulling on the pin (this would also beneficially reduce weight on the arm that extends from the wall). Once the lifter lifts the pin, the locator, still in place, can push the link clear of the coupling mechanism as in Fig. 1.3. Then the locator will be lifted before the arm retracts, allowing the carriages to be moved forward. Fig. 3.3

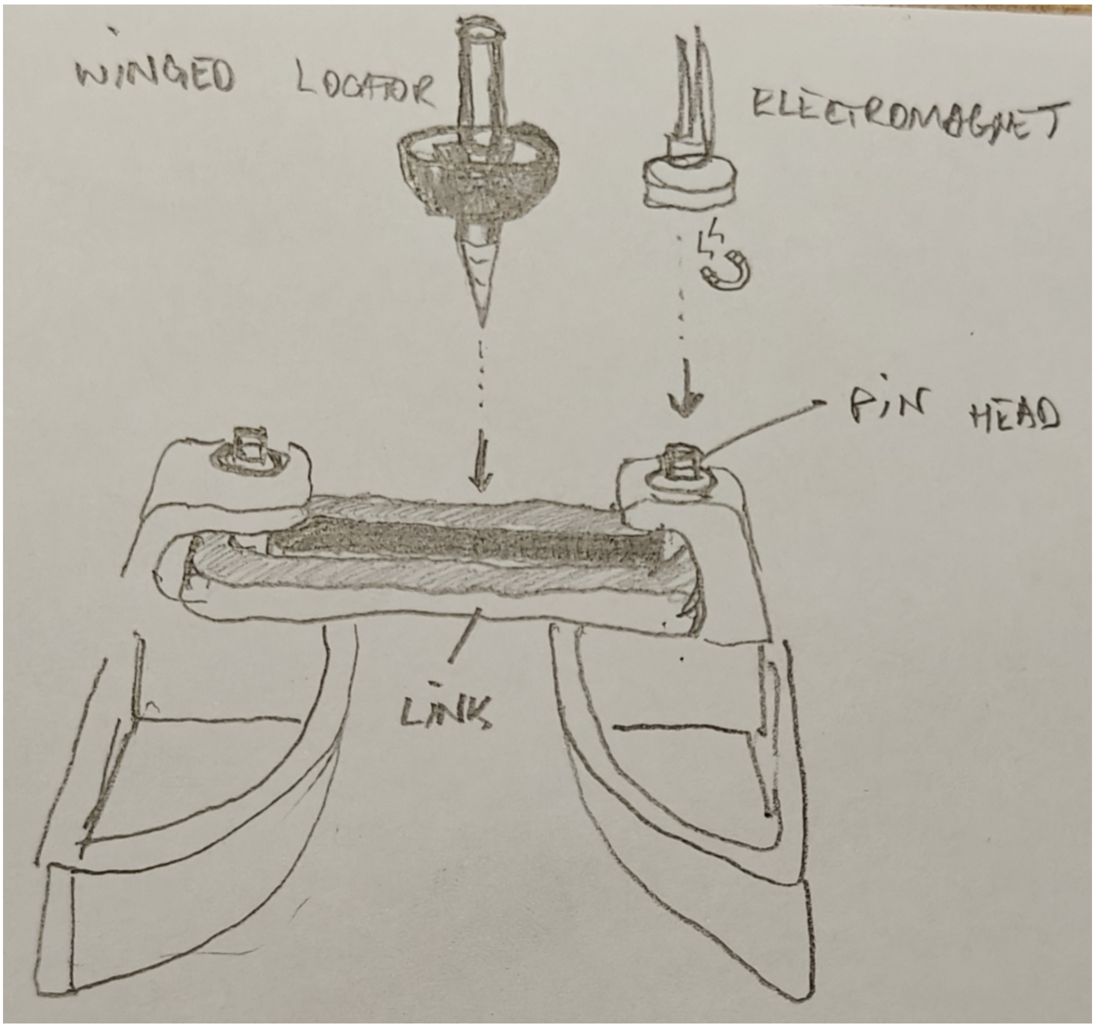

Fig. 3.3 The winged tapered-point locator and lifter.

3.4.3 Assumptions

- Object detection and arm control methods must require minimal computational power so that a small embedded device can be used for computing and control.
- Changes to the coupling mechanism that require greater cost and effort than, for example, a pin modification, are not permissible.

3.4.4 Design Constraints

- Robotic arm to be compatible with existing electrical infrastructure (SCADA, PLCs)

- Overall system cost must be less than $XX

To be deemed a success, the ARD must meet the following requirements:

- have high accuracy (e.g. minimal false positives when detecting chains, pin locations, etc)
- have a 99.9% success rate (success is defined as complete decoupling)

3.5 Data Analysis Methods

Data will first be collected in the lab to ensure all instruments are calibrated and functioning correctly.

A human will perform validation of the object detection algorithm, by comparing the ground truth RGB images with the ToF pseudo-colour depth map images that have had object detection applied to them.

First, the centre of the pin head on the RGB image will be marked by the human. Then, the depth image will be superimposed with the RGB image. If the object detection algorithm correctly identifies the pin head, a circle should be drawn around it. A correct identification will be labelled as "satisfactory" by the human, or be labelled "error" otherwise. The allowable tolerance between the centres of these circles is ± 2 cm.

3.6 Limitations

Due to the risks at MSM during operation, it is not possible to be present while data collection is underway. Instrument setup and pack up can only happen during maintenance, when plant equipment is locked out and safe to be around.

- Determine force required to lift normal pin, jammed pin, etc
-

Load cell: https://core-electronics.com.au/load-cell-200kg-s-type-tas501.html Load cell amplifier: https://core-electronics.com.au/makerverse-load-cell-amplifier.html

Measure weight or resistance to determine presence of tethering chain. Weight requires load cell. Resistance requires open-circuit voltage measurement which requires high-input impedance op-amp (raspi ADC may have around 100k Z-in) (resistance from rail through all the mechanical parts touching to electromagnetic attractor maybe be in the 100 kOhm range).

Jammed pin? Impact driver mechanism to generate vibrations that pass through the attractor to the pin: https://youtu.be/7rcvcDuqOJo

3.7 Progress to Date

3.8 Conclusion

Chapter 4

Project Management Plan

4.1 Timeline (1 – 2 pages only

4.2 Resource Planning

4.3 Risk Assessment

The risk assessment is in Appendix B

4.4 Cost Planning

Chapter 5

Results

Chapter 6

Discussion

Chapter 7

Conclusion

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Appendixes

Appendix A

Scaled CAD Drawings of Carriages

Text of Appendix Scaled CAD Drawings of Carriages

Appendix B

Risk Assessment

Text of Appendix Risk Assessment is Here

Appendix C

Instruments

TABLE I

INSTRUMENT LINKS

Product Name	**Link**
Raspberry Pi 4 Model B - 4GB	https://core-electronics.com.au/raspberry-pi-4-model-b-4gb.html
Raspberry Pi 3 Model B Plus	https://core-electronics.com.au/raspberry-pi-3-model-b-plus.html
RGB Camera Module	https://core-electronics.com.au/raspberry-pi-camera-3.html
Ultrasonic Sensor	https://core-electronics.com.au/a01nyub-waterwaterproof-ultrasonic-sensor.html
ToF Camera Module	https://core-electronics.com.au/time-of-flight-camera-for-raspberry-pi.html
Active Cable Extension Kit for Camera Modules	https://core-electronics.com.au/cable-extension-kit-for-rpi-camera-modules-v1v2hqarducam-series.html

(Click here to return to the instrument table in the methodology section).