



THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

Research Commons

<https://researchcommons.waikato.ac.nz/>

Research Commons at the University of Waikato

Copyright Statement:

The digital copy of this thesis is protected by the Copyright Act 1994 (New Zealand).

The thesis may be consulted by you, provided you comply with the provisions of the Act and the following conditions of use:

- Any use you make of these documents or images must be for research or private study purposes only, and you may not make them available to any other person.
- Authors control the copyright of their thesis. You will recognise the author's right to be identified as the author of the thesis, and due acknowledgement will be made to the author where appropriate.
- You will obtain the author's permission before publishing any material from the thesis.

The Barracuda:
An Investigation of a Novel Cane Pruning Technology for Avoiding Wires
in Structured Vineyard Environments

A thesis
submitted in fulfilment
of the requirements for the degree
of
Master of Engineering (Robotics)
at
The University of Waikato
by
Scott Harvey



THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

2022

Abstract

The viticulture industry, among many others, is trying to improve their product quality whilst facing labour supply challenges and increasing labour costs. The Maaratech research group has been developing human assist technology and an autonomous, prototype grape vine pruning machine to alleviate these issues. The machine is an arched “straddle” platform, containing a camera array, PC, UR5 manipulator, and end-effector. The canes of the grapevine are wrapped around guide wires, making it very difficult for cuts to be made – whether by human or robot. This thesis presents the process of developing and testing a novel technology called the Barracuda, to enable cuts to be made where the wire interferes with a cut. The wire also puts high accuracy requirements on the vision system and manipulator movements if a secondary mechanism was used to separate the wire and cane. The Barracuda was developed as an end effector to alleviate these issues by allowing passive wire separation from the cane. It works by exploiting the diameter difference between the smaller wire, and larger canes. The wire falls into slots, evading the blade, while the cane is cut.

Two Barracuda configurations were tested by making cuts on canes wrapped around the guide wire. Config 1 was a single row of teeth, with larger recesses, flat teeth and a blade-guiding chamfer. Config 2 used two rows of teeth either side of smaller recesses and included rounded teeth tips. The components are CNC machined or laser cut. Results showed for both configurations, the 0° position was most effective. The 0° position is where the wire was below the cane, relative to the handpiece. In this position, Config 1 was effective 40.7% of the time, and config 2, 94.5% of the time. Damage to the wire was caused 8.9% of the time for config 1, and config 2 just 2.6% of the time. Both blades received the same rate of blade damage, however the damage was visibly more significant on config 1. From these results, config 2 was the preferred design, but integrating a chamfer from config 1 should reduce blade damage further.

It also benefits human assist goals. By allowing cuts on the wire, pruners are able to make cuts quickly and easily with Barracuda-modified secateurs or loppers, removing the need to separate the cane from the wire. The design works around the environment, increases the number of points available for decision making, and allows some inaccuracy in the rest of the robotic system by offering passive wire avoidance with the teeth. The performance of the Barracuda in cut situations involving a wire proved it valuable for integration with current manual pruning

methods, and as a cornerstone for robotic pruning development, providing further opportunities for the greater system.

Acknowledgements

Firstly, thank you to everyone in the Maaratech group for allowing me to become part of such an awesome project and such a great challenge. Particularly Craig Hornblow for finding vineyards to visit and to John van der Linden for encouraging me and arranging vineyard visits and expert pruners for feedback.

Thank you to Villa Maria, Church Road, and especially Stoneleigh/Pernod Ricard wineries for allowing us to test the equipment there and for the valuable conversations with pruning experts that have shaped the Barracuda's development.

Thank you to Andrew Tattersall and Michael Bernhard for collecting the cut force data and providing a design sounding board as they designed built and tested an alternative method of integrating the Barracuda. Thank you also to Sam Hodder for helping record cutting data and for collecting cane & shoot diameter measurements.

A big thank you to the Ministry of Business, Innovation and Employment (MBIE, contract number UOAX1810) for funding such a project, and indirectly for funding my scholarship so this work could have the attention it deserved.

A huge thank you to my supervisors Ben, especially for your technical help and Hin, especially for your help with writing this thesis. Couldn't have done this without you guys. A huge thank you to Professor Mike Duke for giving me the great opportunity to do this work and for believing in me.

Lastly, a massive thank you to my parents, Dennis & Brenda, my brother, Luke, and to my partner, Hannah for your consistent love and support during this challenge. I appreciate it more than you know.

Scott

Table of Contents

Abstract.....	ii
Acknowledgements.....	iv
Table of Figures	vii
Chapter 1: Introduction.....	1
1.1 Overview	1
1.2 Grape Vine Pruning.....	2
1.3 Project and Design Considerations	6
1.4 Thesis Objective.....	7
1.5 Thesis Outline	7
Chapter 2: Literature Review.....	8
2.1 Synopsis	8
2.2 Literature Review	9
2.3 Potential Pruning Methods	22
2.3.1. End Mill	22
2.3.2. Laser Cutting.....	22
2.3.3. Waterjet Cutting.....	22
2.3.4. Shears/Secateurs	23
2.3.5. Crushing.....	23
2.3.6. Selection.....	23
2.4 Cutting Forces	23
2.5 Diameter and Roundness of Canes.....	25
2.6 Current Industry Pruning Methods.....	26
2.7 Summary	26
Chapter 3: Development of Barracuda	28
3.1 Barracuda	28
3.2 Development of Anvil.....	29

3.2.1.	Tooth Profile	29
3.2.2.	Anvil strength.....	33
3.2.3.	Integration of Modified parts into Electric Secateurs	34
3.3	Integration with automated system	39
3.3.1.	Housing	40
3.3.2.	Software	43
3.3.3.	Hall effect limit sensing	46
Chapter 4:	Performance Analysis	48
4.1	Barracuda Configurations and Experimental Setup	48
4.2	Performance Metrics	51
4.2.1.	Test 1 Performance Metrics	51
4.2.2.	Test 1 Damage	52
4.2.3.	Test 2 Performance Metrics	53
4.3	Results	54
4.3.1.	Test 1 - Performance of both configurations	54
4.3.2.	Wire and Blade Damage	56
4.3.3.	Anvil damage – A case for rounded teeth.....	60
4.3.4.	Cane Puncturing for Configuration 1	63
4.3.5.	Performance with no wire	64
4.4	Discussion	65
Chapter 5:	Conclusion	68
5.1	Conclusion.....	68
5.2	Future Work	69
Chapter 6:	Bibliography	71

Table of Figures

Figure 1-1 - Cane Pruning vs Spur Pruning. Image: Caroline Courtney, New Zealand on Wine.....	3
Figure 1-2 - Grape vines prior to winter pruning.....	4
Figure 1-3 - Pruned two-cordon, bilateral vine anatomy.....	5
Figure 2-1 2D Jugala apple orchard with ties holding the branches to the guide wires. Source: Fruition.net.nz, 2021	9
Figure 2-2 - A young Kiwifruit orchard with visible wires which hold the plant from above the row. Source: Garcia Contracting Services	10
Figure 2-3 - Geneva Double Curtain layout for an individual vine. Source: Pago de Larrainzar	11
Figure 2-4 – Barrel pruning attachment on a vineyard tractor. Source: Vineyard Mates, Youtube.....	14
Figure 2-5 - Pellenc Optimum Straddle Tractors performing tasks over vineyard rows.....	15
Figure 2-6 - RoboVeg Autonomous Broccoli Harvester. End effector shown on the end of the yellow manipulator	16
Figure 2-7 - Cutting forces for grapevines.....	24
Figure 2-8 - Cut force error distribution	25
Figure 2-9 – Maximum difference in diameter of canes compared to their average diameter	26
Figure 3-1 - Operating principle of the Barracuda. The wire is shown in blue, and the cane in red.	28
Figure 3-2 - Characteristics of the dirty prototype anvils	29
Figure 3-3 - The five Barracuda dirty prototypes labelled 1-5	30
Table 3-1 - Dirty prototype anvil configurations and characteristics	30
Figure 3-4 - Testing the Barracuda tooth profiles.....	31
Table 3-2. Performance of dirty prototype anvils. Higher numbers are better.....	31
Figure 3-5 – Figures show the two main issues with shape 5.....	32
Figure 3-6 - Stress concentration method used to account for recesses in the Barracuda Anvil	33
Figure 3-7 - Thickness (Height) of Barracuda not including teeth height.....	34
Figure 3-8 - FEA loading analysis showing stress distribution	34
Figure 3-9 - Stock Anvil 3D Scan Point Cloud and isolated original.....	35
Figure 3-10 - Onyx 3D printed anvil for test fitting	36

Figure 3-11 - CNC machined anvil for Configuration 1 with additional machining stability holes	36
Figure 3-12 - Standard asymmetrical blade profile (Shown left), and symmetrical blade profile (Shown right).....	36
Figure 3-13 - Configuration 2 attached to Arvipo electric secateurs.....	37
Figure 3-14 - Wire alignment for various configurations viewed from the top of the teeth. Left to right: single row of teeth, double row with flat tooth tops, double row with rounded tooth tops.....	38
Figure 3-15 - Free-Body -Diagram of wire and tooth interaction to find limits of proper function	38
Figure 3-16 - Overall system setup consisting of the straddle vehicle (Archie), manipulator, and end effector.....	40
Figure 3-17 - Full system component diagram showing the primary relationships between the main system components	40
Figure 3-18 - Early prototype robotic pruner using Config 1 hardware	41
Figure 3-19 - Custom housing for robotic Barracuda showing overall design and internal circuitry	43
Figure 3-20 - State Machine for the operation of the end effector which operates on the arduino. Yellow states indicate pre-operation states, likely to be used once. Red states indicate fault states. Green states are operational states to be used repeatedly	44
Table 3-3 - State transition/event list describing key information for transitions labelled in the preceeding figure	45
Table 3-4 - Key Barracuda values used to find allowable overshoot time	46
Figure 4-1 - Configuration 1, pictured left, and Configuration 2, pictured right as they were used for testing.....	48
Figure 4-2 - Cut positions depicting the location of the Barracuda, cane, and wire for a cut sequence. The wire is shown in blue, and the cane in Red. Clockwise from top left: 0°, 180°, 90° and 270°.....	50
Figure 4-3 - Wire nick with resulting cross-section shown in hatched section A-A	53
Table 4-1 - Config 1 Field test performance results by cut position	54
Table 4-2 - Config 2 Field test performance results by cut position	55
Table 4-3 - Successful cuts by configuration.....	55
Table 4-4 - Config 1 blade and wire damage.....	56
Table 4-5 - Config 2 blade and wire damage.....	56

Figure 4-4. Blade damage caused by collision with the guide wire (Left) on Configuration 1. Aggregate blade damage (Right).	57
Figure 4-5 - Blade and teeth contact causing blade damage of Configuration 2.....	58
Figure 4-6 – Figure A (Left) shows the cut success rate. Figure B (Right) shows the blade damage rate.	58
Figure 4-7 - Blade damage of Configurations 2 and 1.....	59
Figure 4-8 - Damage to teeth on Configuration 1, overall view (Left), with detail view (Right)	60
Figure 4-9 – Overview of damage to Configuration 2 teeth tips caused by blade collisions (Left). And detailed view (Right)	61
Figure 4-10 - An unchamfered Configuration 1 depicting an undamaged anvil to illustrate damage chamfers created with use.	62
Figure 4-11- Chamfers illustrating the damage chamfers suffered by Config 1 (Left), and Config 2 (Right).....	62
Figure 4-12 - Puncturing of canes caused by Configuration 1	63
Figure 4-13 - Illustration of Barracuda teeth puncturing a cane.....	64
Table 4-6 - Cut success of Configurations 1 and 2 for cases where no wire was present	65

Chapter 1: Introduction

1.1 Overview

The productivity of food production has increased dramatically over the last 500 years. In the US, the average farm has gone from providing food for approximately 5 people, to 166 people [1]. In developed nations, particularly western Europe, the percentage of people employed in agriculture out of a population has dropped from around 75%, to under 10% today. During approximately the year 1500, 76% of England's population was involved in agricultural production [2]. Today that number is 1.3% [3]. This shows a vast increase in the efficiency and scale of production.

This increase occurred because of selective breeding, crop rotation with planting of turnips and clover between seasons, farm structure, invention of machinery, and the use of fertiliser. Mechanisation in farms began with the creation of the plough and the seed drill, and other new creations have since covered almost every task and every crop. Whilst very useful, this machinery is not perfect. This bulk machinery does not have any capacity to control or manage the inconsistent growth of the plants. As such, many tasks are still completed via manual labour. This is especially true for high value crops such as apples, asparagus, and grapes. This led to many researchers investigating selective robotics to address these challenges since 1984 [4].

Traditionally, automation and robotics have found their place within factories and other industrial applications. From a technical view, industrial situations are highly suited to automation because they are often simple, repetitive tasks taking place in an unchanging environment where inputs and outputs are controlled, consistent, and deterministic. This makes them ideal candidates for tasks such as manoeuvring and installing components, welding, and packaging. The first commercial robot, the Unimate, was sold to General Motors in 1961 [5]. Ever since, the uptake of robots in society has been on the rise. The world currently has 2.25 million robots operating, and is projected to have 20 million operating by 2030. Currently, 86% of these robots are used in industrial applications [6]. Industrial tasks are commonly automated with robots as their tasks are often dangerous, physically demanding, or unpleasant for humans, not to mention expensive from a labour perspective.

This type of automation is not suited to the complex horticultural environments and tasks mentioned, at least not without integration with other technology. The reason these tasks are done by hand is their complexity. They often require dexterity, strength, crop knowledge, intelligent decision making, and high speed. The unique growth of plants does not suit traditional automation techniques and robotic systems. A great example of this is the sporadic growth of grape vines.

Viticulture is a big industry globally, and particularly for New Zealand, exporting \$2.01 billion of wine in 2020 [7]. However, the industry is struggling to secure the vast number of skilled workers required to perform in-field tasks. Thousands of hectares require seasonal workers to plant, grow, prune, wrap, spray, and harvest every year. The number of workers cannot be found domestically, therefore growers rely heavily on foreign workers, typically from island nations such as Samoa, Tonga, and Vanuatu. Coupled with travelling backpackers looking for temporary work, the proportion of full time NZ based workers amounts to just under half of the total workforce in these industries [8]. Labour supply has long been an issue; however, it has been greatly exaggerated by the COVID-19 pandemic. Many vineyard tasks are dominated by manual labour, especially pruning [9].

It is well established that manual pruning work is arduous and physically demanding, as well as requiring high levels of skill. With fully autonomous solutions at least a decade away. As a result, a push for human assist has been made. Human assist is the intention is to make current labour more efficient, or easier.

1.2 Grape Vine Pruning

The most expensive manual task on vineyards is pruning. [10]; [9] The purpose of pruning is to maximise yield and allow sufficient growth for the following season. There are two main pruning styles used by New Zealand vineyards, cane pruning, and spur pruning. Cane pruning is by far the most common [11], especially for Sauvignon Blanc. Figure 1-1 shows the difference between cane and spur pruning. With cane pruning, old canes are completely cut away from the wires and replaced every year. Spur pruning has permanent cordons. A vineyard row prior to winter pruning is shown in Figure 1-2.

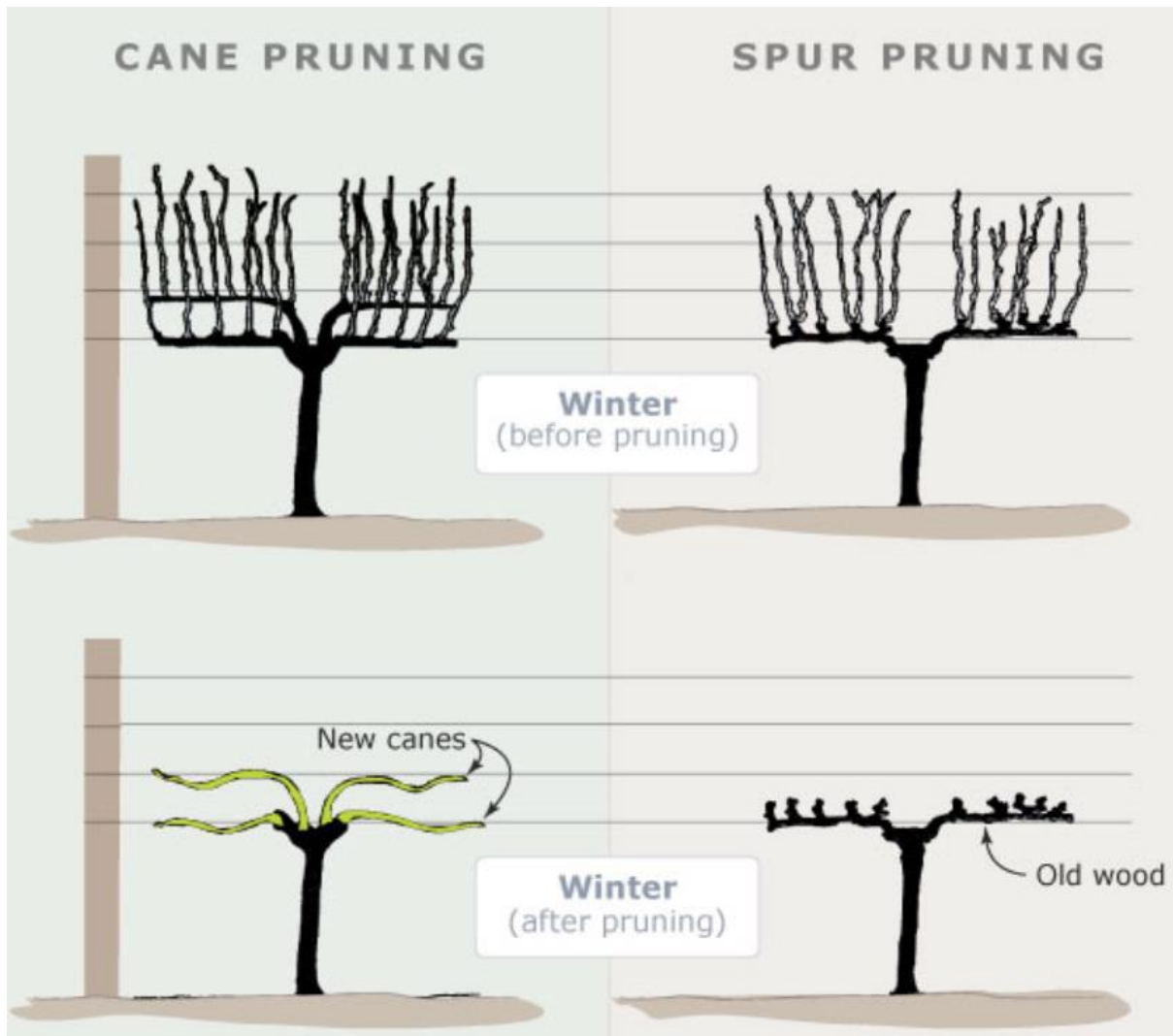


Figure 1-1 - Cane Pruning vs Spur Pruning. Image: Caroline Courtney, New Zealand on Wine

For cane pruning, growers typically aim for between two to four cane structures, depending on the crop and geographical specifics. Canes are wrapped around the guide wire from which the shoots will spawn from. The shoots that come off these canes bear the Grapes. Additionally, two renewal spurs will be left. Renewal spurs are promising, healthy shoots which are cut leaving two nodes behind, with the intention of each node producing a healthy cane close to the head for the following year. Multiple cuts are usually required to remove the canes from the wires as they are tightly wrapped around the wire and are difficult to remove by hand. Some vineyards mechanise this process with machines such as the Klima which lifts the wires out of holding slots and aggressively strips the wood from the wire. This process requires one cut on the cane close to the head of the plant, as the machine is strong enough to strip the severed caned without requiring additional cuts.

Pruning is challenging because there are several factors the pruner will consider, to provide the healthiest and most productive plant. The complexity of these decisions means that untrained pruners can often leave undesirable results which affect not only the current season's harvest, but also subsequent years. This places significant importance on pruning, causing growers to seek help in innovating solutions to assist them for the following decades in this changing landscape.



Figure 1-2 - Grape vines prior to winter pruning

Vines during the pruning period are roughly 1.8m wide, by 2.0m tall at maximum, although this varies from vineyard to vineyard. Cane pruned vines are then laid flat and wrapped around the guide wire to maintain plant structure and stability. New canes grow upwards off these where they spawn shoots containing leaves and fruit. These cordons are generally cut after one season and replaced with new ones.

Generally, the vineyard rows have a three-wire format consisting of a bottom, middle, and top wire. These are spaced approximately at 600mm, 1150mm and 1700mm respectively from the ground. The two cane levels are tied to the lower and middle wires, with the top wire being used to secure the ends of the canes and some shoots if necessary. This is important because the bearer canes are wrapped around the wire as shown in Figure 1-3. If a cut needs to be made where the two are touching, or in very close proximity, the wire can interfere. The wire must

be avoided. Currently, either the cut point is moved slightly to suit, or the person must grab the wire and pull it away to get the secateurs in to make the cut. If the wire were to be cut, it would likely damage the blade as the wire is steel. In the event of damaging the wire, it could force a tedious and expensive repair job. As well as these issues, the cut would likely not be properly executed.

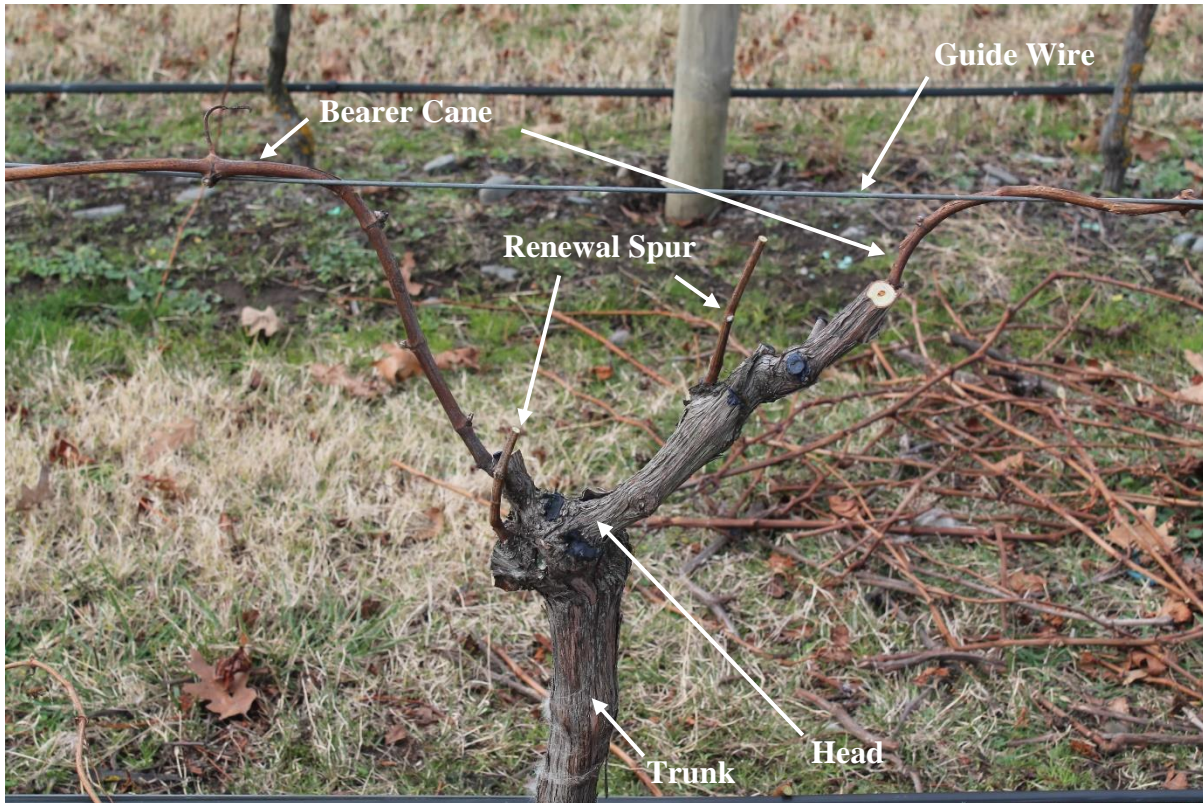


Figure 1-3 - Pruned two-cordon, bilateral vine anatomy

Currently, pruning is done using secateurs and loppers. Due to comparatively lower mechanical advantage, secateurs are typically used for cutting smaller, younger shoots. Whereas loppers would be used to cut bearer canes, which require higher cutting force. For this reason, secateurs are more common among spur-pruned structures than cane-pruned. The nature of cane pruning requires the pruner to analyse the vine holistically before making cuts. This encourages the pruner to stand back to gain a better view of the plant which favours the use of loppers over secateurs, for their extended reach. The physical nature of this work spawned mechanically operated secateurs, which are predominantly electrically powered. These offered some level of human assist, however vineyards in NZ have stated uptake of this has been minimal due to cost of the units, and the operating speed of highly skilled pruners are faster with manual versions.

1.3 Project and Design Considerations

This study is part of an MBIE funded project called Maaratech (Project code: UOAX1810) to produce human-assist and fully automated systems for cane pruning grape vines. These solutions consist of many subprocesses requiring the following things:

1. Imaging and 3D reconstruction
2. Metric extraction to analyse the plant and identify key features
3. Decision making – analysing the vine to choose optimal cut points.
4. Cut execution

This investigation focusses on 4). The scope of this investigation is focussed on the pruning end effector. To develop the pruning end-effector, the following criteria were identified as key:

- Ability to execute the cut cleanly
- Wire navigation ability
- Low size and weight
- Controllability and ease of greater system integration

The proximity of the wire to the cane has been identified as THE major challenge to performing the cut. The canes are wrapped tightly around the wire to maintain plant structure and stability.

For the autonomous system there are additional considerations as it must integrate with other hardware. This physical system will consist of a straddle vehicle, stereo camera pair, PC, 6-D.O.F UR5 manipulator and end-effector and associated control system which is integrated into the autonomous system.

1.4 Thesis Objective

The objective of this thesis is to describe the design of a novel grapevine pruning technology and evaluate its effectiveness. It will be tested in vineyards on cane-pruned structures, primarily in situations where cuts are obstructed by guide wires. This technology must benefit a human-assist approach, and a robotic end-effector in a fully autonomous system.

1.5 Thesis Outline

Chapter 2 will present a review of current literature related to mechanised pruning and relevant horticultural end-effectors. It will also discuss commercial offerings and why there is currently no solutions that improve the cane pruning process from an automation point of view.

Chapter 3 will present the development of the Barracuda and related hardware and software created.

Chapter 4 will present and discuss the methods and results from the field trials. Will discuss the evaluation of two configurations of varying constituent features to find the best overall design.

Chapter 5 will present the conclusions from the data gathered and summarise the value and connection to future work and the future system.

Chapter 2: Literature Review

2.1 Synopsis

This literature review discusses the progression of horticulture from ancient history, into the modern vineyards. It discusses how intensive, structured plants influenced mechanisation in the viticulture industry. The limitations of bulk mechanisation are presented, and reasoning for the need of selective pruning presented. Key features and processes of smart, selective systems are explained with numerous examples of research and commercial offerings. Their merits and gaps are deliberated to paint a picture of the current state of grape vine pruning and relevant technology from similar tasks. Gaps in this literature which give a silhouette of how a new grape vine technology can influence automation and human assist efforts for cane pruned grape vines by avoiding the guide wire whilst making cuts.

2.2 Literature Review

Agriculture has been one of the most influential activities that humankind has ever undertaken. It has seen many significant advances and milestones such as crop rotation by planting turnips and clover, mechanisation, use of fertiliser, and selective breeding to name but a few. Our first step was planting of plants and crops, but the next big step, was planting our crops in rows. By planting in rows, yields could be increased by turning the soil. The rows also spawned and facilitated early use of agricultural implements such as the plough, and the seed drill. The seed drill planted seeds much more precisely, at consistent depths and more control over seed drop rate. This wasted less seed and provided gave each plant a higher chance of successful growth. This arguably laid the foundation for all future mechanisation efforts in agricultural, growth consistency, and less waste. Row-based growth formats transcended vegetable crops and have also seen use in other species, namely fruit trees such as apples. In recent times, this has extended beyond just planting in rows, to controlled structuring through use of 2D or V shaped canopies as seen in Figure 2-1. These are now becoming more commonplace due to the increased yield and reduced labour costs [12].



Figure 2-1 2D Jugala apple orchard with ties holding the branches to the guide wires. Source: Fruition.net.nz, 2021

Another variation of structured environments are kiwifruit orchards, which use an overhead structure supported by wires and posts as shown in Figure 2-2.



Figure 2-2 - A young Kiwifruit orchard with visible wires which hold the plant from above the row. Source: Garcia Contracting Services

Millenia ago, plants with random growth styles became deliberately structured to reduce their disorderly nature, in particular grape vines. Trellises were used to ensure plants grew in certain places, and directions. This principle is still used to this day. Currently, Stakes are used at early life stages to ensure a straight and healthy trunk. Once the trunk has grown high enough, canes will grow from it, at which point, they are wrapped horizontally around galvanised steel guide wires to train canes them into particular structures. From this point here, growth is closely managed and controlled by pruning. This trellising is coupled with the aforementioned row format. The wires run the length of the row, supported by being stapled to large wooden posts every one or two plants. The specific layout of these trellises does vary however. Examples for spur pruned varieties include the mid wire, high wire, and Geneva Double Curtain arrangements. Mid wire configurations have the trunk grow part way up the height of a post to the first guide wire. Here, the permanent wood (Cordons) will grow horizontally either side, parallel to the row, with spurs growing into shoots vertically upwards towards the top wires. High wire configurations have the trunk grow to the top wire, with cordons growing either side parallel to the row, and spurs growing shoots vertically downwards. Geneva Double Curtain layout is a two-wire version of the high wire arrangement as shown in Figure 2-3.

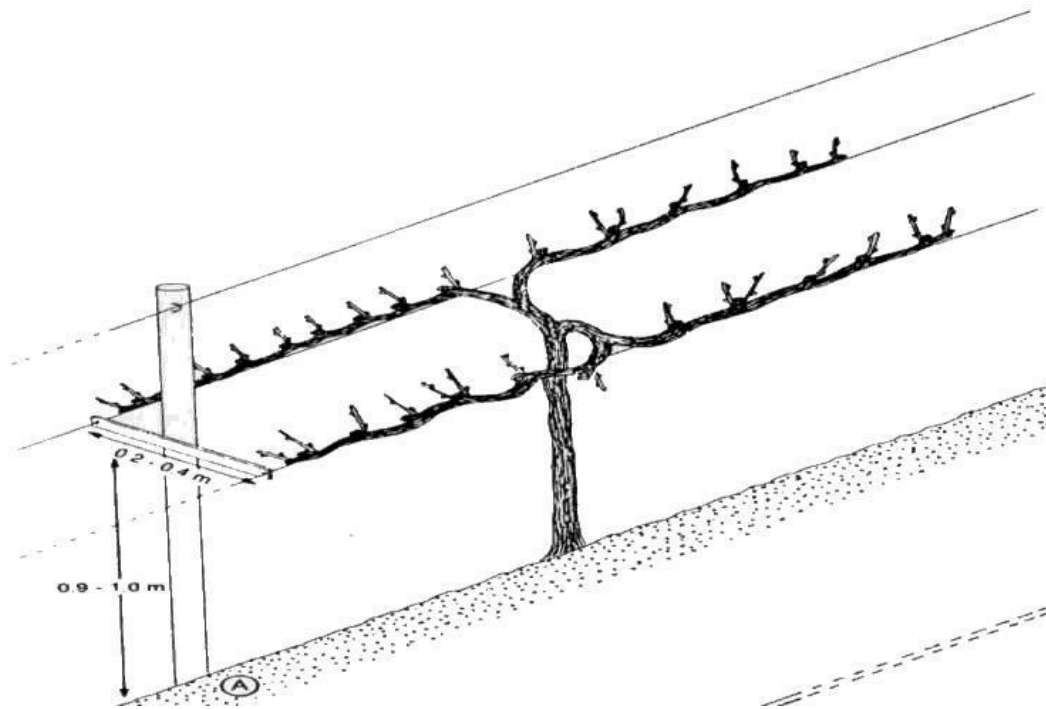


Figure 2-3 - Geneva Double Curtain layout for an individual vine. Source: Pago de Larrainzar

Cane pruned structures require the trunk to grow vertically until the first wire, where canes split off either side, growing parallel to the row and are wrapped around the wire. There can be between two and four canes laid and wrapped in this fashion. If more than two canes are laid, a second wire, around 150mm higher is used to bear subsequent canes. These canes which are wrapped are called bearer canes. Canes and shoots will then grow from the bearer canes. These steps are important to get right as each vine will typically have a productive life of between 40 – 60 years after just 3-4 years of maturing which is a long-term investment for the businesses [13].

The fundamental principle of row-based, structured growth is now used for many different crops. Particularly when grown in 2D (planar, wall like) structures, occlusion is reduced, allowing more light to fall on exposed leaf, increasing photosynthesis, and increasing fruit quality. The benefits of rows became particularly apparent in the 20th century with the introduction of the tractor. Previous use of implements was via horses, but with tractors, greater loads and speeds could be achieved. The power available from the tractor could also be used for many other tasks, such as powering towed implements. This led to the creation of many

new mechanised technologies, such as the combine harvester (Alias: Combine). These new mechanised technologies greatly increased productivity.

These bulk operation machines were designed for use with crops where growth was uniform. Uniform growth meant operations could be done at the same time, and therefore indiscriminate methods could be used. Some examples of crops which are bulk processed include wheat, rapeseed, potatoes, and carrots. Planting, fertilising, and harvesting are just some of the tasks handled in bulk. The Viticulture industry also uses bulk mechanisation of some tasks, such as vine stripping, de-leafing, and mulching. There are a variety of commercial machines out there such as the Klima wire stripper and mulcher [14], Langlois wire stripper and mulcher [15], and ERO [16]. ERO claims their product saves 30-50hrs of labour per hectare and can be used for spur pruned, and cane pruned vineyard configurations. This mechanisation is valuable to businesses with Poni et al. stating the Klima saves 35-50c per vine compared to hand-stripping [17].

The task of pruning is another goal of mechanisation and automation. Hand pruning is labour intensive and thus expensive, with Zabadal et al. claiming hand-pruning is the most labour-intensive task in a vineyard [9]. Gatti et al. found that using mechanised pruning, labour requirements could be reduced by 54-70% down to 70hrs/ha [10]. Whilst Intrieri and Poni found mechanisation can reduce labour by 50-90% [18]. Whilst these ranges vary, they are, even at their minimums of 50% and 54%, significant. Bates and Morris found that by using a Morris-Oldridge pruner, costs for Concord grapes were reduced by 56% for mechanised with hand pruning, and 80% for mechanised pruning with hand pruning and manual fruit thinning compared to purely hand pruning [19]. Their results also showed similar yields, acidity and juice colour for each of the three tests. Sims et al. found that the most intensely hand-pruned muscadine vines produced the lowest yield, compared to mechanised pruning. They also found it affected the aroma due to increased berry weight and altered pH in early years, before normalising as the plant matured [20]. There is some contention around this however, with Jenson et al stating bulk mechanised pruning reduced the yield for most varieties and that some hand pruning was still required afterwards [21]. Zabadal et al. also claim pruning severity of bulk pruners is not high enough, and that some hand pruning is required, which may impact the cost benefit [9]. Even if the yield was reduced however, the evidence cited of 50-90% reduction in labour requirement is compelling and outweighs the potential loss in yield. Although this cost benefit may only apply to larger, commercial-quantity vineyards.

For this technology to work, it is heavily reliant on the vineyard configuration. Galinato stated that two-cider apple orchards must be built around the mechanisation technology to facilitate its use and make it economically viable, the same is true for vineyards [22]. This was implicitly backed up by Poni & Tombesi et al. who claimed bulk pruning was only made possible as early as the 1970's because of the Geneva Double Curtain growing structure which is conducive to mechanisation [17].

The bulk pruning mechanisation is uses barrel pruners, which have a barrel appearance from multiple stacked blades as shown in Figure 2-4, although some use just saw blades such as the Langlois pruner in [23]. Both use a similar fundamental philosophy, cut all spurs at a certain height, and use guide arms to avoid important, but damageable objects such as posts. These methods indiscriminate in their function, cutting anything in their path. As a result, they can only be used on spur-pruned setups, where everything past the base of the spurs are cut, leaving only cordons behind. They cannot be used for cane-pruned configurations because of the selective pruning requirements and neither can pre-pruning for the same reason [24]. The comparably complex pruning requirements of cane-pruned systems means more selective solutions must be used. This transition into smart systems began in the 1980's with one of the earliest systems being Kawamura's work on harvesting tomatoes [4]. Kawamura et al. used a vehicle, camera system, 5 Degree-of Freedom (DOF) manipulator, and an end effector. Manipulators generally have prismatic joints, denoted by a P, or a revolute joint, denoted by an R, often alongside a number to represent the amount of that joint type, or as a string of characters such as RRRP. Whilst individual specifications vary, this format forms the basis of many research and commercial attempts of modern agricultural robotics tasks.



Figure 2-4 – Barrel pruning attachment on a vineyard tractor. Source: Vineyard Mates, Youtube

A smart system could be defined as one that must actively make decisions based on analysing key metrics, and be selective in operation. An example of something which may be considered smart outside of this context, but not by the prescribed definition is the ploughing and seeding robot from Amrita et al [25]. This is passive in ploughing and seeding operations, but navigation is actively guided, so is not considered smart. This is due to no active decision making based on inputs. The system used by Kawamura et al. is common because it addresses the main issues these complex challenges impose. The vision system comprises visible light cameras, sometimes individual, sometimes as a stereo pair. Other imaging techniques can include different technologies e.g. hyper-spectral, and time of flight (TOF) cameras. Captured images are then analysed with computer vision algorithms to determine and digitally reconstruct the environment, or subsets of it. This is then used for metric extraction, where the metrics are used to inform the decision-making algorithm how it should instruct the system to act. Once an action has been determined, the computer will move the manipulator to a position where an end effector can perform the relevant physical task. Each robot will use different subsystems based on the crop characteristics and task. An example of a smart system, which does not use the typical manipulator and end effector is the robot by Shivaprasad et al. They use a detection loop to determine points of interest to act upon [26]. This implies decision making which directs action. By the definition, this is a smart system.

Many of these systems require vehicles which can navigate the vineyard and orchard environments either with a driver, or autonomously. Currently, commercial orchard and vineyard vehicles are either in-row i.e. tractors, or for 2D structured environments, an over-row, straddle type such as the one in Figure 2-5. Research vehicles will usually use in-row vehicles with wheels or tracks, such as OXIN [27] for single side tasks, or over-row vehicles such as that made by Botterill et al. [28]. An uncommon vehicle choice is that of Vinium's quadruped grape vine pruner, however this is slow compared to wheeled and tracked vehicles [29]. Vehicles in smart systems use on-board electrical power from either batteries, hydraulic-electric converters, or generators to provide power for other systems. They also house the components of the system.



Figure 2-5 - Pellenc Optimum Straddle Tractors performing tasks over vineyard rows

Examples of these systems cover a broad spectrum, from the laser weeding of Verdant Robotics, to the radicchio harvester of Foglia et al. [30], [31]. Performance of these systems have been improving rapidly, with Oliveira et al. reporting a 23% increase in harvesting success rate, and an average reduction in cycle time of 43% between 2014 and 2021 [32]. This progress is important, but the future improvements are still challenging. Bac et al says to overcome these challenges, secondary systems to reduce occlusion or to increase working space are likely necessary, and that the complexities of crops give us requirements, but are often neglected [33]. Gao and Lu suggest 2D structures as another way help, as they simplify digital reconstruction,

and cut point selection [34]. This perspective indicates the crops and environments need to drive more of the design decisions. Tinoco et al agree in their review of pruning and harvesting manipulators, saying tech needs to be more crop specific as tech does not translate well between crops and tasks [35]. They also mention major challenges going forward will be in path planning and collision avoidance for example in structured environments like vineyards, but also other features on the plant. Motzki used a reconfigurable and adaptable end effector to help cope with path planning challenges and vision inaccuracies [36]. Progress with path planning challenges were also made by Yandun et al. who found using a Reinforced Learning Policy (RLP), followed by an inverse kinematics solver to be most effective for navigating towards grape vines [37].

Lapalme Agtech is an example of an early-stage commercial product used to harvest Broccoli [38]. They use vision, an off-the-shelf robotic arm, and custom end effector to cut, grab and move the vegetable head. RoboVeg is another example of a Broccoli harvesting robot. It is similar in process to Lapalme but uses part of the end effector to head occlusion, prior to the cut [39]. The end effector is shown in Figure 2-6. This is a great example of how an end effector can directly address environmental challenges without requiring secondary active systems such as that from Lapalme Agtech.



Figure 2-6 - RoboVeg Autonomous Broccoli Harvester. End effector shown on the end of the yellow manipulator

Apples are another variety which has seen harvesting automation attention. Research groups De-An et al, and Silwal et al. created apple harvesting robots [40], [41]. Silwal et al. used passive compliance in the end effector joints, enhancing grasping robustness. De-An et al. had a 77% success rate with a 15 second cycle time. This relatively low cycle time and high success was in part, due to their manipulator. It was a PRRRP configuration, which is different to the commonly used 6R configuration seen on many commercial manipulators such as the UR5. Translating this manipulator approach, it must be noted the end effector must be designed with the manipulator in mind, in order to function properly. In this situation, the passive compliance principles of Silwal et al. could provide useful if integrated. Two prominent commercial apple harvesters were developed by FF Robotics and Abundant Robotics [42], [43]. The former used a PPP manipulator with a rotational axis on the end effector to spin the apples off. The latter used a PPP manipulator with a suction-based end effector. These custom manipulators simplify the movements, reducing path planning complexity and allowing higher speeds, especially for Abundant Robotics. Another factor in the success of their manipulators, was how it worked with the end effector, not inhibiting its function, nor the end effector inhibiting the manipulator. The inclines of the systems are also a useful example of how solutions must work with the structured environments.

Harvesting research has also been done on other varieties. Foglia et al. investigated Radicchio harvesting by using a pneumatic activated which has spring-like tendencies to allow passive compliance. As a result, it was considered successful [31]. Tanigaki et al. investigated cherry harvesting with a robot using a 4 DOF manipulator and gripper to pull the peduncle of the cherry off the tree. Tanigaki et al. noted obstacle detection was challenging and that their passive system for selecting only one fruit was unreliable. They also noted a vision system prohibiting their solution due to its inaccuracy [44]. Melon harvesting was endeavoured by Edan et al. who found it challenging due to the constantly changing environment and variation from fruit to fruit. He also noted the differences between crop types preventing tech from being transferred between system, however did not comment specifically about whether this was end effector related [45]. An example of harvesting smaller fruit is found with Advanced Farm, who build a strawberry harvesting robot. Their robot uses a PPP manipulator, and a multi-process end effector. The end effector latches onto the fruit with a suction action, then grips the fruit with a tri-gripper to secure it. This helps remove occlusion from the strawberry environment and secures the fruit well once the gripper is closed [46]. Footage from the website shows the suction cup with mixed success.

Pruning research is sparse compared to harvesting [33]. According to Zhang et al. literature mostly focusses on forest trees and “green fences”, not orchard scenarios due to lack of structured growth [47], Silwal et al also share this perspective of lack of research, attributing it to the complexity of the task [41]. Current systems mostly use combination of vision, 6R manipulator, and end effectors to prune plants [48]. Zahid et al’s review. also state end effectors mostly comprised of spinning saw blades, or shear blades but they must be compact for manipulation purposes and produce clean cuts to minimise plant damage and disease propagation. Some papers such as those by Kawasaki, Ueki, and Soni, present a view of pruning from outside the orchard structures [49], [50], [51]. Their work revolves around climbing robots, powered vehicles that climb vertically up trees, before pruning unwanted branches. This seems abstract to consider, but provides inspiration for pruning cases where for instance, canes wrapped around a grapevine wire must be cut. Their principle of climbing could potentially ‘climb’ horizontally along the wire in vineyard, from which canes could be cut. The improved grip system devised by Soni et al could be useful if cutting continuously when travelling along the wire to maintain good contact.

Strisciuglio et al. developed a garden pruning robot for autonomously maintaining gardens [52]. The environment they have designed it to work in has minimal occlusion and collision potential they have been able to use more bulk style pruners, with multiple fitted depending on the pruning style required. This robot has minimal transferrable usefulness however due to it not being able to cope with more challenging environments. But does highlight how leveraging your specific environment can provide opportunity for more bulk style pruning. Zahid et al. discussed the manoeuvring of a pruner whilst avoiding collisions for apple trees [53]. They used secateurs on a UR5 manipulator, noting the importance of orientation of the end effector, but also how the end effector and manipulator can cause collisions to not prevent cuts being made. This is very reminiscent of a vineyards challenge of pruning grapevines wrapped around a wire. From the same project, they determined the end effector must be task specific, and that building flexibility into the end effector rather than flexibility of the manipulator to achieve good results [54]. Their system configuration was discussed in another paper, where they used a 3P manipulator with a 3R end effector. Issues of note were that to get to certain cut positions, the pose of the end effector may have to be angled. This causes a reduced working area between the blades which is undesirable. This stresses the importance of being able to make cuts where

necessary and the end effector must be able to cope with obstructions in order to do this effectively. These specific and collision prone positions also put high accuracy of the vision system, where small errors can mean missed cuts [55]. The aforementioned papers by Zahid et al. present some important findings for pruning apple trees, but also for similar tasks such as grape vine pruning. The only absent exploration from their analysis was that of more structured environments such as those found in 2d orchards and vineyards, where supporting wires present collision opportunities. This is somewhat critical as He and Schupp insist that using thoughtfully arranged growing structures is key to the success of automating orchard production through their review of apple tree pruning [56]. They state introducing the intensive structures help by simplifying this challenging task, but note it is still challenging. In their review they also discuss how fixed cutter end effectors put high spatial specificity requirements on the system, at the best of times, creating complex manipulation routines to gain access. At the worst of times, preventing cuts entirely. From this they determined end effector development is equally important as tree architecture.

Other varieties are also challenging, such as cherry tree pruning. You et al. listed their challenges for their Cherry pruning robot coming from complexity in seeing the entire plant first, sporadic branch arrangement, manipulation accuracy and collision avoidance [57]. Their system used a Red, Blue, Green, Depth (RGB-D) camera and simple pruning rules, with a UR5 and bypass secateurs end effector. This yielded a 58% success rate. Their efforts are however, not reflective of the full difficulty as the cut points were selected to remove edge cases and complex scenarios, particularly around the guide.

Zhang et al. had an 85.16% success rate for Jujube pruning using an RPRRR manipulator with a bypass secateurs end effector. Their end effector integrated a trigger sensor to help guide the manipulator [47]. Other fruit trees with small branch diameters and unstructured growth were attempted to be pruned, and pulverised, by Huang et al. who built a custom end effector which was tested on Loquat plants. They noted its large size and weight to be an issue with navigation despite being within the manipulator's load capacity [58].

Grapevine pruning presents a number of the same challenges as many of these other pruning examples, yet the common difference is most of the aforementioned pruning examples lack the intensive growing structures. Vineyards make extensive use of these growing structures to manage the vines. These structures provide an elevated amount of access to certain cut points

compared to 3D, or unstructured growth, but present their own challenges. Chiefly, the wires which canes are wrapped around in cane pruned vines, as they must not be cut, but cuts must be made around them. This task is made considerably easier with spur pruned varieties. Vision Robotics showed success with an early commercial prototype of a fully autonomous spur pruner [59]. Their video shows successful cuts being made, and no apparent issues arising from occlusion, or wire interference. The system was not fast, but leads with success and in showing the direction the technology will follow in the future.

Silwal et al. also developed an autonomous vine pruning robot [41]. They used a 3D digital reconstruction from stereo images, a UR5, mounted on a prismatic axis (P6R manipulator) with a compact, custom bypass shears manipulator. Their tests were conducted on pre-pruned (By an OXBO V-Mech bulk pre-pruner) and proved a successful system, with pruning from 1 side taking 137 seconds, but missed 32% of cut points. By cutting from both sides, these cuts were made, but total vine pruning time increased to 213 seconds, slow compared to manual pruning, however proved capable overall. This system was used on spur-pruned structures however. This meant no wire was obstructing cuts, as was the case with Vision Robotics machine. The lack of discussion around the growing structure means it would not be transferrable to cane pruned configurations as they presented no method to alleviate the issue.

For cane pruned systems, the most progress was made by Botterill et al. with their autonomous pruning platform [28]. It consisted of cameras, a UR5 manipulator, and end mill end effector. Their system could detect canes, make cut point decisions, and manoeuvre the manipulator into position. From field trials, they could prune an entire vine in 2 minutes. Their end effector however, struggled. The end mill struggled to cut canes, often pushing them away. It also required additional path planning to enact a sweeping movement to move the cutter through the cane. They did not address the issue of wire interference in their analysis. This limited their overall success rate, and stressed the importance of designing a system around an end effector, as much as it is often the other way around. As a result of this, they would use a secateurs-based end effector in future. A potential solution to this could be an additional feature to resist cane deflection when being cut. Zhang et al. make a similar suggestion from their review, suggesting pruning mechanisms would often benefit from an integrated gripper to assist [60]. They could also reduce the path planning complexity by integrate the cutting sweep movement into a dedicated end effector mechanism. This would contain the movement of the end mill to the end effector only, making movements of the entire arm superfluous.

This notion of placing the manipulator in position and then containing the final movements to the end effector is also present in other pruning literature. Molina and Hirai simulated a drone based pruning solution for high up, access limited tree branches [61]. The drone integrated a pair of jaws to act as a gripper, latching on to a branch. The gripping area, when viewed in 2D was designed to be larger than branches it intended to cut. This meant there was a small reduction in flying accuracy required. Once the drone had the branch within this region, it would close its gripper. This is similar in principle to the suggestion for the Botterill-type system, and that of Zhang et al, where the final movement is made by the end effector, where its motion is constrained. Once in this position, the cutter could engage to prune the branch. This was field tested in their second paper [62]. The results showed it working, however it took 8 minutes per branch to prune. A potential drawback of this design, is how well it operates under partially, or fully obstructed scenarios due to the working space requirement of the gripper. This was not tested in the trials described.

2.3 Potential Pruning Methods

2.3.1. End Mill

Previous testing by Botterill et al. concluded this was unsuccessful. Would require a separate, sturdy arm to hold the branch in place. Other cons include needing to be extremely accurate to avoid wire and other objects, leaves a rough edge on vine which may damage the remaining end. The end mill is also more exposed than other options, which could pose a safety risk.

2.3.2. Laser Cutting

The laser cutter has two major strengths: accuracy, & the ability to set the power level between that needed to cut the vine and the wire. The wire requires significantly more power from the laser to cut, whilst the wood is much lower. This means the power level could be set above that required to cut wood, cutting the vine, but simply pass straight over the wire. The laser creates a health and safety risk however, due to the exposure, radiation and potential to impact more than just the cane, especially if the robotic arm were to behave erratically. It also poses a fire hazard. The laser would likely be slower than other methods too based on the cut time for other, easier to cut wood. It may also permanently damage the vine, which would not be an issue for old, dead cane, but for Renewal Spurs this would be counterproductive. This is not confirmed, however.

A laser cutter was predicted to be expensive (Even DIY/cheap MDF laser cutters cost in the order of \$10,000 NZD) and therefore not easily prototyped/tested without making a substantial financial outlay. Due to the large gas tubes and mirrors required, would not fit onto an end effector. A laser this powerful also presents significant safety and fire risk. These were the two major shortcomings, however.

2.3.3. Waterjet Cutting

Water jet cutting is like laser cutting in that it follows a path with a beam to cut the material. The beam uses extremely high-pressure water (~50,000 PSI), with a garnet to cut the material. This process allows it to cut a very wide range of materials even compared to laser cutting. Water jet cutting has been used by Lapalme Agtech in their SAMI 4.0 robotic Broccoli harvester.

The ability to cut a wide range of materials would allow easy cutting of the cane, but unfortunately also the wire. In addition to this, pumps and storage tanks would be required in

addition to the end effector which would be impractical due to the greater system restraints such as availability of space on the test platform and limited energy supply from the batteries. The lack of material discrimination of water jet cutting poses a substantial safety risk to surroundings and people considering the potential of path planning errors creating unpredictable movements.

2.3.4. Shears/Secateurs

Shears/Secateurs are the tried and tested method of cutting vines, it leaves a clean edge, has good control and dexterity. They are traditionally manually operated; powered secateurs are becoming more commonplace as prices drop. There are also multiple methods of powering them. However, this solution would require an additional solution to separate the wire and cane or enable cutting with the wire present. Secateurs being commonplace indicates they are a reliable technology and availability would offer prototyping benefits. The simplicity of an electric motor (Which powers electrically driven versions) meant easier integration into the greater Maaratech system through its controllability and shared power system. Whilst the strength of cutting and sharp blade poses a safety risk, the small size of the blade means the dangerous region is minimised.

2.3.5. Crushing

Crushing is simplistic in nature and relatively easy to implement, however causes significant damage to the cane. A clean cut is required for renewal spurs, as a result, crushing was ruled out.

2.3.6. Selection

Based on these characteristics, the end mill was eliminated due to potential of wire damage. Laser cutting was eliminated due to high prototyping costs and significant safety concerns. Water jet cutting also posed safety risks, and due to the proprietary required water storage, pumps and garnet supply was eliminated. As crushing was also eliminated, secateurs were the only plausible option. This decision was reinforced by the development of the Barracuda.

2.4 Cutting Forces

Research around cutting forces for a standard secateurs blade is sparse, however some figures from [63] indicate peak forces, for the toughest grape vine species tested, was 1397.6N and the

lowest, 981.65N. Their testing included samples from 4-10mm in diameter. These values were obtained with double-shear apparatus, not a secateurs blade. Because of the double shear, assuming both shear planes are equal in area, these values can be halved to give, 698.80N and 490.83N. They do not specify the diameters at which these values were obtained however it has been assumed these were the maximum values in their described range, 10mm.

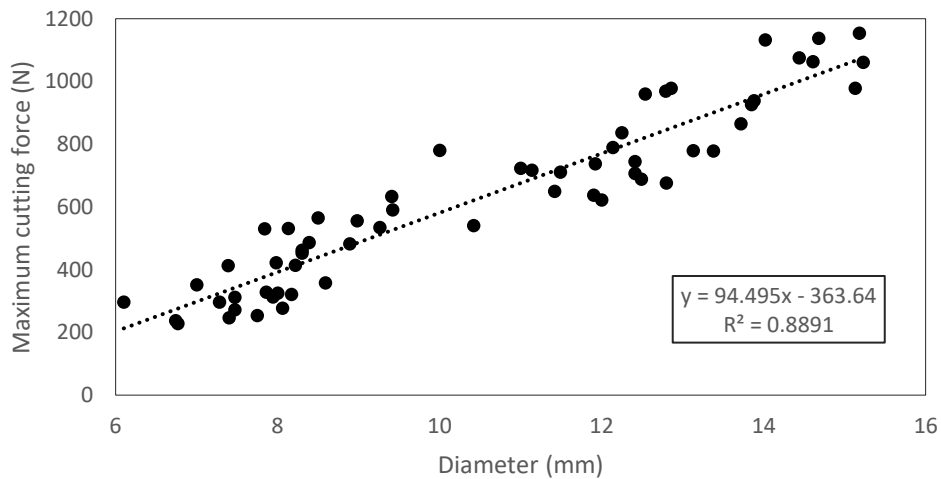


Figure 2-7 - Cutting forces for grapevines

Empirical data on maximum cutting force was taken for 60 cuts. Maximum cutting force was graphed against cane diameter. As seen in Figure 2-7, there was a linear relationship between the diameter and cutting force with an R^2 value of 0.8891. Whilst the relationship is clearly linear, the R^2 value indicates reasonable spread in the data. By using the straight-line equation to predict the cut force at each of the diameters, and measuring the difference as a percentage of the cane's cut force to find an error value. The absolute error values are shown in Figure 2-8.

The errors were hypothesised to be due to the non-roundness of the canes, and the single diameter measurement. This is discussed further in Section 4.4. Other variables such as moisture content could be a cause, however more research is required. These values do however correlate to the findings of [63]. For a 10mm diameter cane, it can be expected, based on the straight-line equation from Figure 2-7, to require a cutting force of 581N. This sits approximately halfway between the 698.8N and 490.83N from their findings.

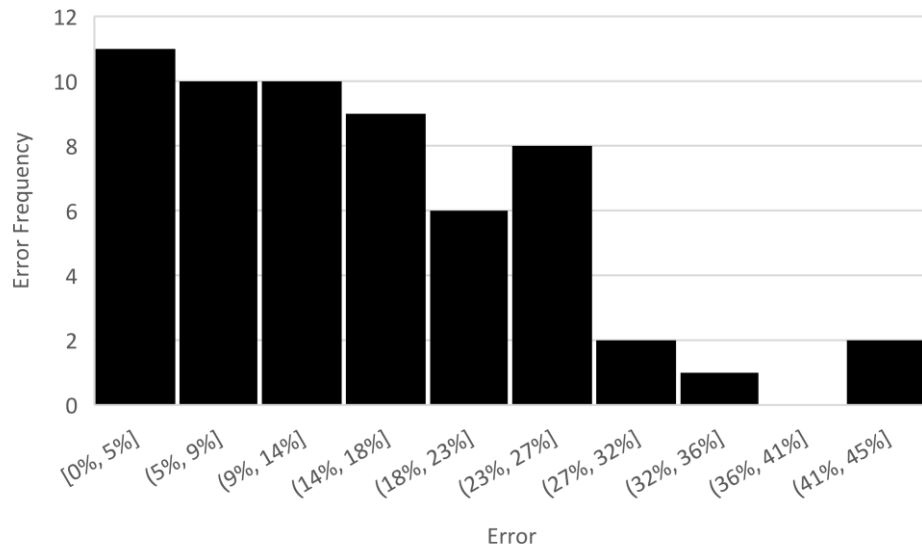


Figure 2-8 - Cut force error distribution

Commercially available electric secateurs claim peak blade axis torques of between 80Nm-300Nm. If taking the approximate maximum value of 1400N at 40mm (0.040m), an approximate cutting distance of common shears, a torque value of 56Nm is obtained which indicate commercial offerings can easily cope with these forces. Zahid et al. stated these cutting torques can vary however, due to the angle of cutting, and that cutting perpendicular to the axis of the branch is preferable to keeping torques low [28].

2.5 Diameter and Roundness of Canes

Data was collected to document the level of roundness of a cane at 3 points along its central axis between nodes. 20 diameter measurements were taken with Vernier callipers at each point. Data was collected on various shoot and cane sizes. The smallest non-tendrill shoot had an average diameter of 6.5mm, and the largest cane, an average of 16.5mm. Figure 2-9 shows the frequency of error, of a cane's maximum difference in diameter, to its average diameter. The graph shows all canes and shoots showed eccentricities between 12% and 34% with the most frequently occurring errors between 12% and 18%.

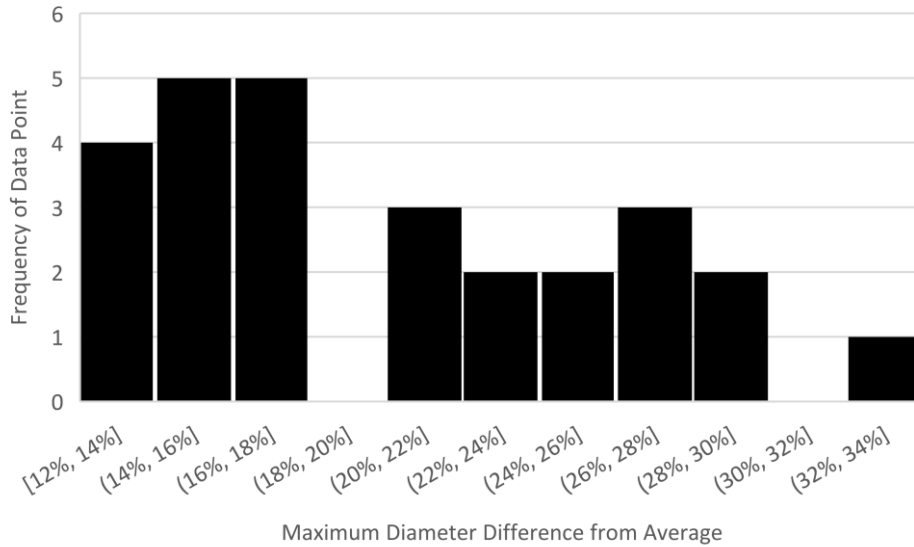


Figure 2-9 – Maximum difference in diameter of canes compared to their average diameter

2.6 Current Industry Pruning Methods

Currently the most widely used method of pruning is to use secateurs, mostly human operated, however electrically actuated secateurs have become more common as prices have come down. This is due to them being faster, less required effort, increasing financial feasibility, as well as reducing Repetitive Strain Injuries (RSI) compared to hand actuated versions. Pneumatically actuated secateurs also exist, but are less common, mostly due to inconvenience of requiring a portable air supply, however they generally offer higher cutting forces. Experienced workers will generally opt for hand-operated secateurs and loppers. To get around the wire, they rely on technique, gripping the cane with the blade, pulling it away then making the rest of the cut. Less skilled pruners will rely on forcing the cane and wire apart by putting the lopper blades between them. Both instances are physically demanding, and particularly the latter, can be slow. Romano et al. agree with this, stating that strain on the human hand is high for manually operated pruning situations, even with the mechanical advantage [64].

2.7 Summary

The literature showed there are large incentives to automate production of vineyards. Bulk mechanisation has provided cost benefits through the use of pre-pruners and vine strippers. This technology does not assist cane-pruned vineyards however. Their complex, non-uniform pruning requirements require a selective approach where individual vines are analysed, and appropriate cuts made. This is a challenging process. The marriage between vision systems,

metric extraction, decision making, path planning and cut execution must be robust, and well-integrated. Literature was sparsely published on pruning, likely a reflection of the challenge. This was especially true for grape vine pruning. Random vine architecture, complex decision making and tight spaces for cut poses are contributing factors to this challenge. Such a marriage has been achieved with machines designed for spur pruned vines, but not cane pruned vines. Why not exclusively grow spur pruned vineyards? Many varieties and regions prefer cane pruned configurations, such as Sauvignon Blanc, New Zealand's most popularly grown variety.

A common theme was identified in the literature. All pruning was done with minimally structured plants, 3D plants. Harvesting had some examples in intensive structures, however the harvested fruit was away from the wires and posts where it would not obstruct the end effector. Other research used sanitised, simplified scenarios which are not representative of the true difficulty. Intensive growing structures with guide wires were largely not present. Yet they are central to vineyards and reviews indicate the path most conducive to automation will, require carefully managed tree architecture, predominantly using wires alongside development of end effectors.

Unfortunately, end effectors were often treated as after thoughts, dependant on the rest of the system, not *influential* on the rest of the system. However, literature clearly shows the best performing end effectors, and often most effective overall systems, have put considerable thought into the integration of the end effector, and its effect on other sub-systems. It also shows they must be designed specifically for the task at hand, and whose performance may benefit from the introduction of secondary mechanisms. An analysis of various technologies which could be used for cutting canes found secateurs most favourable. Unfortunately, many cuts cannot be made by secateurs as the canes are wrapped around guide wires.

By culminating these findings, the following question arises:

How can a grape vine pruning technology be designed for secateurs to simply address the obstruction of the guide wire, cut canes cleanly, reduce physical fatigue for manual pruning, and enhance opportunities for the rest of an autonomous machine as an end effector?

Chapter 3: Development of Barracuda

This chapter presents the development of a novel grape vine pruning mechanism. Section 3.1 describes the principle of operation of the proposed design. Section 3.2 outlines the initial prototyping and development phase of integrating the technology into the modified anvil. For the end-effector version, custom electronics and software was required to operate. Section 3.3 details this phase of development.

3.1 Barracuda

The design of a novel anvil for grape vine pruning is shown in Figure 3-1.

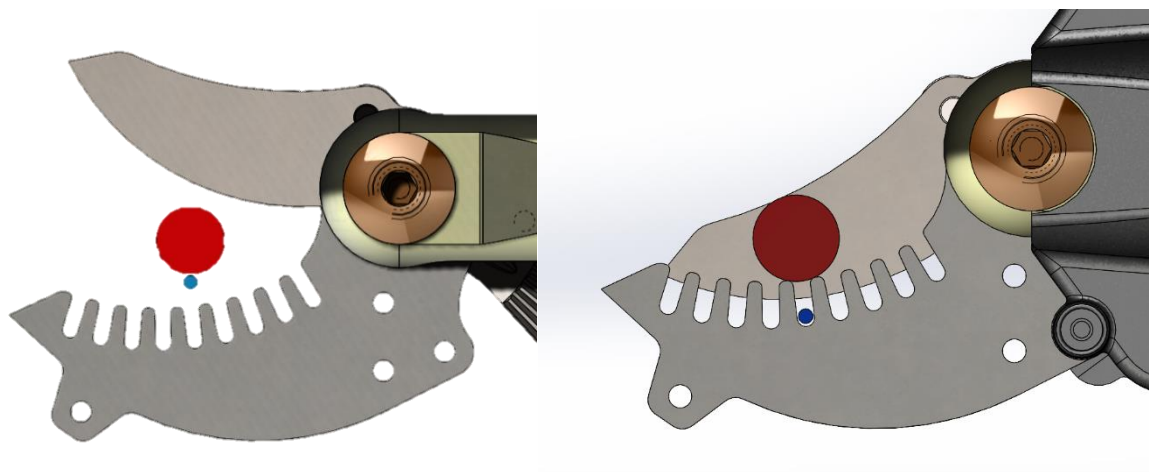


Figure 3-1 - Operating principle of the Barracuda. The wire is shown in blue, and the cane in red.

The name is derived from the aesthetic of the technology resembling that of the teeth of a Barracuda fish. The Barracuda's function is to allow cuts to be made without the need to separate the cane from the wire. 2.5mm diameter wire was commonly used in vineyards. Average diameters of shoots and canes discussed in Section 2.5 were between 6.5mm and 19mm in diameter. This considerable difference in diameters between wire and cane provided an exploitable trait. This was the driving factor behind the design of the Barracuda profile.

During a cut, the smaller wire is pushed into the recesses between teeth, whilst the thicker cane cannot fit in these slender gaps, forcing it to remain on the top of the teeth where the blade cuts it. The recesses allow the wire to remain out of the way of the blade, protecting it from being cut or damaged. This invention is of great benefit in cane pruning as wire damage is very common and the cutting of canes around the wire, very difficult. Such a simple solution that can impact both challenges, provides cost benefits in implementation, reduced complexity of other system components, and reduced damage to the growing structure. These attributes

directly address the question outlined in the summary of section 2.7. To test the principle and gain some basic understanding of how the technology performs in actual cane-wire situations, prototype profiles were made.

3.2 Development of Anvil

3.2.1. Tooth Profile

For the anvil to work properly, some optimisation was required. To evaluate unknown performance characteristics, simple prototypes with different teeth and recess profiles were created. They were created by laser cutting 4 mm mild steel with various teeth profiles and were integrated with a handle to function like standard manually operated secateurs.

Descriptors for these profiles are illustrated in Figure 3-2. A cutting edge was ground onto the upper blade with a grinder. Five different anvil shapes were produced as shown in Figure 3-3. shows a schematic of the tooth profiles with the different features labelled. The parameters for the five anvil shapes are summarised in Table 3-1.

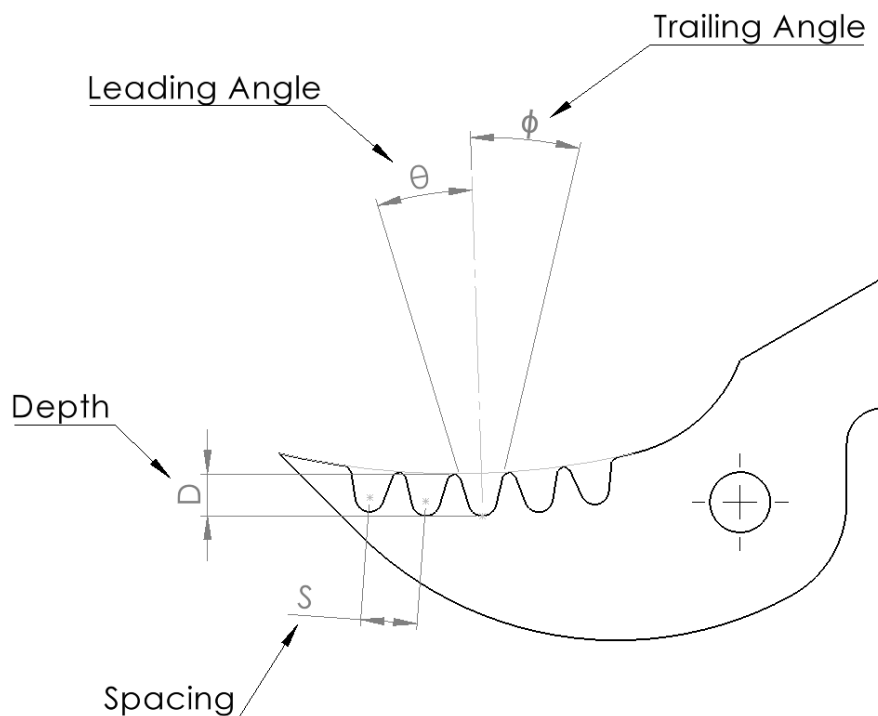


Figure 3-2 - Characteristics of the dirty prototype anvils



Figure 3-3 - The five Barracuda dirty prototypes labelled 1-5

Table 3-1 - Dirty prototype anvil configurations and characteristics

Shape ID	θ	ϕ	D	S
1	0	0	6	6.4
2	5	5	6	7
3	45	0	6	10
4	15	15	6	8
5	0	45	6	10

The configurations were tested with a lab grape vine structure as shown in Figure 3-4, and with the blade on canes with a 3mm diameter screwdriver to simulate the wire as pictured in Figure 3-5.



Figure 3-4 - Testing the Barracuda tooth profiles

Table 3-2 shows the results of testing these shapes and the following passages detail why they scored as such:

Table 3-2. Performance of dirty prototype anvils. Higher numbers are better.

Shape Tested	Cut Effectiveness	Wire Trap/Release	Wire Avoidance	Gouge Reduction	Total
Shape 1	5	4	5	3	17
Shape 2	4	4	3	2	13
Shape 3	2	1	1	2	6
Shape 4	4	4	2	2	12
Shape 5	2	5	1	2	10

Shape 1 was quite effective with the wire being pushed down into adjacent recesses when it was on the sides and even when it was slightly on top for the thin cane. The smaller spacing meant if it got pushed to the side it easily slipped into an adjacent recess rather than getting caught in the same one. The small opening size due to parallel, vertical sides meant even the small shoot size didn't fall far into the recess, therefore not evading the blade's cutting range. The only downside for this design is the pointy teeth tips heavily gouged the large cane size, it did show the least gouging of all configurations, however.

Shapes 2 and 4 scored well, however the larger opening caused the small shoots to sit lower in the teeth which bordered the cut range limit. This allowed them to partially evade the blade. Their shape also meant the teeth were pointier than shape 1 and gouged the large cane even

more. The increased spacing still worked well to deflect the wire into adjacent recess however it was predicted to get stuck for shape 4 due to the large 30° opening with smaller canes.

Shape 5's strongly angled inlet meant the cane and wire were caught easily as shown in Figure 3-5. If going in with higher speed, it often separated the cane and wire into separate recesses. This shape gouged the larger cane less than shape 3; the blade shape pushed the cane forwards slightly, therefore for this shape, away from the teeth, reducing the gouging. One notable drawback is that due to the large opening, the wire got stuck at the top of the recess next to the cane, trapped. This would mean the cane was not cut properly and the wire would take the force.

Shape 3 scored lowest. It didn't allow the wire easily in or out due to the tooth direction, suffered the same issue as shape 5 where the wire would get stuck on the top side as demonstrated in Figure 3-5 (Note this image is of shape 5 but shape 3 suffered the same disadvantage). The major issue was the significant gouging of the larger cane. As the blade shape pushes the cane forward slightly, it pushes it directly into the tooth's point, gauging the cane an estimated 4-5mm deep, further than the blade cut range. Scoring low on all criteria in Table 3-2, shape 3 was eliminated.

Shape 5 showed promise with ease of wire trapping and releasing. Shape 2 and 4 did not offer any advantages over shape 1 but had less effective wire avoidance. For these reasons shape 1 scored the highest in Table 3-2 and was selected for further development.



Figure 3-5 – Figures show the two main issues with shape 5

3.2.2. Anvil strength

The Barracuda was designed to withstand the 150 Nm of output torque from the Arvipo secateurs without experiencing plastic deformation. The design would meet this requirement, the loading scenario was analysed at each tooth based on the applied maximum torque. As the recesses have a round bottom region, they act as stress concentrators. As they are located at the edge of the plate, a stress concentration factor of between 1.5 and 1.18 was most representative of the Barracuda stress concentration, depending on the geometry at the given tooth based on the method shown in . This loading was back calculated to find a cross sectional area capable of withstanding the load for mild steel. As the material was a uniform thickness of 4.75mm, the height would be found at each tooth. By marking these required cross-sectional anvil heights below each tooth, a profile of the Barracuda could be built up as seen in Figure 3-7.

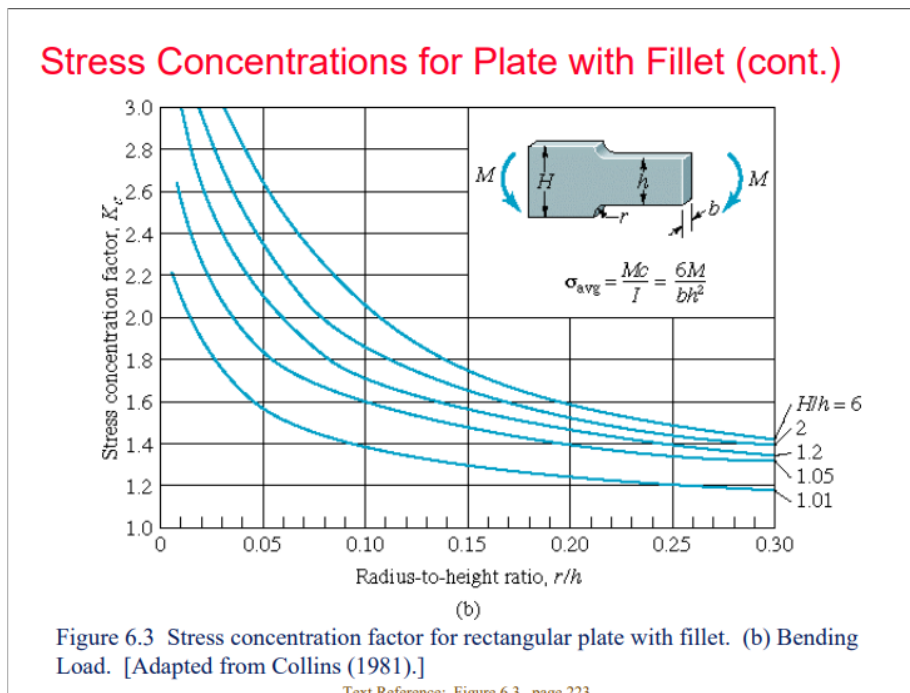


Figure 3-6 - Stress concentration method used to account for recesses in the Barracuda Anvil

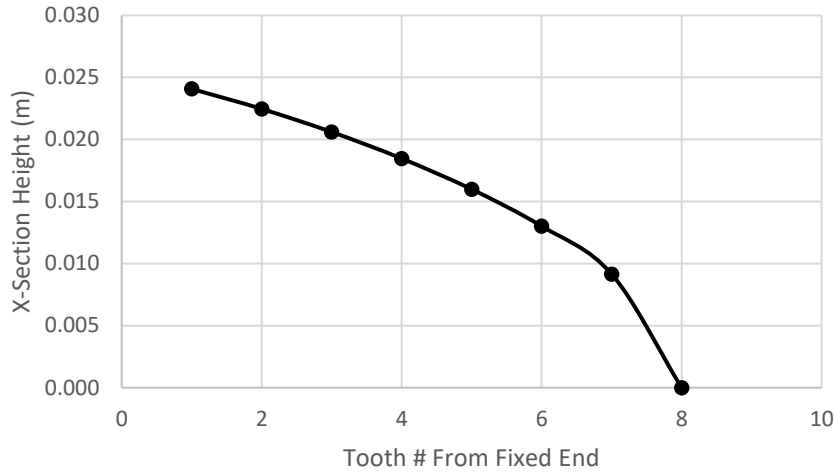


Figure 3-7 - Thickness (Height) of Barracuda not including teeth height

The profile was then analysed using FEA in Solidworks to ensure it would cope with the loading scenario as shown in Figure 3-8 - FEA loading analysis showing stress distribution.

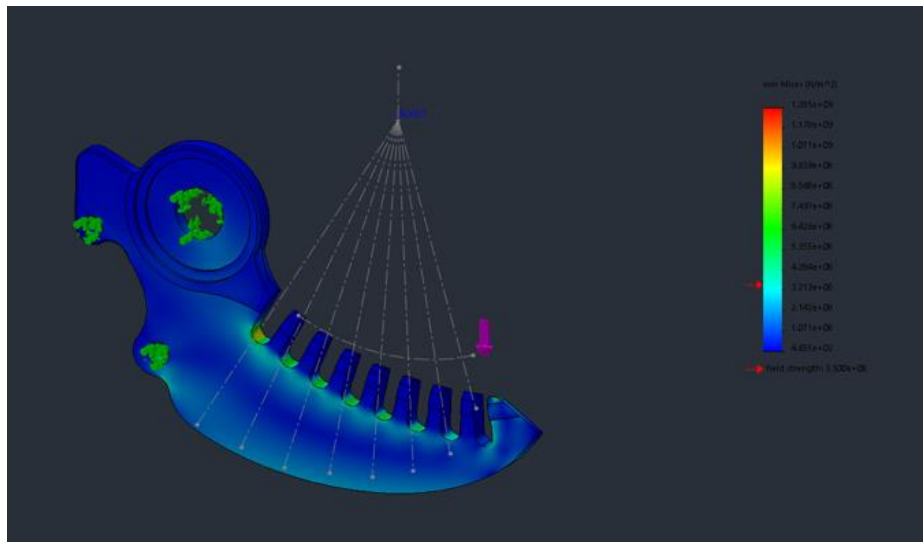


Figure 3-8 - FEA loading analysis showing stress distribution

3.2.3. Integration of Modified parts into Electric Secateurs

A pair of Arvipo EC40 Electric Secateurs were purchased as a platform from which modifications and testing of the Barracuda could be done. The secateurs feature an electric DC brushed motor, planetary gearbox, and bevel gear final drive reduction. To install the Barracuda modification, the unit was deconstructed, and the original anvil measured to so the Barracuda version would fit well.

As the Barracuda is replacing the stock anvil, it needed to include the base section consisting of mounting screws holes, bearing and O-ring faces, and positioning contours. As this needed to replicate the original as close as possible to fit well and function correctly. 3D scans shown in Figure 3-9, were taken with a Shining 3D Einscan Pro 2x, and Vernier callipers were used to accurately measure and recreate these areas in Solidworks. These designs were then 3D printed on a Markforged Mark Two from a carbon fibre and nylon material, Onyx (Figure 3-10). The main reason for using this material was its accuracy. These were tested, modified, and re-printed until a tool-less fitment, with no play was achieved. Next, a mild steel version was created on a CNC mill (Figure 3-11).



Figure 3-9 - Stock Anvil 3D Scan Point Cloud and isolated original

For machining purposes, the design included holes (Figure 3-11, bottom right) to screw the blank down to reduce deflection and chatter during machining. The parts for Config 1 and 2 were machined on a CNC mill for accuracy from Mild Steel. The spacing plate and second row of teeth for Config 2 were laser cut as they did not require location fits or bearing faces.



Figure 3-10 - Onyx 3D printed anvil for test fitting



Figure 3-11 - CNC machined anvil for Configuration 1 with additional machining stability holes

A secondary benefit of the twin rows of teeth, is the 3-point bend scenario reduces dependence on the shearing action, already reduced from not using a bypass system, such as the second blade edge found on the original secateurs. This elimination of the shearing face means a symmetrical blade could be used. A symmetrical profile as shown in Figure 3-12 would allow it to pass the teeth tips with a considerably reduced chance of collision, reducing blade damage.

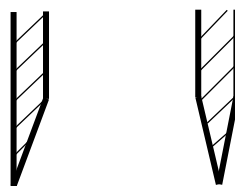


Figure 3-12 - Standard asymmetrical blade profile (Shown left), and symmetrical blade profile (Shown right)

Config 2 with machined anvil and laser cut spacer and second row of teeth fully assembled into the Arvipo electric secateurs handpiece shown in Figure 3-13.



Figure 3-13 - Configuration 2 attached to Arvipo electric secateurs

Config 2 was machined in the same fashion as Config 1 for the primary piece, however the spacer and 2nd row of teeth were laser cut from the same steel. This was cheaper than machining, but still suitable as it did not require smooth and accurately bearing faces.

One negative consequence of using double teeth rows is working angle. Working angle is the angle between the wire and the recesses axis when viewed from top of the teeth. Using a single row of teeth with 4mm wide recesses and flat teeth tops (Config 1, which will be mentioned in Chapter 4), a maximum working angle of 16.0° is obtained. If using a double row configuration, this angle drops to just 1.8° for the wire to be fully inside the recesses. Config 2 (Introduced in Chapter 4) has rounded teeth tips. By using the rounded tips, the initial contact angle increases to a maximum of 22.8° before it sits directly on top. At this point the blade would just crush the wire rather than push it into the recesses due to the normal force direction being vertical. In this situation, to smoothly allow the wire to be guided down, the end effector must be able to yaw by the difference in these angles at minimum. Using the geometry of Config 2, this would be 21.0° minimum. This analysis does not include frictional effects however, which further reduce the working angle.

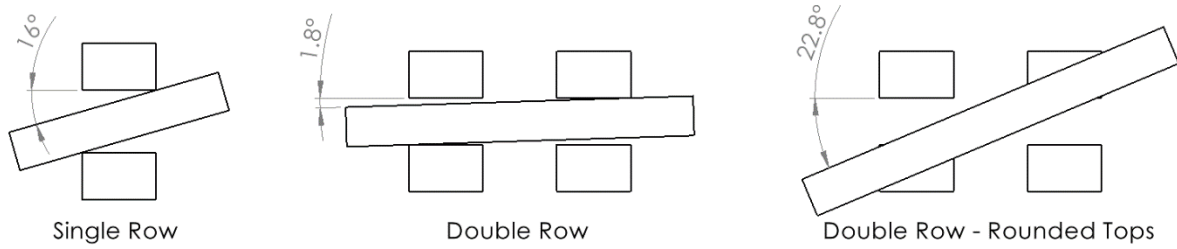


Figure 3-14 - Wire alignment for various configurations viewed from the top of the teeth. Left to right: single row of teeth, double row with flat tooth tops, double row with rounded tooth tops.

Using a simplified 2D analysis, based on the free body diagram for Figure 3-15 this can be further evaluated. This assumes the wire is parallel with the tooth top fillet axis.

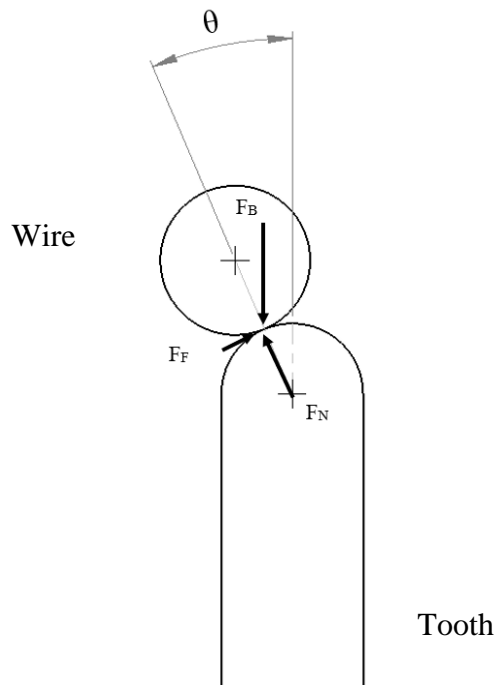


Figure 3-15 - Free-Body -Diagram of wire and tooth interaction to find limits of proper function

From Figure 3-15 we can deduce the following equations:

$$F_N = F_B \cos \theta \quad 3-1$$

$$F_F = \mu F_B \cos \theta \quad 3-2$$

The component of F_B opposing F_F is given by the term F_P , where F_P is:

$$F_P = F_B \sin \theta \quad 3-3$$

By setting F_F equal to F_P , we get:

$$\mu F_B \cos \theta = F_B \sin \theta \quad 3-4$$

Which simplifies to:

$$\theta = \tan^{-1} \mu \quad 3-5$$

Substituting μ for 0.423 (Coefficient of friction for galvanised steel on mild steel, [65]) we get an angle of 22.9° . This is the equilibrium angle. Beyond this angle the wire will be pushed into the recesses. This contact point was marked in Solidworks, where a wire at an angle was matched to it. The resulting position was a reduction of 1.05mm inwards from each side. The resulting maximum angle the wire can achieve then becomes 15.3° . By subtracting the 1.8° we get 13.5° of maximum angular displacement from parallel to the recess axis.

3.3 Integration with automated system

As seen in **Error! Reference source not found.**, the full system for this project was to consist of a moving vehicle that straddles a vine row with a UR5 robot arm mounted to it. The end effector and camera array were to both be mounted to the UR5. The design was not to integrate the cameras at this stage however, as the specific camera setup was not finalised. The relationships in **Error! Reference source not found.** describe how these parts interact.

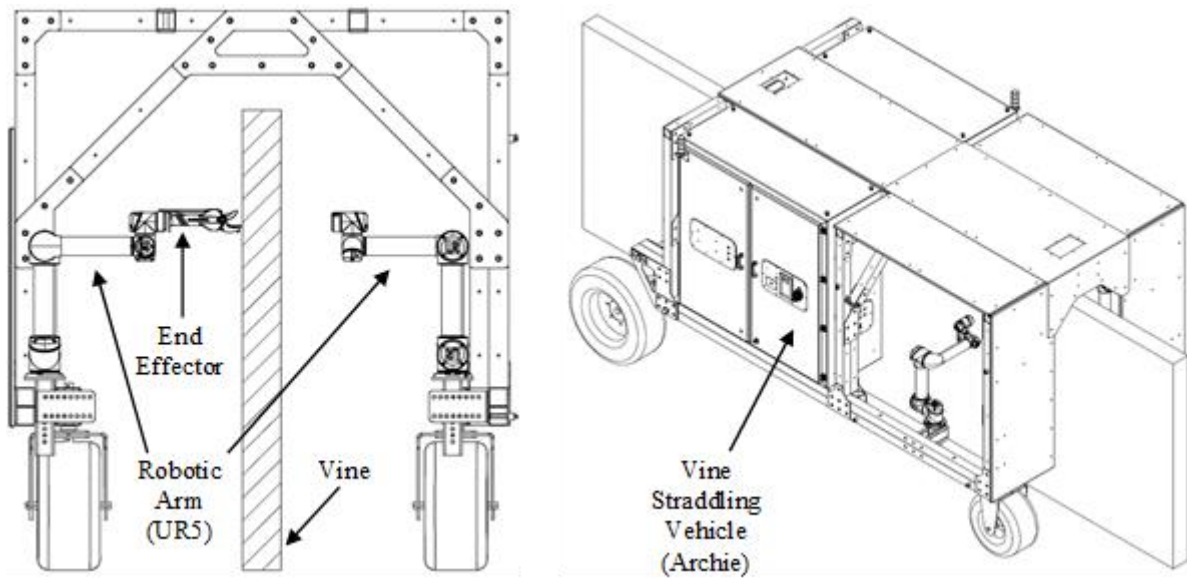


Figure 3-16 - Overall system setup consisting of the straddle vehicle (Archie), manipulator, and end effector

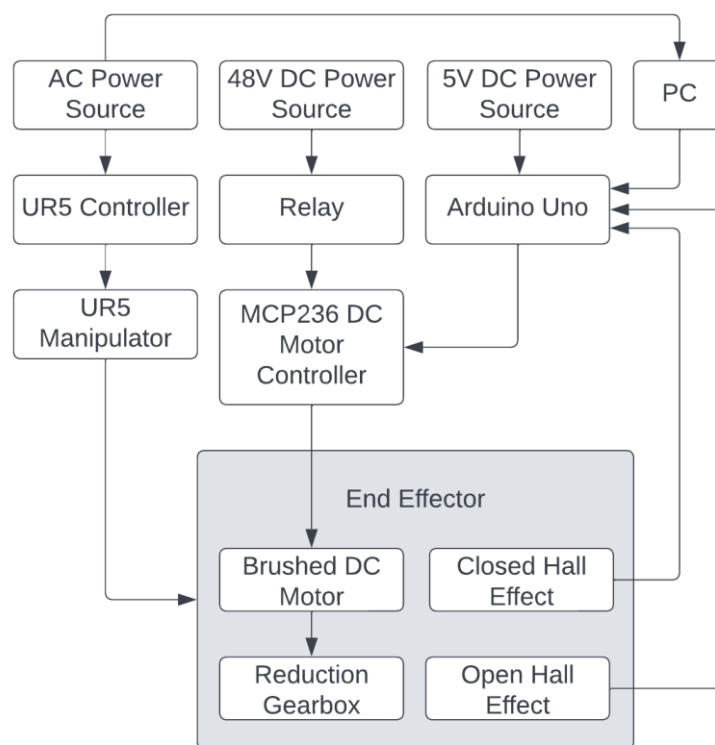


Figure 3-17 - Full system component diagram showing the primary relationships between the main system components

3.3.1. Housing

To go from a handheld unit to the robotic system, there were two major requirements:

1. Integration with greater power, communication and control systems
2. Compact end-effector size

A prototype robotic end-effector, shown in Figure 3-18, was created to hold and actuate the handheld unit remotely. This worked but was large and rather crude to be mounted on the end of the robot arm. Key issues were:

- Difficult to manage, large power cable protruding backwards
- Auxiliary power from backpack
- Bulky electronics, servo, and housing required to perform actuation at the end effector

To address these issues, a custom housing was designed.

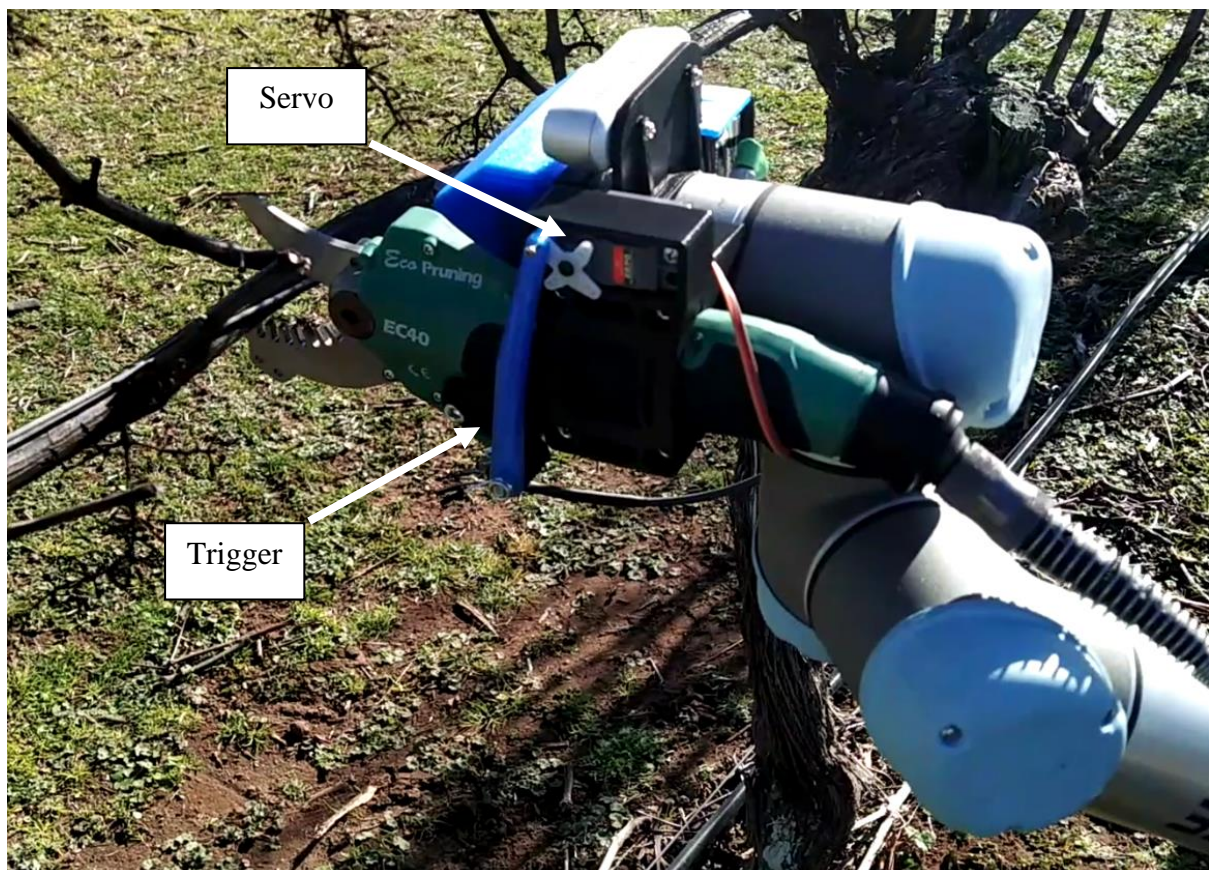


Figure 3-18 - Early prototype robotic pruner using Config 1 hardware

A video showing the operation of robot mounted secateurs with the Barracuda anvil can be found here: <https://youtu.be/LCMyF-cAXaQ>

To minimise the size of the end effector, the motor driver and Arduino were housed on Archie instead, where space is abundant. The mechanical components such as the motor, gearbox, and blade were put into a custom housing with an integrated mounting solution to the arm. The housing is shown in Figure 3-19 contains an area for mounting low profile hall effect sensors for limit switches. These sensor signals exited via one cable at the front, whilst the power wires to the motor exited via a separate cable at the rear. The resulting end effector protrudes 297mm from the mounting face and its maximum height is 51mm. This fits within the 55mm limit to avoid self-collision with the manipulator forearm.

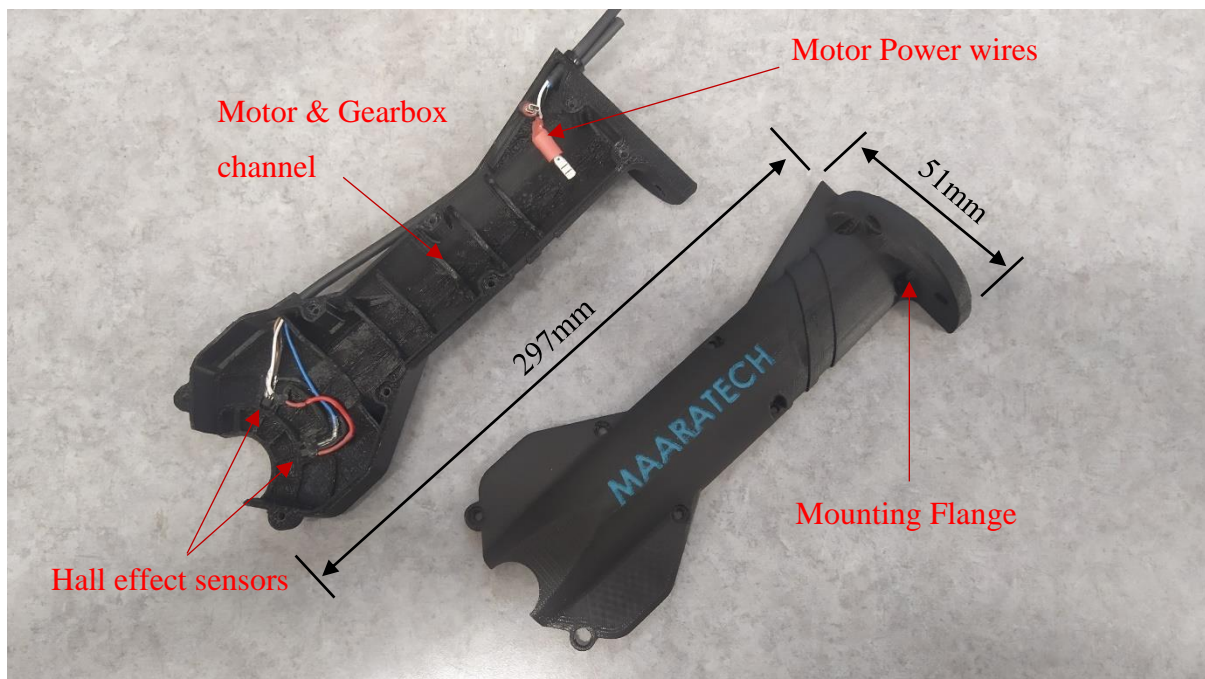


Figure 3-19 - Custom housing for robotic Barracuda showing overall design and internal circuitry

3.3.2. Software

The system consists of an Arduino Uno, a motor controller for issuing instructions to the motor, and two hall effect switches to act as limit switches. The controller provides PWM and direction control for the motor. The Arduino will be instructed for the final system by the PC onboard Archie via TTL Serial. The PC gives the Arduino cut signals and interfaces with the Arduino. As the first round of testing on the manipulator was to be controlled by human, several interfacing and safety states were introduced. This state machine can be seen in Figure 3-20 below:

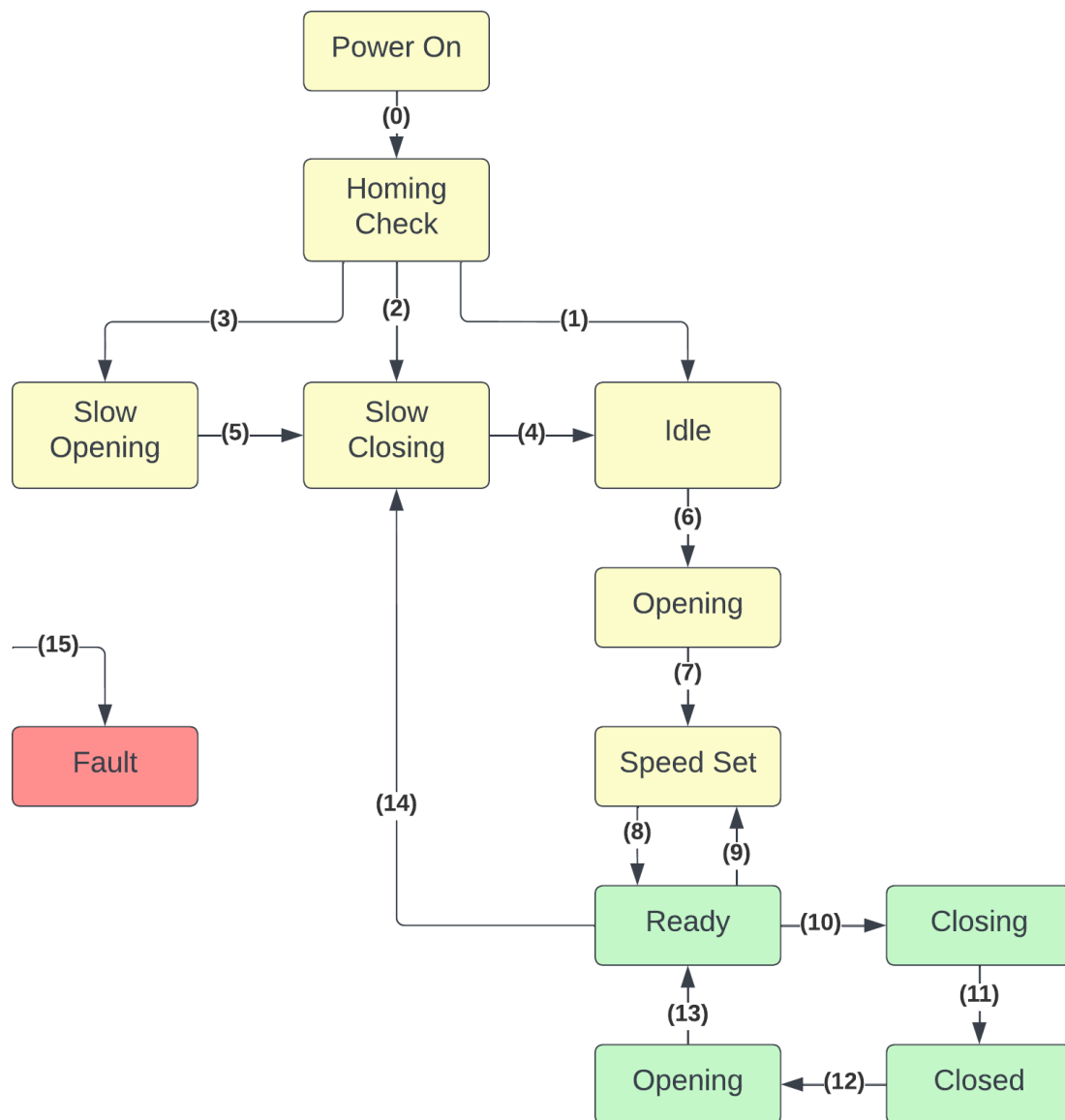


Figure 3-20 - State Machine for the operation of the end effector which operates on the arduino. Yellow states indicate pre-operation states, likely to be used once. Red states indicate fault states. Green states are operational states to be used repeatedly

The state machine has 3 areas of operation. Those coloured yellow are pre-operation states that action when the machine is started from a powered off state. Their purpose is to ensure the end effector has started properly, is ready for operation, and that these steps are done safely. The red state is a fault state. The fault check runs around the state machine, every loop. If a fault is detected it puts the system in the fault state where, for safety, it requires a hard reset. The green states are operation states for cut operations. These can be repeated in rapid succession and are the states the system operates within for most of the use case. An advantage of using a state

machine is to have good control over transitions. The sensors give clear responses which provide a great point of action to initiate transitions. It also allows an easy path to integrating or modifying features in the future. Table 3-3 describes the transitions between these states.

Table 3-3 - State transition/event list describing key information for transitions labelled in the preceding figure

Event	Description
0	Automatic transition when device is powered on
1	Automatic transition if closed position sensor is active, blade is closed, idle state is confirmed
2	Serial instruction initiates slow closing state for safety. Done if open sensor is active (Blade is open)
3	Serial instruction initiates slow opening state for safety. Done if neither open or closed sensor are active (Blade is in between positions)
4	Automatic transition when blade causes closed switch to become active.
5	Automatic transition when blade causes open switch to become active.
6	Serial instruction causes switch to prime the system
7	Automatic when blade causes open switch to become active.
8	Automatic once current speeds have been confirmed or altered
9	Serial instruction initiates transition to allow speed altering.
10	Serial instruction initiates cutting sequence.
11	Automatically initiated when blade causes closed switch to become active.
12	Automatically initiated once closed state code has completed
13	Automatically initiated once blade causes open switch to become active.
14	User input "Idle" initiates transition to close the blade.

3.3.3. Hall effect limit sensing

The hall effects were used in with the Arduino’s 10-bit analogue input reading to determine the position of the blade. As the magnetic in the back of the half gear approaches the sensor, the magnetic field in the sensor region increases. A threshold variable was used to control the open and closed positions.

The hall effect sensors caused issues with the threshold and because the threshold could only be checked once per loop, was slow to react. The fastest way to respond with the Arduino was to use hardware interrupts. But interrupts only operate with switch signals, not analogue inputs that vary in magnitude. Therefore, the analogue sensors were swapped out for half effect switches. These output a binary signal which triggered the interrupt code.

A limitation of the analogue hall effect sensors is the reaction time they cause the system to have. Due to their variable output values, the sensors needed to have a user-determined threshold to establish when the signal should be acted upon. To check the signal value, the program polls it, checking once per loop of code. It takes time for this loop to execute and return to the polling request. In this time, the system will continue to run the motor, even once the motor has obtained a stop signal, it cannot stop instantly due to rotational inertia. Even though the motor speed is reduced significantly through the gearbox, these extra rotations from when the hall effect is originally triggered, lead the blade to overshoot the ideal stop position. Using values from the system, listed in Table 3-4, the calculation below provides an estimation of the allowable time delay:

Table 3-4 - Key Barracuda values used to find allowable overshoot time

Motor no-load speed (With GB attached)	N_0	6237	rpm
GB total Ratio	GR	227	
Allowable angular overshoot	θ	3.9	Deg.

The rotational speed of the blade, N_{Blade} is given by:

$$N_{Blade} = \frac{N_0}{GR} = \frac{6237}{227} = 27.5rpm = 2.88rad/s \quad 3-6$$

The maximum allowable overshoot, from the minimum allowable closing position, θ_{rad} , is given by:

$$\theta_{rad} = \frac{2\pi\theta}{60} = 3.9 \times \frac{2\pi}{360} = 0.068rad \quad 3-7$$

The maximum time the system can take to respond to reaching the closed position, t , is given by:

$$t = \frac{\theta_{rad}}{N_{Blade}} = \frac{0.068}{2.88} = 0.023 s \quad 3-8$$

This calculation shows the whole system, from the blade position activating the hall effect sensor, to the blade coming to a complete stop, must happen within 0.023s, to prevent the blade from overshooting the maximum stopping position and colliding with the wire.

This calculation shows the importance of ensuring the system can act quickly, in order to be accurate, and prevent blade overshoot. Two ways to alleviate this, are to alter the threshold so the process is triggered earlier. The second is to move the sensor from its nominal position as to trigger the process earlier. These are compensation techniques rather than active position control.

Chapter 4: Performance Analysis

This chapter describes the field testing of the Barracuda. Methodology is outlined before presenting and discussing the results. Key metrics investigated are cut success, blade damage, and wire damage. Results are discussed at end-effector level, as well as a higher level of how they fit into, and influence the greater system and industry.

4.1 Barracuda Configurations and Experimental Setup

The aim was to evaluate how well an end effector, designed to aid vision, decision making, and path planning can perform in “on wire” and “off wire” situations. Two configurations were evaluated, which had different design features to see which version performed best, and therefore which features would be ideal to include if it were to be made again. These two configurations are shown in Figure 4-1 and have the following physical features:

- **Configuration 1:** Single row of teeth, with 4mm wide recesses, flat tooth tops and chamfered teeth to aid blade closing.
- **Configuration 2:** Two rows of teeth, 3mm wide recesses, rounded tooth tops and no chamfer on the teeth.

These were chosen to analyse performance and damage characteristics of each concept. The damage was broken down into wire damage and blade damage, whilst successful cuts were characterised by how well it cut through the cane.



Figure 4-1 - Configuration 1, pictured left, and Configuration 2, pictured right as they were used for testing

Both configurations were also tested by cutting a variety of canes where no wire was involved. When cutting robotically, most of the time it will be making cuts away from the wire, especially when cutting renewal spurs. The hand operated version will also be making large numbers of

cuts away from the wire, so the Barracuda needs to function to a high level to be useful. Often renewal spurs will be cut away from the wire and their cuts must be as clean as possible to promote healthy cane growth for the following year.

The Barracuda configurations were tested by affixing them to the commercial electric secateurs with the stock handheld housing, new blade, and the stock power pack.

The following cutting process was followed for each cut:

1. Select cut-point
2. Measure the cane diameter with Vernier callipers
3. Align secateurs with cane and wire
4. Position of secateurs relative to cane and wire was recorded
5. Make cut
6. Record cut success, wire damage, blade damage
7. Record any miscellaneous comments around

Cut points were selected based on whether there was adequate room to position the secateurs when they were being tested, not on actual cut points a professional pruner would choose when pruning a vine. This was because focus was on the cutting capability of the Barracuda when the cane was wrapped around the wire. This approach was more efficient as many cuts could be made along the same segment, rather than needing to be spread over more vines. Alignment of the secateurs with the cane was done by referencing the position of the secateurs to the cane and wire, specifically the position of the Barracuda teeth. As seen in Figure 4-2, testing was conducted over 4 different positions: 0°, 90°, 180° and 270°.

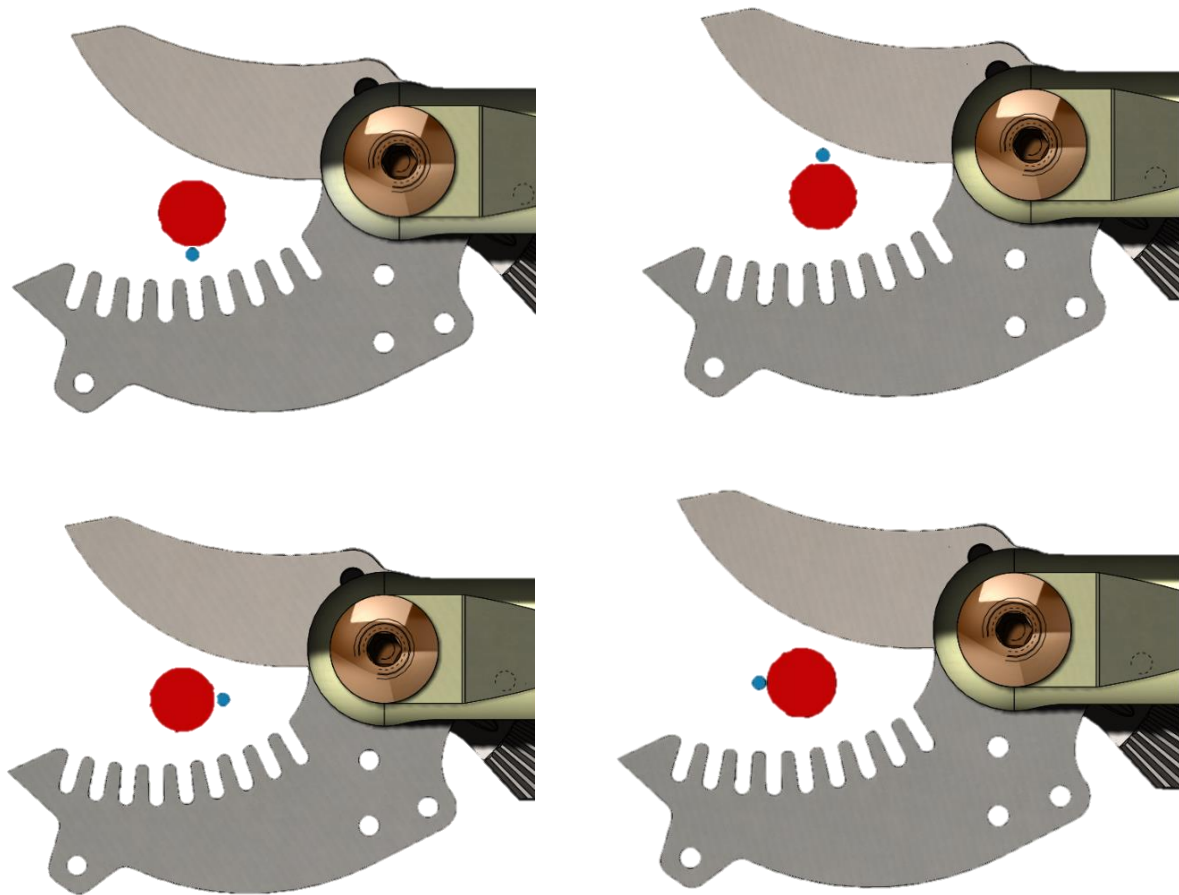


Figure 4-2 - Cut positions depicting the location of the Barracuda, cane, and wire for a cut sequence. The wire is shown in blue, and the cane in Red. Clockwise from top left: 0°, 180°, 90° and 270°

The tests with no wire were conducted with new blades for config 1, and for config 2. Both conducted approximately 100 cuts each, on canes that were not on the wire to determine the cutting performance of the Barracuda. A variety of diameters were pruned. The steps were as follows:

1. A cane was selected at random if it was not on the wire.
2. The diameter was measured with Vernier callipers to the nearest 0.5mm
3. The cane was cut by the secateurs

The cut success was noted down as clean cut, <2mm remaining, >2mm remaining, failed cut, crushed only. Any other relevant notes were taken.

4.2 Performance Metrics

The structure of the vines were cane pruned, 4-cane arrangements. Cuts were made on sections of the cane where the cane was wrapped around the wire, and unless moved, the wire would obstruct a clean cut through. The cuts in the second test, were only grading cut success, as the wire-blade interaction which causes damage was not a factor.

4.2.1. Test 1 Performance Metrics

Testing was done over two trials on different days at Church Road Vineyard, Hastings, and at Stoneleigh Vineyard, Blenheim for Config 1. Config 2 was tested over three trials over different days at Villa Maria Winery, Auckland, and Stoneleigh Vineyard, Blenheim. Performance was graded based on how well the secateurs cut through the cane. There were 5 different ways the success was categorised from least desirable, to most desirable: Failed Cut, Crushed Only, over 2mm Remaining, Under 2mm Remaining, and Clean Cut. The latter two were considered successful cuts.

Failed cut was where no incision was made into the cane, or where the cane was unable to be bent enough by hand to expose how deep an incision was.

Crushed only is where no incision was created, or where the cane was unable to be bent enough by hand to expose how deep an incision was, but that the cane was deformed such that the cross-sectional area was no different but may have been deformed into a different shape. It could also have meant the Barracuda teeth had punctured the cane, instead of, or as well as deforming the cane's cross-sectional area.

Over 2mm Remaining was where an incision was made but the remaining amount of cane cross-section was over 2mm thick.

Under 2mm remaining was where an incision was made that resulted in a remaining diameter of less than 2mm thick. This result was considered a successful cut. This benchmark of a successful cut was decided from discussing with pruning experts. They stated the fundamental goal is to remove the canes from the vine, but that the purpose of pruning was to weaken the canes as much as possible, so they are easier for humans to remove. As such, they said having

a “couple of millimetres left” was acceptable as it would still make it easy enough to remove the cane.

A *Clean Cut* was the most desirable cutting result, leaving behind no cross-sectional area of the cane, or some very thin, stringy outer bark on the teeth side of the cane.

4.2.2. Test 1 Damage

Damage was recorded for both the blade and the wire. Damage for the blade was categorised in binary “Yes”, or “No”. Yes, meant that a deformation to the blade edge had occurred, mostly seen as a deformation of the blade’s shape. This did not include surface blemishes such as scratches or deformations that did not occur on the blade edge itself that did not inhibit the function of the secateurs.

Wire damage was categorised into no damage, scratch, nick, or cut through. A nick and cut-through were classified as wire damage, scratches were not.

No damage indicates no surface blemish or effect on the cross-sectional area of the wire. This was the most desirable outcome from a cut being made.

A *scratch* indicates there was a surface blemish, where a small amount of galvanising was removed from the wire but had no effect on the cross-section of the wire. Scratches were of interest as it was noted they may create issues with the galvanising in future, causing rust. The removal of small amounts of galvanising was deemed acceptable by the vineyard managers as there were other processes used by them which damage it more, and that scratches in the galvanising occur frequently anyway.

A *nick* was where the wire had a cut that did not penetrate all the way through the diameter of the wire but reduced the cross-sectional area of the wire enough to be seen visually. The shape of a nick appeared as a notch shape as shown below in Figure 4-3.

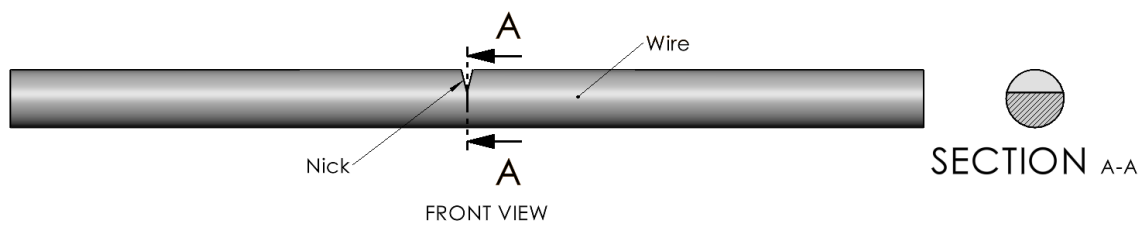


Figure 4-3 - Wire nick with resulting cross-section shown in hatched section A-A

A **cut-through** was where the wire was cut into two pieces, with no remaining cross-sectional area. This was the worst-case scenario for wire damage as it mean replacing the wire for the entire row, which is costly.

4.2.3. Test 2 Performance Metrics

The purpose of this test is to see how the Barracuda configurations perform when cutting renewal spurs. Since these are cut close to the head of the vine, they do not have to contend with the wire. Renewal spurs need to be cut as cleanly as possible since the wood will be used as the following year's bearer cane. This means the only successful cut is a **clean cut**. All other results are considered unsuccessful attempts.

4.3 Results

4.3.1. Test 1 - Performance of both configurations

Config 1 was tested over 272 cuts in all four positions. Only 3 cuts were made in the 180° position as it was predicted to cause high rates of damage to the blade and wire. As 2 of the 3 cuts caused damage, to preserve the blade, cuts made in this position were abandoned for future testing. The 90° and 270° positions shared similarly low success rates of 34.2% and 31.1% respectively compared to the 0° position's 40.7% as displayed in Table 4-1 below. Puncturing of the canes with the teeth, a suspected cause of these low numbers, is talked about in section 0. All three positions showed only 4.1-11.1% clean cuts, a very low percentage, whilst they all had around 60% of cuts leaving over 2mm of cane remaining post-cut.

Table 4-1 - Config 1 Field test performance results by cut position

Success Type	0°		90°		270°	
	# Times	%	# Times	%	# Times	%
Clean Cut	15	11.1	3	4.1	5	8.2
1-2mm Remaining	40	29.6	22	30.1	14	23.0
Over 2mm Remaining	78	57.8	47	64.4	40	65.6
Crush Only	1	0.7	0	0.0	1	1.6
Failed Cut	1	0.7	1	1.4	1	1.6
Total Cuts @ Position	135		73		61	
Successful Cut %	40.7		34.2		31.1	

Config 2 was tested over a total of 603 cuts over 3 tests. Table 4-2 shows Config 2 performed much better than Config 1 overall, with a 0° success rate average of 94.5%, compared to Config 1 at 40.7%. Breaking this down further, Table 4-2 shows that Config 2 had around 6 times more clean cuts than Config 1 shown in Table 4-1. Both tables show 90° and 270° positions for each configuration had lower success rates than the 0° position. Config 2 had a much larger difference than Config 1 however. The increase of clean cuts from the 90° and 270° to the 0° position is more than double. This is important as cuts must be as clean as possible to reduce the chance of disease. The final recommendations for an ideal design will be discussed in Section 4.4. These tables show the most effective operating position is in the 0° position. Averages for the 90° and 270° positions were 76% and 78.2% respectively which indicates a maximum drop in cutting effectiveness of 18.5%, compared to 0°.

Table 4-2 - Config 2 Field test performance results by cut position

Success Type	0°		90°		270°	
	# Times	%	# Times	%	# Times	%
Clean Cut	229	59.8	23	24.0	36	29.0
1-2mm Remaining	133	34.7	50	52.1	61	49.2
Over 2mm Remaining	21	5.5	20	20.8	26	21.0
Crush Only	0	0.0	0	0.0	0	0.0
Failed Cut	0	0.0	3	3.1	1	0.8
Total Cuts @ Position	383		96		124	
Successful Cut %		94.5		76.0		78.2

Table 4-3 presents a summarised dataset comparing Config 1 and Config 2. It shows both configurations reported higher success rates when in the 0° position. It also shows Config 2 provides more than twice the success rate of Config 1.

Table 4-3 - Successful cuts by configuration

Position	Configuration 1	Configuration 2
0°	40.7%	94.5%
90°	34.2%	76.0%
270°	31.1%	78.2%

4.3.2. Wire and Blade Damage

The wire damage rate of Config 1 was for the 90°, and 270° positions, was 32.9%, and 34.4% respectively as seen in Table 4-4. Whereas the 0° position had considerably lower damage rate of 8.9%. The result for the 180° position can be ignored however due to the small data set of 3 cuts (To avoid excessive blade and wire damage, testing of this position was stopped due to the anticipated high damage, where 2 of 3 cuts caused wire damage.). The blade damage for Config 1 was approximately proportional to the wire damage rate, between 38%-45%. This correlation is discussed further in Section 4.3.3. This analysis shows the 0° position is more favourable than the 90° or 270° positioning.

Table 4-4 - Config 1 blade and wire damage

Position	Wire Damage		Blade Damage	
	Config. 1	Config. 2	Config. 1	Config. 2
0°	8.9%	2.6%	3.7%	3.7%
90°	32.9%	17.7%	15.1%	19.8%
270°	34.4%	21.0%	13.1%	20.2%

Config 2 achieved a wire damage rate of 3.7% in the 0° position and the 90° and 270° positions had 17.7% and 21.0% respectively as seen in Table 4-5. The damage caused in the latter two positions is considerably higher than that of the 0° position. A difference observed between Config 1 and 2 is the rate of blade damage to wire damage. For Config 2, the blade was damaged 96%-142% of the time the wire was damaged. Whereas for Config 1, the blade was only damaged around 40% of the time. This will be discussed more in Section 4.3.3 These observations align with the hypothesis that the 0° position should perform best due to the easier navigation of the wire into the recesses. This has been shown for both Config 1 and 2.

Table 4-5 - Config 2 blade and wire damage

Wire Position	# Cuts @ Pos	Wire Damage		Blade Damage	
		# Damaged	%	# Damaged	%
0°	383	10	2.6%	14	3.7%
90°	96	17	17.7%	19	19.8%
270°	124	26	21.0%	25	20.2%

For Config 1, the blade damage was significant by the end of the trials, with it becoming hard to determine new instances of blade damage after the 180th cut. The damage was equally significant on the anvil's teeth tips. Figure 4-4 shows how this occurred on the left image. The tooth has a clear channel deformation from the impact with the wire as it was squeezed onto the tooth. Similarly, the blade has a rounded indentation in the opposing direction. This sandwiching of the wire is found on all teeth except for the outer two. This shows the wire was becoming stuck on the top of the tooth during a cut. It was predicted the rounded tip teeth would alleviate this issue such as Config 2.



Figure 4-4. Blade damage caused by collision with the guide wire (Left) on Configuration 1. Aggregate blade damage (Right).

Config 2 had 7 of the 24 total blade indentations line up clearly with the teeth on the Barracuda as shown in Figure 4-5. The anvil also had chamfers in the direction of the blade travel on 7 of 8 teeth. It also had a partial gouge on the farthest end which stopped where the blades farthest travel arc does, further indicating blade collision. The anvil piece not in shear with the blade however, had none, further implicating the cause of teeth chamfering to be blade collision.

It was anticipated that after several cuts causing blade damage were made, the damaged blade would cause cut success rates to suffer. However, when graphing the cumulative number of blade damages, against the cumulative number of successful cuts, the success rate did not taper off as seen in Figure 4-6. This indicates the secateurs can perform regardless of sharpness. Since sharpness is reduced due do the chipped and deformed blade, it was hypothesised to be attributed to an increase in torque from the motor, drawing more current.

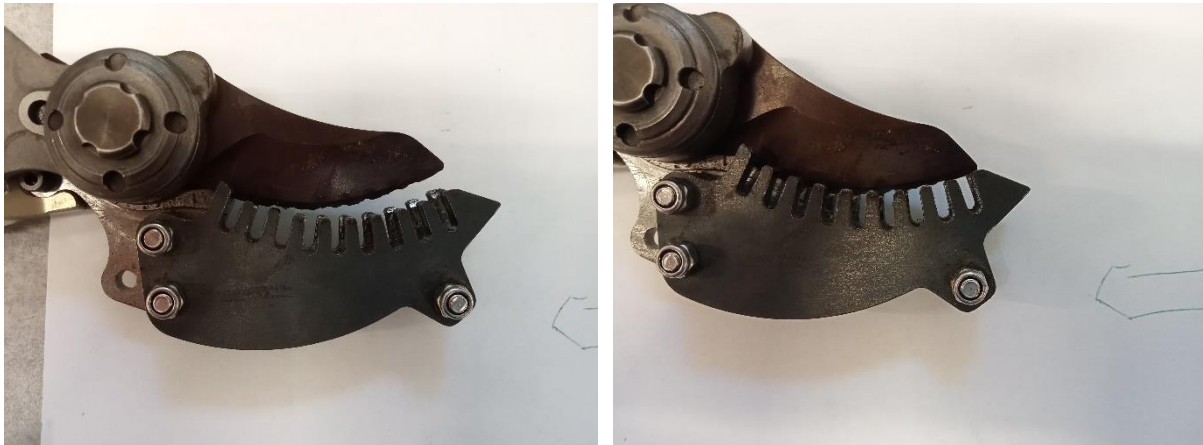


Figure 4-5 - Blade and teeth contact causing blade damage of Configuration 2

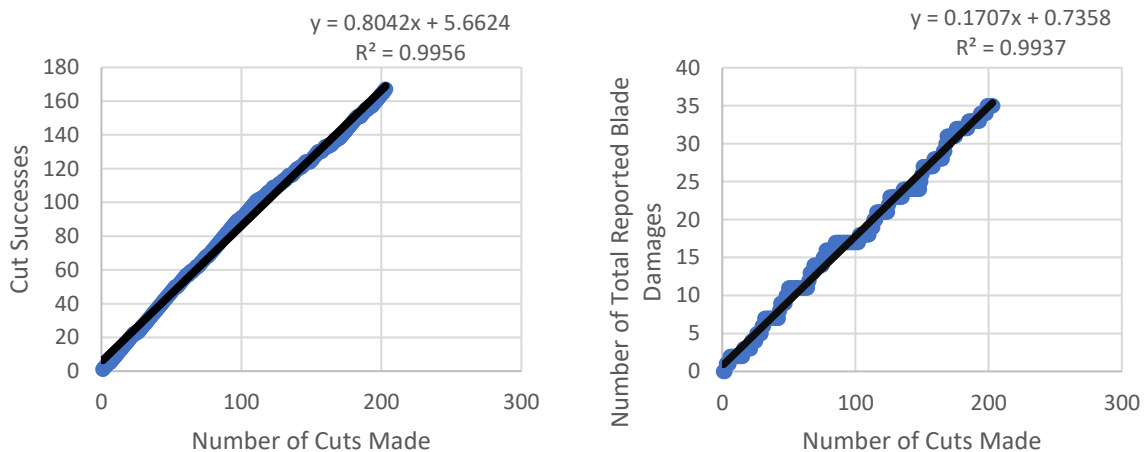


Figure 4-6 – Figure A (Left) shows the cut success rate. Figure B (Right) shows the blade damage rate.

As mentioned in Section 4.3.2 and seen in Table 4-5, Config 2 had higher a 98%-142% blade to wire damage ratio. Config 1 however had a 38%-45% blade to damage rate. From this, it could be debated that blade damage is caused by impacts with the wire about this percentage of time, considering teeth collision does not appear to be a cause. But for Config 2, for the blade damage to be caused by wire damage, the wire would expect to be damaged as well. But

if this was true, the blade would be unlikely to be damaged up to 142% of the time the wire is. This further reinforces the hypothesis that teeth impacts are the source of at least some of the damage.

Figure 4-7 shows the blade damage for three tests:

1. Config 2, ~200 cuts in the 0° position
2. Config 2, ~200 cuts in the 0°, 90° and 270° positions
3. Config 1, ~200 cuts in the 0°, 90° and 270° positions



Figure 4-7 - Blade damage of Configurations 2 and 1

The figure shows significantly more indentations in blade 3 which aligns with the data showing many more blade damage reports. The blade was visually inspected for alterations to shape, considered an instance of damage after each cut. This method means there may be cuts which would have damaged the blade but occurred in an area that was already damaged. This could mean any damage inflicted is harder to see or that no damage was inflicted where it would have been on a fresh blade. However, this situation was true for all tests, yet config 1 still shows significantly more damage upon post-inspection.

4.3.3. Anvil damage – A case for rounded teeth

From analysing the damage to the anvil of configurations 1 and 2 after the pruning trial, it was observed that each suffered damage in different ways.

Config 1 experienced a chamfer on the edge of the teeth in a direction that aligns with the wire axis. The direction and position eliminate the possibility of the blade causing this chamfer, leaving only the wire to be the only thing hard and strong enough to inflict such damage. Further evidence of is the striped micro ridges created from the finishing process were still present after the trial This shows the wire must be getting stuck on top of the square teeth and is being pushed into the teeth by the force of the blade during a cut. The wire getting stuck on the teeth tops could have been a contributing factor to the relatively low success rates of Config 1. If the wire is getting stuck, it cannot as easily fall into the recesses, which means it is more likely to be damaged as seen in Figure 4-8. and potential to stop the blade short of a full cut motion, leaving some cane outside of the blade's range causing some cane to not be cut, resulting in lower levels of success.



Figure 4-8 - Damage to teeth on Configuration 1, overall view (Left), with detail view (Right)

Config 2 experienced a chamfer in the direction and manner that Config 1 had applied to it during manufacturing (Shown in Figure 4-9). The direction means the wire could not have caused it. The fact the second row of teeth, not in shear with the blade edge, did not experience such a chamfer also indicates it was unlikely the wire had caused it. Looking at the indentations on the blade edge, several of them line up with the teeth, indicating one of two things: the blade is impacting the wire, or the blade is impacting the teeth. Since impact with the teeth is confirmed, the damage to the blade is more likely caused by this, explains the blade being damaged of 142% of the time the wire was damaged as presented in section 4.3.2. The lack of chamfers caused by the wire getting stuck on the top of the teeth reinforces this theory. Since the wires are able to easily move out of the way of the blade, they offer less resistance, meaning less reaction force on the blade edge from the wire. **Error! Reference source not found.** shows a standard, unchamfered Barracuda. **Error! Reference source not found.** features exaggerated chamfers to illustrate the direction of damage chamfers experienced for both configurations.

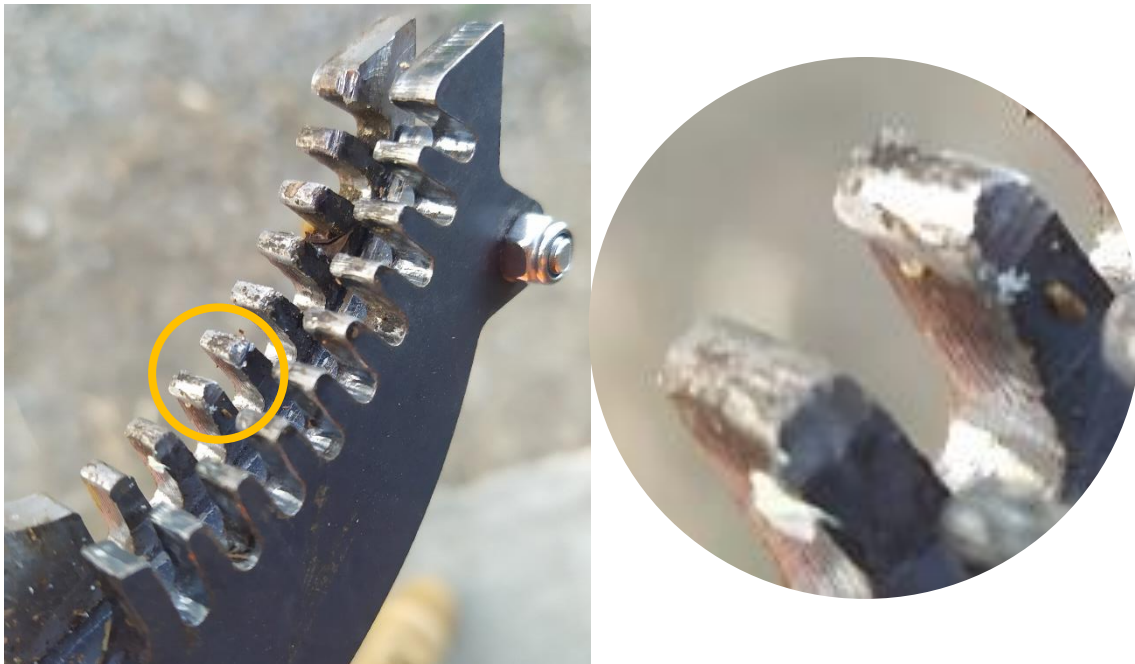


Figure 4-9 – Overview of damage to Configuration 2 teeth tips caused by blade collisions (Left). And detailed view (Right)

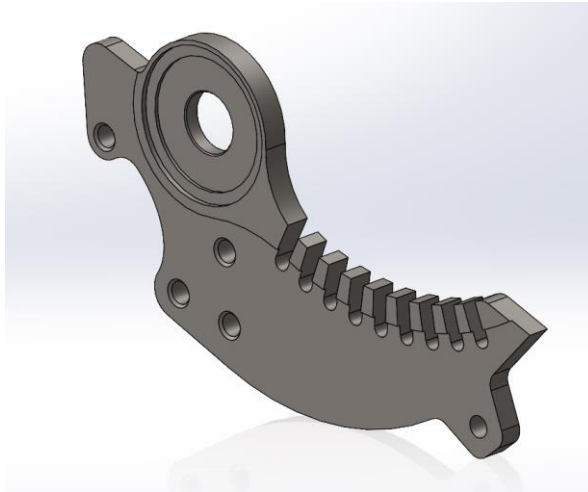


Figure 4-10 - An unchamfered Configuration 1 depicting an undamaged anvil to illustrate damage chamfers created with use.

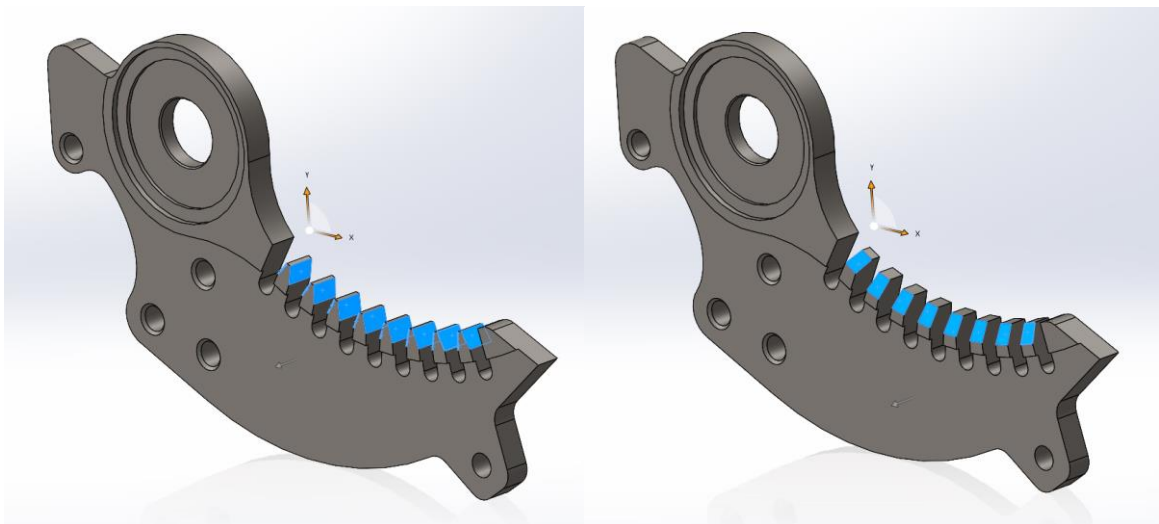


Figure 4-11- Chamfers illustrating the damage chamfers suffered by Config 1 (Left), and Config 2 (Right)

4.3.4. Cane Puncturing for Configuration 1

For Config 1, a notable circumstance occurred. The canes were being punctured by the teeth of the Barracuda as seen in Figure 4-12.



Figure 4-12 - Puncturing of canes caused by Configuration 1

An illustration of the mechanism that causes this is shown in Figure 4-13. This puncturing caused the cane to sit lower than the top of the teeth, partially evading the blade, reducing cut success, and becoming stuck to the teeth. This is not only detrimental to the cut performance of the secateurs, but in a robot mounted scenario, it would cause significant path planning issues. The robot would have to know it is caught on the cane, and then act to move the arm to dislodge the teeth from the cane. This would require a detection method but also introduce another path planning step which significantly increases complexity and goes against the purpose of this thesis – To investigate a novel pruning end-effector that can improve and simplify other system areas. Having to make this extra movement may also be challenging for the robot to execute in tight spaces.

This phenomenon did not occur for Config 2. This is because Config 2 contains two rows of teeth, essentially doubling the area contact pressure is applied over. This discovery indicates the puncturing was a contributing factor to the lack of success of Config 1, especially at the 0° position. Not only does this improve cut success, but the reduction of puncturing means no further movements are required to separate the cane and secateurs, due to them being stuck. This is especially pertinent for an autonomous variant as it will reduce the complexities of path planning for the robot.

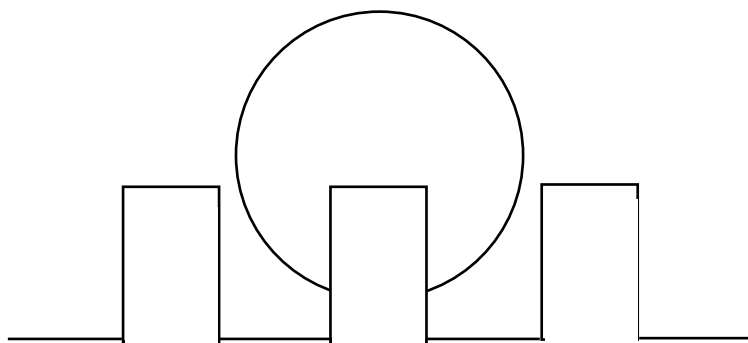


Figure 4-13 - Illustration of Barracuda teeth puncturing a cane

4.3.5. Performance with no wire

For situations where no wire was present, as seen in Table 4-6, Config 2 performed much better than Config 1, with 97% successful cuts. Another noteworthy observation is that only 10% of Config 1 cuts were clean cuts (The ideal result), whereas Config 2 had 76%. This makes Config 2 more favourable as renewal spurs must be cut as cleanly as possible.

Config 1 had four failed cuts, at diameters of 4.5, 3, 2 and 2mm. These are very small with only the 4.5mm cane being larger than the recess width. These canes can fit into the recesses in their entirety, avoiding the blade. It can be concluded it performs with mixed results on the small canes. The remainder of Config 1's results did not produce any appreciable difference in cut success or failure. The 3 failed cuts experienced by Config 2 were ≤ 3 mm in diameter, where they were pushed entirely into the recesses, avoiding the blade. The two cuts with >2 mm remaining were 3.5mm, and 2mm in diameter, very small, and avoided full blade contact. From these findings it can be concluded that Config 2 provides mixed results on canes with a diameter close to, or less than that of the recess width. Cuts of this nature should be avoided, using regular secateurs instead. Considering Config 2 made clean cuts 76% of the team, regular secateurs would need to be used as well to ensure clean cuts were always made.

Table 4-6 - Cut success of Configurations 1 and 2 for cases where no wire was present

Success Type	Configuration 1		Configuration 2	
	# Times	%	# Times	%
Clean Cut	10	10.0%	76	76.0%
1-2mm Remaining	57	57.0%	21	21.0%
Over 2mm Remaining	29	29.0%	2	2.0%
Crush Only	0	0.0%	0	0.0%
Failed Cut	4	4.0%	3	3.0%
Total Cuts Made	100		102	
Successful Cut %		67.0%		97.0%

4.4 Discussion

Observations from comparing the two test configurations have shown which design attributes would make up an effective overall pruner modification. The design would include two rows of teeth with 3mm wide recesses, rounded teeth tips, and a chamfer to guide the blade's closing movement. This summarises to using Config 2 but applying a chamfer to the teeth tips such as that found on Config 1. Based on the data discussed in section 4.3.1, Config 2 would give the highest levels of performance, least blade damage, and least wire damage based on the configurations tested, and their constituent features. To give even higher performance, there is one primary recommendation: install a blade with a symmetrical cross-section. This would move the blade's sharp edge to the middle of the two rows of teeth, avoiding any potential collisions between it, and the teeth, reducing blade damage.

Whilst the cutting position of the secateurs was broken down into four basic positions, 0°, 90°, 180°, and 270°, the exact angle they were executed at was unknown. This is because they were only aligned by eye, and whilst roughly correct, they were not quantifiable. The solution to this problem would be to use the barracuda with the UR5 robot arm since its position is known to high accuracy. If this was done, the arm could be moved by hand to align relative to the cane-wire. Here it could be zeroed before movements were accurately made relative to this original state. This was not convenient to test however due to the number of cuts which need to be made to provide enough data. During the testing times, the union of the vision and the path planning of the UR5 was not complete so cut point locations and movements would have to have been set manually. This process took far too long for even one cut to be practical. Once the greater system integration is working consistently and quickly this test would be useful to conduct

given the expected accuracy of positioning. Since the testing was done with the handheld unit, the accuracy of the approach angle was unquantifiable, but was approximately in the stated orientation.

Comments from growers were that cut-through damage was the worst-case scenario as they would have to fix what was often a large length of wire and must deal with vines. They said nicks were very common, even from experienced pruners, so they were not worried about nicks from the robotic pruner. From their perspective, people cutting wires was not the most prominent cause of wire cutting/failure.

During testing of Config 2 it was noticed that when inverted, blade damage was occurring more frequently than when it was not inverted. Of the last 201 cuts made, 6 damaged the blade, and 46 cuts were made in an inverted position. 3 of these blade damages were inflicted during an inverted cut, giving the inverted position a damage rate of 6.5% compared to just 1.9% for a normally oriented cut. This indicates there may be a discrepancy between the positioning of the two. It was hypothesised this was due to misjudgement of alignment when inverted due to it being handheld. However, to confirm this, the angular position accuracy of the UR5 would be required, but as discussed earlier, was too impractical to test.

For simplicity, the canes were assumed to be round, however data collected showed this was not the case. The data collected 20 diametral measurements at a singular point along the cane's longitudinal axis, 3 points (Top, middle, and bottom) were measured per segment, 8 segments were measured. Diametral differences were compared to the average diameter at that point. These differences were between 12% and 32%. indicates the eccentricity of canes is not only common, but also significant. Comparing with cut force data, the max cut force difference from average was 45%, excluding three outliers, this comes down to 28%, very close to that of the difference in diameters. This correlation would be worth investigating further in the future to build a clearer picture of the relationship between cut forces and cross-sectional metrics.

This potential difference of up to 32% from the mean diameter means diameters recorded per cut would likely be at best, estimates. This means that cut results could be dependent on, and/or affected by the diameter of the cane but would not be visible due to the data collected not containing this resolution of diametral measurements. In a worst-case scenario of a deeper

analysis, the diameter of the cane could negatively affect the cut success. This may eliminate otherwise convenient cut locations but would at least highlight undesirable cut locations. This would be a hinderance to an automated system, but the strong knowledge around cut success predictions would hopefully enable a higher percentage of successful cuts, providing a more deterministic system result.

For canes where the wire is not obstructing a cut, Config 2 was the preferred variation. The mixed results for small canes warrants more discussion. As these tiny shoots, typically tendrils are not located where renewal spurs are cut, their cut success does not need to be as high as that required of cutting renewal spurs.

A comment made by experts about cuts in general is they should be made as perpendicular as possible to the axis of the cane at the point of the cut. By doing this, the cross-sectional area exposed is minimised, which reduces the chance of the plant contracting disease.

Chapter 5: Conclusion

5.1 Conclusion

As the need for automation in viticulture becomes ever more prevalent, the robotics industry must look to develop pragmatic solutions to meet the demand in time. Whilst technology is inevitably moving towards a full automation asymptote, an interim stage of creating Human-Assist technology is critical. The literature review exposed the gap in products, and knowledge around creation of a technology to simply make cuts in a secateurs-based system where a wire was obstructing cuts. The creation of the Barracuda has addressed this.

The Barracuda is a novel technology designed to allow pruning cuts to be made in situations where the wire interferes with the ideally chosen cut-point. It works by exploiting the diameter difference between a cane and wire. The smaller wire evades the blade by falling between teeth, upon which, the larger cane sits. The technology can be integrated into hand operated secateurs or robotic end effectors. When integrated with the hand-operated secateurs, it reduces the need to separate the wire and cane, a physically challenging task. For the robotic system, it allows cuts to be made, where they previously could not, increasing the number of available cut-points and reducing the need for high accuracy between the vision and manipulator systems.

There have been many attempts to automate tasks for other horticultural operations such as harvesting kiwifruit, and weeding crops with lasers. These have covered bulk operations, and increasingly selective systems. Selective systems often operate on a see-decide-act framework using computer vision, metric driven decision-making AI, 6 DOF manipulators and end effectors. However, the end-effector is often an afterthought, driven by the system, rather than driving and helping the system operation. The Barracuda offers new opportunities for decision making and makes secondary mechanical separation systems superfluous.

The Barracuda was fitted to handheld electric secateurs by replacing the original bypass blade. For the robotic version, a custom housing was made to securely mount the secateurs to the manipulator with a small size. This required custom sensing and software to function but allowed control of the unit by the rest of the robotic system. Testing was conducted with handheld electric secateurs fitted with the Barracuda. Two configurations were tested to analyse the constituent features, these were tested with the wire in 3 various positions. Both configurations suffered the least wire and blade damage, as well as highest cut success rates when in the 0°

position with Config. 1 and 2 reporting 40.7% and 94.5% successful cuts respectively. For situations where the wire was not present, and a clean cut was required, Config. 1 and 2 reported successful cuts 76% and 10% of the time respectively. This shows profile optimisation is critical to the success of the Barracuda but once achieved, it is valuable. It allows pruners to make cuts easily where prior to the Barracuda, it would have taken much more strength and skill. The Barracuda also displays merit for autonomous systems, allowing the system to make cuts where it otherwise could not, or would require a complex cane-wire separation mechanism and accurate vision and manipulator. The inclusion of the Barracuda into future products would provide benefits to the viticulture industry and to the future of pruning robotics.

5.2 Future Work

This thesis has covered in primary the performance of a novel end effector that has been designed to increase the amount of cutting opportunities, and reduce required path planning accuracy. Areas that would be interesting to explore further would be an in-depth look into the difference in feasible workspaces and available cut points of the robot and end effector. However, this will require mature decision-making algorithms.

From a design perspective, there are a few areas which could offer further improvements or make for an interesting investigation:

- A system that can cope with the wire and produce clean cuts 100% of the time when not on the wire.
- An encoder-controlled version to better control cutting action.
- A reduced size, especially length, to provide more dexterity.
- A custom chassis to provide symmetrical mounting to the barracuda anvil to greatly reduce the roll moment applied during cutting.
- A symmetrical blade to reduce blade and teeth collisions

As discussed in section 0, the Barracuda has limited possible yaw angles when cutting on the wire due to the small recess widths. The secateurs, when hand operated can be rotated to align nicely during the cutting movement. The robot lacks an inherent ability to cope with this. One solution is to ensure the robot arm is set to torque mode instead of position mode once in the cutting position. This will allow the robot to be aligned naturally (Akin to being hand operated). Another option is to ensure the accuracy between vision, and path planning is

within the yaw requirement of 1.8° . Torque mode would also allow for the small longitudinal adjustment required for smooth function.

The third option is to incorporate passive compliance into the end effector to allow such movement. This option would be a great extension of the work outlined in this thesis and would address what may be the last remaining hurdle to creating an effective end-effector. To test this however would require the integration of vision and path planning which was unavailable

A more detailed investigation into the relationship between cutting forces and cane diameters, moisture content, and variety would be useful. In particular accounting for the non-circularity of the canes to obtain more accurate cross-sectional areas. This would build on the data collected for this trial, as well as the work by [66], [63]

A better solution would be to use hall effect switches in conjunction with an encoder and PID loop. The encoder would track positioning much more accurately. The switches would then act purely as overshoot limit shut off switches, and for homing routines.

Chapter 6: Bibliography

- [1] American Farm Bureau Federation, “Fast Facts About Agriculture & Food,” 2020. [Online]. Available: <https://www.fb.org/newsroom/fast-facts#:~:text=2%20million%20farms%20dot%20America's,in%20the%20U.S.%20and%20abroad..>
- [2] R. C. Allen, “Economic Structure and Agricultural Productivity in Europe 1300-1800,” *European Review of Economic History* 4(1), pp. 1-25, 2000.
- [3] Central Intelligence Agency (CIA), The World Factbook 2013-14, Washington DC: Central Intelligence Agency, 2013.
- [4] N. Kawamura, K. Namikawa, T. Fujiura and M. Ura, “Study on Agricultural Robot (Part 1),” *Journal of the Japanese Society of Agricultural Machinery* 4, pp. 353-358, 1984.
- [5] M. Li, “Robotics in Manufacturing - The Past and The Present,” *Technical, Economic and Societal Effects of Manufacturing 4.0*, pp. 85-95, 2020.
- [6] Oxford Economics, “How Robots Change The World,” 2019.
- [7] NZ Wine, “2021 New Zealand Winegrowers Inc. Annual Report,” 2021.
- [8] M. Chapman, “Where are the workers?,” 04 March 2021. [Online]. Available: <https://www.hortnz.co.nz/news-events-and-media/mikes-blog/where-are-the-workers/>.
- [9] T. Zabadal, G. VanEe, R. Ledebuhr and M. Partridge, “Considerations for the Mechanical Pruning of Concord Grapevines,” Southwest Michigan Research and Extension Center, Michigan, 2004.
- [10] M. Gatti, S. Civardi, F. Bernizzoni and S. Poni, “Long-Term Effects of Mechanical Winter Pruning on Growth, Yield, and Grape Composition of Barbara Grapevines,” *American Journal of Enology and Viticulture*, pp. 199-206, 2011.
- [11] C. Courtney, in *Wine in New Zealand*, Auckland, Godwit, 2003, pp. 218-219.
- [12] T. Robinson, “The Evolution Towards More Competitive Apple Orchard Systems in the USA,” *Acta Hort.* 772, pp. 491-500, 2008.
- [13] Tupu NZ, “Land Use Fact Sheet - Wine Grapes,” Tupu New Zealand, 2022.

- [14 Klima, “Klima Landing Page,” 2014. [Online]. Available: [klima.co.nz](http://www.klima.co.nz).
]
- [15 Langlois, “Langlois Vine Stripper,” 2007. [Online]. Available:
] <http://www.langlois.co.nz/>.
- [16 ERO, “ERO-Cane Pruner Viteco,” 2022. [Online]. Available:
] <https://www.ero.eu/en/cane-pruner-viteco>.
- [17 S. Poni, S. Tombesi, A. Palliotti, V. Ughini and M. Gatti, “Mechanical Winter Pruning
] of Grapevine: Physiological Bases and Applications,” *Scientia Horticulturae Vol. 204*,
pp. 88-98, 2016.
- [18 C. Intreiri and S. Poni, “Physiological Response of Winegrape to Management Practices
] for Successful Mechanization of Quality Vineyards,” *Acta Hortic. 526*, pp. 33-48, 2000.
- [19 T. Bates and J. Morris, “Mechanical Cane Pruning and Crop Adjustment Decreases
] Labor Costs and Maintains Fruit Quality in New York 'Concord' Grape Production,”
HorTechnology Vol. 19, Issue 2, pp. 247-253, 2009.
- [20 C. A. Sims, R. P. Johnson and R. P. Bates, “Effects of Mechanical Pruning on the Yield
] and Quality of Muscadine Grapes,” *American Journal of Enology and Viticulture, Vol.*
41, Issue 4, pp. 273-276, 1990.
- [21 F. L. Jensen, L. P. Christensen, R. H. Beede and G. M. Leavitt, “Effects of Mechanical
] Pruning on Grapes,” *California Agriculture*, 1980.
- [22 S. P. Galinato, A. Kendall and C. A. Miles, “Costs and Profitability for Mechanized
] Pruning and Harvest in Two-Cider Apple Orchard Systems,” *HortTechnology, Issue 32*,
Vol. 3, pp. 275-287, 2022.
- [23 Langlois, “Langlois Spur/Cordon Cutter,” 2009. [Online]. Available:
] <http://www.langlois.co.nz/langlois-vine-stripper/spurcordon-cutter.html>.
- [24 J. Fiola, “Balanced Pruning 3: Pre-Pruning,” 30 April 2021. [Online]. Available:
] <https://extension.umd.edu/resource/balanced-pruning-3-pre-pruning>.
- [25 A. S. A., A. E., A. A., R. Praveena and R. Srimeena, “Agricultural Robot for Automatic
] Ploughing and Seeding,” *IEEE International Conference on Technological Innovations*
in ICT for Agriculture and Rural Development, pp. 17-23, 2015.

- [26 B. S. Shivaprasad, M. N. Ravishankara and B. N. Shoba, “Design and Implementation of Seeding and Fertilizing Agriculture Robot,” *International Journal of Application or Innovation in Engineering & Management*, Vol 3, Issue 6, pp. 251-255, 2014.
- [27 OXIN, “OXIN Homepage,” 2022. [Online]. Available: <https://www.oxin.nz/>.
- [28 T. Botterill, S. Paulin, R. Green, S. Williams, J. Lin, V. Saxton, S. Mills, X. Chen and S. Corbett-Davies, “A Robot System for Pruning Grape Vines,” *Journal of Field Robotics*, 34, pp. 1100-1122, 2017.
- [29 Vinium Robot, “Vinium Homepage,” 2022. [Online]. Available: vinum-robot.eu/.
- [30 Verdant Robotics, “Verdant Robotics Homepage,” 2022. [Online]. Available: <https://www.verdantrobotics.com/>.
- [31 M. M. Foglia and G. Reina, “Agricultural Robot for Radicchio Harvesting,” *Journal of Field Robotics Issue 23, Vol. (6/7)*, pp. 363-377, 2006.
- [32 L. F. P. Oliveira, A. P. Moreira and M. F. Silva, “Advances in Agriculture Robotics: A State-of-the-Art Review and Challenges Ahead,” *Robotics*, Vol. 10, Issue 2, 2021.
- [33 W. C. Bac, E. J. van Henton, J. Hemming and Y. Edan, “Harvesting Robots for High-Value Crops: State-of-the-art Review and Challenges Ahead,” *Journal of Field Robotics* Vol. 31, Issue 6, pp. 888-911, 2014.
- [34 M. Gao and T.-F. Lu, “Image Processing and Analysis for Autonomous Grapevine Pruning,” *IEEE International Conference on Mechatronics and Automation*, pp. 922-927, 2006.
- [35 V. Tinoco, M. F. Silva, F. N. Santos, L. F. Rocha, S. Magalhaes and L. C. Santos, “A Review of Pruning and Harvesting Manipulators,” in *ICARSC*, Santa Maria da Feira, 2021.
- [36 P. Motzki, F. Khelfa, L. Zimmer, M. Schmidt and S. Seelecke, “Design and Validation of a Reconfigurable Robotic End-Effector Based on Shape Metal Alloys,” *IEEE/ASME Transactions on Mechatronics PP(99): 1-1*, 2019.
- [37 F. Yandun, T. Parhar, A. Silwal, D. Clifford, Z. Yuan, G. Levine, S. Yaroshenko and G. Kantor, “Reaching Pruning Locations in a Vine Using a Deep Reinforcement Learning

Policy,” *2021 IEEE International Conference on Robotics and Automation (ICRA 2021)*, pp. 2400-2406, 2021.

- [38 Lapalme Agtech, “Lapalme Agtech SAMI 4.0 Cultivez La Revolution,” 2021. [Online].
] Available: <https://lapalmeagtech.com/en/>.
- [39 RoboVeg, “RoboVeg Homepage,” 2022. [Online]. Available: roboveg.com.
]
- [40 Z. De-An, L. Jidong, J. Wei, Z. Ying and C. Yu, “Design of an Apple Harvesting
] Robot,” *Biosystems Engineering, Vol. 110, Issue 2*, pp. 112-122, 2011.
- [41 A. Silwal, F. Yandun, A. Nellithimaru, T. Bates and G. Kantor, “Bumblebee: A Path
] Towards Fully Autonomous Robotic Vine Pruning,” 2021.
- [42 FF Robotics, “FF Robotics About Us,” 2020. [Online]. Available:
] <https://www.ffrobotics.com/>.
- [43 Abundant Robotics, 2021. [Online].
]
- [44 K. Tanigaki, T. Fujiura, A. Akase and J. Imagawa, “Cherry Harvesting Robot,”
] *Computers and Electronics in Agriculture Vol 63, Issue 1*, pp. 65-72, 2008.
- [45 Y. Edan, D. Rogozin, T. Flash and G. E. Miles, “Robotic Melon Harvesting,” *IEEE
] Transactions on Robotics and Automation, Vol. 16, No. 6*, pp. 831-834, 2000.
- [46 Advanced Farm, “Advanced Farm BetterPick Strawberry Harvester,” 2022. [Online].
] Available: www.advanced.farm.
- [47 B. Zhang, X. Chen, H. Zhang, C. Shen and W. Fu, “Design and Performance Test of a
] Jujube Pruning Manipulator,” *Agriculture, 12(4):552*, 2022.
- [48 A. Zahid, M. S. Mahmud, L. He, P. Heinemann, D. Choi and J. Schupp, “Technological
] Advancements Towards Developing a Robotic Pruner for Apple Trees: A Review,”
Computers and Electronics in Agriculture, Vol. 189, 105837, pp. 1-16, 2021.
- [49 H. Kawasaki, S. Murakami, H. Kachi and S. Ueki, “Novel Climbing Method of Pruning
] Robot,” in *2008 SICE Annual Conference*, 2008.
- [50 S. Ueki, H. Kawasaki, Y. Ishigure, K. Koganemaru and Y. Mori, “Development and
] Experimental Study of a Novel Pruning Robot,” *Artif Life Robotics Vol. 16*, pp. 86-89,
2011.

- [51 D. P. Soni, R. M, N. A. Gokul and S. S., “Autonomous Arecanut Tree Climbing and Pruning Robot,” *INTERACT-2010*, pp. 278-282, 2010.
- [52 N. Strisciuglio, R. Tylecek, N. Petkov, P. Biber, J. Hemming, E. van Henten, T. Sattler, M. Pollefeys, T. Gevers, T. Brox and R. B. Fisher, “TrimBot2020: An Outdoor Robot for Automatic Gardening,” 2020.
- [53 A. Zahid, L. He, D. D. Choi, J. Schupp and P. Heinemann, “Collision free Path Planning of a Robotic Manipulator for Pruning Apple Trees,” *ASABE Meeting Presentation*, 2020.
- [54 A. Zahid, L. He, L. Zeng, D. Choi, J. Schupp and P. Heinemann, “Development of a Robotic End-Effector for Apple Tree Pruning,” *Transactions of the ASABE (American Society of Agricultural and Biological Engineers) Vol. 63, Issue 4*, pp. 847-856, 2020.
- [55 A. Zahid, M. S. Mahmud, L. He, D. Choi and P. Heinemann, “Development of an Integrated 3R End-Effector with a Cartesian Manipulator for Pruning Apple Trees,” *Computers and Electronics in Agriculture, Vol. 179, 105837*, pp. 1-10, 2020.
- [56 L. He and J. Schupp, “Sensing and Automation in Pruning of Apple Trees: A Review,” *Agronomy 2018, 8, 211*, pp. 1-18, 2018.
- [57 A. You, N. Parayil, J. Gopala Krishna, U. Bhattarai, R. Sapkota, D. Ahmed, M. Whiting, M. Karkee, C. M. Grimm and J. R. Davidson, “An Autonomous Robot for Pruning Modern, Planar Fruit Trees,” *Journal of Robotics and Automation Letters*, 2022.
- [58 B. Huang, M. Shao and W. Chen, “Design and Research on End Effector of a Pruning Robot,” *International Journal of Simulation: Systems, Science & Technology Vol. 17, Issue 36*, pp. 1-5, 2016.
- [59 Vision Robotics Corporation, “Intelligent Autonomous Grapevine Pruner,” 23 March 2014. [Online]. Available: <https://www.visionrobotics.com/vr-grapevine-pruner>.
- [60 B. Zhang, Y. Xie, J. Zhou, K. Wang and Z. Zhang, “State-of-the-art Robotic Grippers, Grasping and Control Strategies, as well as their Applications in Agricultural Robotics,” *Computers and Electronics in Agriculture*, p. 105694, 2020.
- [61 J. Molina and S. Hirai, “Kinematic Analysis of a Novel Skew-Gripper for Aerial Pruning Tasks,” in *International Conference on Mechatronics and Robotics Engineering*, Paris, 2017.

- [62 J. Molina and S. Hirai, “Aerial Pruning Mechanism, Initial Real Environment Test,”
] *Robot. Biomim Vol. 4:15*, 2017.
- [63 G. Ozdemir, A. Sessiz, R. Esgici and A. K. Elicin, “Cutting Properties of Wine Grape
] Cultivars,” *Scientific Papers. Series B, Horticulture, Vol. LIX*, pp. 151-158, 2015.
- [64 E. Romano, R. Bonsignore, D. Camillieri, L. Caruso, A. Conti and G. Schillaci,
] “Evaluation of Hand Forces During Manual Vine Branches Cutting,” in *International
Conference, Work Safety and Risk Prevention in Agro-Food and Forest Systems*,
Ragusa, Italy, 2010.
- [65 Crown Plastics, [Online]. Available: [https://crownplastics.com/wp-](https://crownplastics.com/wp-content/uploads/CoefficFrict.pdf)
] [content/uploads/CoefficFrict.pdf](https://crownplastics.com/wp-content/uploads/CoefficFrict.pdf).
- [66 A. Sessiz, R. Esgici, G. Ozdemir and A. K. Eliçin, “Cutting Properties of Different
] Grape Varieties,” *Agriculture & Forestry, Vol. 61, Issue 1*, pp. 211-216, 2015.