University of Southern Queensland

School of Engineering

Control of Insect Pests Using Agricultural Robots – Development of an Insect Pest Eliminating End-Effector

A dissertation submitted by

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towards the degree of

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Supervised by: Dr Tobias Low

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ENP4111 Dissertation Project

(This is a 2-unit research project in the Bachelor of Engineering Honours Program)

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CERTIFICATION OF THESIS

I Stacey Keith Rummenie, declare that the Thesis entitled "Control of Insect Pests Using Agricultural Robots – Development of an Insect Pest Destroying End-Effector" is not more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references, and footnotes. The thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

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Date: 4th November, 2024.

Endorsed by:

Dr Tobias Low
Principal Supervisor

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ABSTRACT

The control of insect pests via pesticides is an issue of growing concern. While alternate methods exist, they are often slow, expensive or have issues with worker availability. Due to historical difficulties in the identification of insects using robotic visual systems, little work has been done in attempting to use robotics to help address these issues. With recent advances in robotics, this issue may soon be addressed, however, there are currently few end-effectors available for non-chemical control of insects. This is an area where further research is required. This project aimed to identify one or more non-chemical pest control approaches able to be integrated with robotics, through designing and testing a range of prototype end-effectors. Attempted approaches used for insect control by these prototypes included: application of a crushing force (the "Gripper" prototype); application of an electric field (the "Zapper" prototype); and application of a suction force (the "Sucker" prototype).

Prototype development occurred through use of an iterative, design-based methodology, with preliminary prototypes based loosely around devices of a similar nature. This was followed by viability testing, analysis and refinement of each of the three preliminary designs, so as to develop fully functional prototypes. The final prototypes were then subjected to three rounds of testing, including testing against Mealworms (Tenebrio molitor), Cabbage White Butterflies (Pieris rapae), and Ladybeetles (Family Coccinellidae).

The Gripper prototype, while showing poor effectiveness against killing larval Tenebrio molitor, proved highly effective in removing and killing pupal forms as well proving effective against larval forms of Pieris rapae and adult ladybeetles. From a build and host damage perspective this prototype showed good potential for integration with a robotic arm and limited potential for causing host plant damage. Results from the Gripper prototype were, furthermore, indicative of different control methodologies as being better suited to specific insect species and life cycle stages. While the Zapper prototype was the cheapest and smallest prototype, and ultimately proved to have some ability in killing both larval and pupal forms of Tenebrio molitor, it appeared far less effective against Pieris rapae and had very limited pest removal ability across all species tested. Though appearing well suited for integration with a robotic arm, this prototype was observed to cause damage to the host plant (Brassica oleancea) tissue and was prone to accidental discharge when in proximity to leaves. Testing against Tenebrio molitor (larvae & pupae) and Pieris rapae (larvae) proved the Sucker prototype to be extremely effective in removing and killing these specimens without damaging the host plant. This prototype was, however, noted to be the most expensive and largest of those examined, with significant work needed before it could be attached to a robotic arm.

In summary, the project demonstrated the Sucker prototype end-effector as having the most promise in controlling pest insects without chemicals, with the Gripper prototype also showing good potential. The Zapper prototype, while being the worst performer, showed sufficient potential to justify further investigation. Overall, the project effectively demonstrated use of non-chemical based control approaches, delivered via robot end-effectors, are a viable option for future insect pest control. With further development, such devices could significantly reduce the amount of pesticide currently used within agriculture, having the potential to provide great benefit to the health of agricultural workers, the community, and the environment. In consideration of recent advances in robotics with respect to machine vision and pest identification, the successful progression of end-effector technologies achieved by this project provides clear justification for the continuation of further work in this field.

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ABBREVIATIONS

3D – Three Dimensional

AC – Alternating Current

CPU – Central Processing Unit

DC – Direct Current

DCPA – Dimethyl Tetrachloroterephthalate

DL – Deep Learning

DNA – Deoxyribose Nucleic Acid

EF – Electric Field

EPA – Environmental Protection Agency (United States of America)

ID – Inner Diameter

IPM – Integrated Pest Management

OD – Outer Diameter

PC – Personal Computer

PE - Polyethylene

PWM – Pulse Width Modulation

RAS – Robotic and Autonomous Systems

RGB – Red, Blue, and Green

RGB-D – Red, Blue, Green, and Depth

RF – Random Forest

ROS – Robot Operating Systems

SLP – Supervised Learning Process

SVM – Support Vector Machines

UAV – Unmanned Aerial Vehicle

UGV – Unmanned Ground Vehicle

UniSQ – University of Southern Queensland

USB – Universal Serial Bus

UV – Ultra-violet

CHAPTER 1: INTRODUCTION

1.1 Background

Insect and plant pests pose a significant global challenge to humanity, negatively impacting food and resource production, resulting in billions of dollars of losses annually (FAO 2019). Over the last century, increasingly intensive agricultural practices have exacerbated this pest problem, leading to a growing need for more effective control measures.

Though chemical control of pests is typically considered highly effective, pesticide resistance in pest species, as a result of long-term pesticide use, is becoming of increasing concern (Duckett et al. 2018; Barnes et al. 2021). Furthermore, there are a growing number of reports and studies indicating pesticide use is resulting in significant negative impacts on the environment and on human health (Gonzalez-de-Santos et al. 2016; Duckett et al. 2018). While manual control methods would initially seem to be a viable alternative, issues such as worker shortages and growing labour costs (Downham & Litchfield 2022) within the Agricultural space are making such measures increasingly untenable. Though acknowledging biological pest control methods have proven very successful in some areas, they are typically highly specific and can be slow to act, making control of some pest species very difficult. Alternative approaches for pest control, are thus clearly needed.

In recent years, new and advanced precision agricultural technologies have emerged that are beginning to enhance both the volume and sustainability of food production. These technologies, which include drones (also referred to as unmanned aerial vehicles or UAVs), sensors and robotics, are collectively being referred to as Robotic and Autonomous Systems or RAS, and their integration within the agricultural sector forms the basis of what is now known as "Agriculture 4.0" (Degieter et al. 2023). RAS is observed to be playing an increasingly important role in meeting the challenges being experienced by the agricultural sector. Of note, is the role these technologies are beginning to play in the management and control of agricultural pests.

Recent examples of developments within agricultural pest control include the introduction of robotic mechanical weed control measures (Shamshiri et al. 2018; Vijayakuma et al. 2023) and the release of devices such as the "Laserweeder™" by Carbon Robotics (2022), which, as the name suggests, uses lasers to control weeds. Alongside these, there is a continuing development of smart spraying technologies being utilised for precision weed management (Vijayakuma et al. 2023). These technologies are already reducing the volume of herbicides used and thus helping to reduce their associated environmental impacts. While there is evidence of robotic control of insect pests using chemical control measures, unlike with plant pests, there appears to be limited work occurring around non-chemical robotic insect control (Obasekore et al. 2019).

With concerns around pesticide usage indicating the need for alternate forms of weed and insect control without the use of chemicals, combined with a diminishing ability to control such pests manually, there exists a significant argument for further research and development of RAS to be undertaken within the agricultural realm. Furthermore, there exists a specific need for improved robotic sensory systems, and further development of simple manipulators (Duckett et al. 2018; Shamshiri et al. 2018). The second of these points is the primary research gap this study begins addressing, through the design and testing of several non-chemical based end-effectors, with the potential to help in the control of insect pests.

1.2 Objectives and Aims

The primary aim of this project was to progress the development of a robotic end-effector, able to remove and/or destroy insect pests without use of pesticides.

To meet this primary aim, five principal objectives were ultimately identified, these being:

1. To design and build three basic prototype end-effectors, each using a different approach to remove and potentially kill insect pests.
2. To test each of these prototypes against a range of pest species, including adult and larval forms.
3. To use collected data to identify which of the prototypes offered the most insect control potential, through examination of their: relative success in removing and/or killing insect pests; ease of operation; ease of construction; cost; potential for robot connectivity; and potential for negative impacts.
4. To improve on and optimise the design of the most favourable protype.
5. To ensure that any end-effector developed was safe, affordable, and easy to construct (this being a significant consideration in the execution of objective number four).

1.3 Expected Outcomes

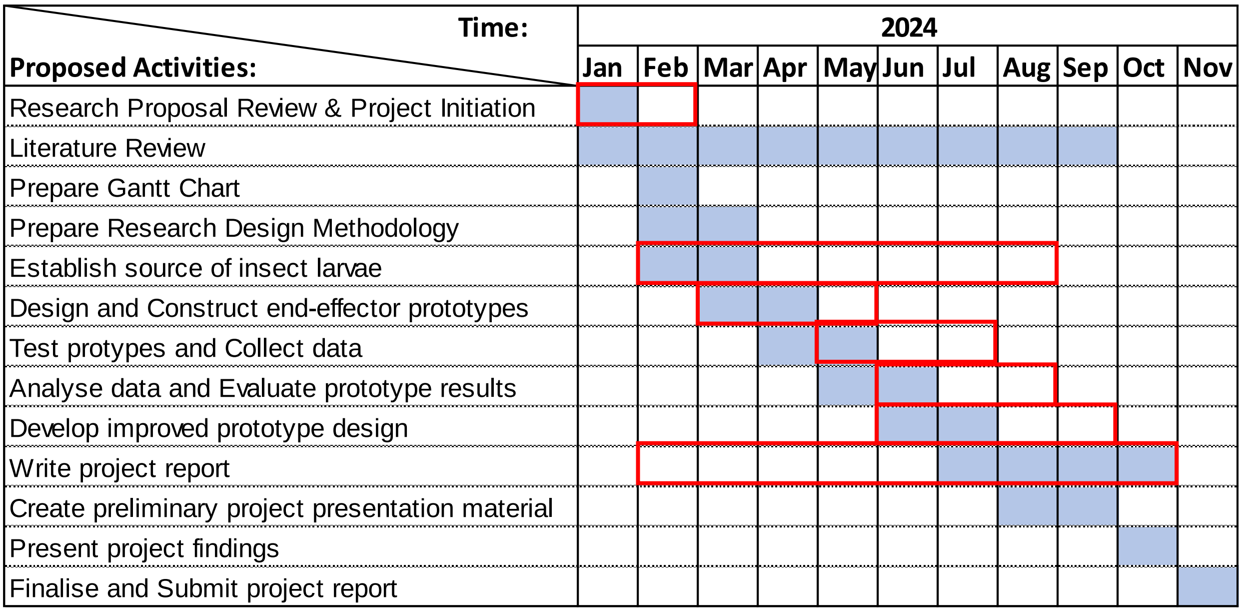
At the end of this project, it was expected a range of potential end-effectors for the non-chemical control of insect pests would be developed and tested, with the most effective prototype design having then been identified. Flaws and limitations of the most effective prototype design were also expected to have been established, including considerations around safety, ease of construction, cost, and functionality of the final prototype. A modified design addressing these identified flaws and limitations, that furthermore incorporated the ability to attach this end-effector to an existing robot arm, was to ideally have been proposed.

Ultimately, through producing one or more viable end-effector prototypes, and successfully establishing a methodology able to improve on any preliminary developed prototypes, achievement of these outcomes was identified as being proof of the project having successfully addressed the stated aim.

1.4 Work Plan

The preliminary work plan was as per the blue shaded boxes in the Gantt chart as displayed in Table 1. Due to changes in the original proposal occurring as the project progressed, with constraints, limitations and numerous unforeseen events having had some impact on the proposed timing and length of time spent on tasks, the final workplan differed somewhat from the original plan, as indicated by the red outlined boxes shown in Table 1. Primary differences between the planned and actual work plan, were in the failure to establish a source of insect larvae, requiring continuous seeking of test specimens throughout the project, along with all prototypes being further developed (based upon a combination of findings and project constraints). Furthermore, writing of the project report commenced in February and was ongoing through until the end of October.

Table 1. Gantt Chart Outlining Project Work Plan



Preliminary Work Plan: Changes to Work Plan:

1.5 Resource Requirements and Considerations

Resources initially expected to be required for successful completion of the project, along with some of their specific considerations, were as follows:

- Time: Estimated at over 320 hours (Approx. 10+ hours per week over 32 weeks).
- Supervisor assistance: Required for advice and feedback at key stages/milestones.
- Facility access: Some laboratory/workshop access was identified as desirable but due to travel and time constraints, the project design was adjusted so that this was not mandatory. Access to 3D printing services was identified as necessary.
- Insect Breeding Resources:
  - Aquarium, fly-screen mesh, cabbage leaves, Cabbage White Butterfly eggs/larvae or similar.

  - Considerations: Where issues in sourcing Cabbage Butterfly eggs/larvae occurred, sourcing of alternative species (e.g. Heliothis moths, Army worms) was identified as needing to be investigated. In the event these also proved difficult to obtain, the experimental design was to be adjusted to allow for procurement and use of any insects able to be sourced. Changes were to be noted and recorded within the experiment methodology.
- End-effector Prototypes (Non-attachable) Resources:
  - 3D modelling software (Creo or similar), basic circuitry equipment, DC power source, vacuum pump, small fans, micro servo, 3D printer, silicon glue, pipe, adhesives and screws/bolts.
  - Considerations: Access to a vacuum pump along with a number of electrical components was desired, but if these proved unavailable, or cost of acquisition was prohibitive, alternative devices or means of achieving similar experimental outcomes was instead to be considered. Any such changes were to be noted and recorded within the experiment methodology.
- End-effector Testing Resources:
  - Constructed end-effector prototypes, 10 insect larvae per prototype, laboratory scales, camera, cabbage leaves (or similar), visual damage chart.
  - Considerations: Access to laboratory scales sensitive to 0.01 g was identified as highly desired. Digital callipers were to be considered as an alternative for measurement of key larvae dimensions where scales were established as being unavailable.
- Data Analysis and Reporting:
  - Spreadsheeting software and word-processing software.

Materials to be: available commercially; able to be provided by the author; or, accessible through UniSQ. Where not possible, adjustments to the methodology to be considered and documented. Total budget was established as preferably not exceeding $150 for any necessary purchases.

Whilst actual requirements were largely aligned with these expectations (final material and equipment requirements and methodology as per Chapter 3), a few key points of difference were noted:

- Captive breeding of Cabbage White Butterflies failed. No Heliothis moths were able to be located as a replacement. Captive breeding of Armyworm moths failed. Adjustments were made to allow for use of other insect species including establishment of host plant test plots and collection of insects from these plots and other locations.
- A vacuum pump was unable to be sourced. Use of an air compressor and air blow gun, to achieve a similar outcome, was required.
- Broccoli were used instead of cabbages, and were the host plant used in the test plots.
- Laboratory scales were unable to be sourced, so digital callipers were used to measure test subject dimensions.
- While total budget was calculated as around $300, actual spend was closer to $150, with the purchase of an air compressor and air blow gun not required.

CHAPTER 2: LITERATURE REVIEW

The following literature review aims to provide a general overview of some of the key pest related issues currently faced by agriculture, discuss the challenges resulting from these issues, and examine potential solutions and alternative pest control approaches that may be used to address issues. This includes an examination of the role that robotic and autonomous systems (RAS) have started to play in agriculture, along with consideration of how RAS has been increasingly applied to pest control issues within agricultural systems. With respect to pest control, the review first examines the area of plant pest control, where significant work appears to have been occurring, through providing an overview of the research occurring with and without the use of pesticides. An examination of the area of insect control is then undertaken in a similar fashion, establishing what has been occurring within this field, where this research appears to be heading, and identifying areas where work is currently lacking. An overview of the approach taken can be seen in Figure 1, which outlines the project's conceptual development.

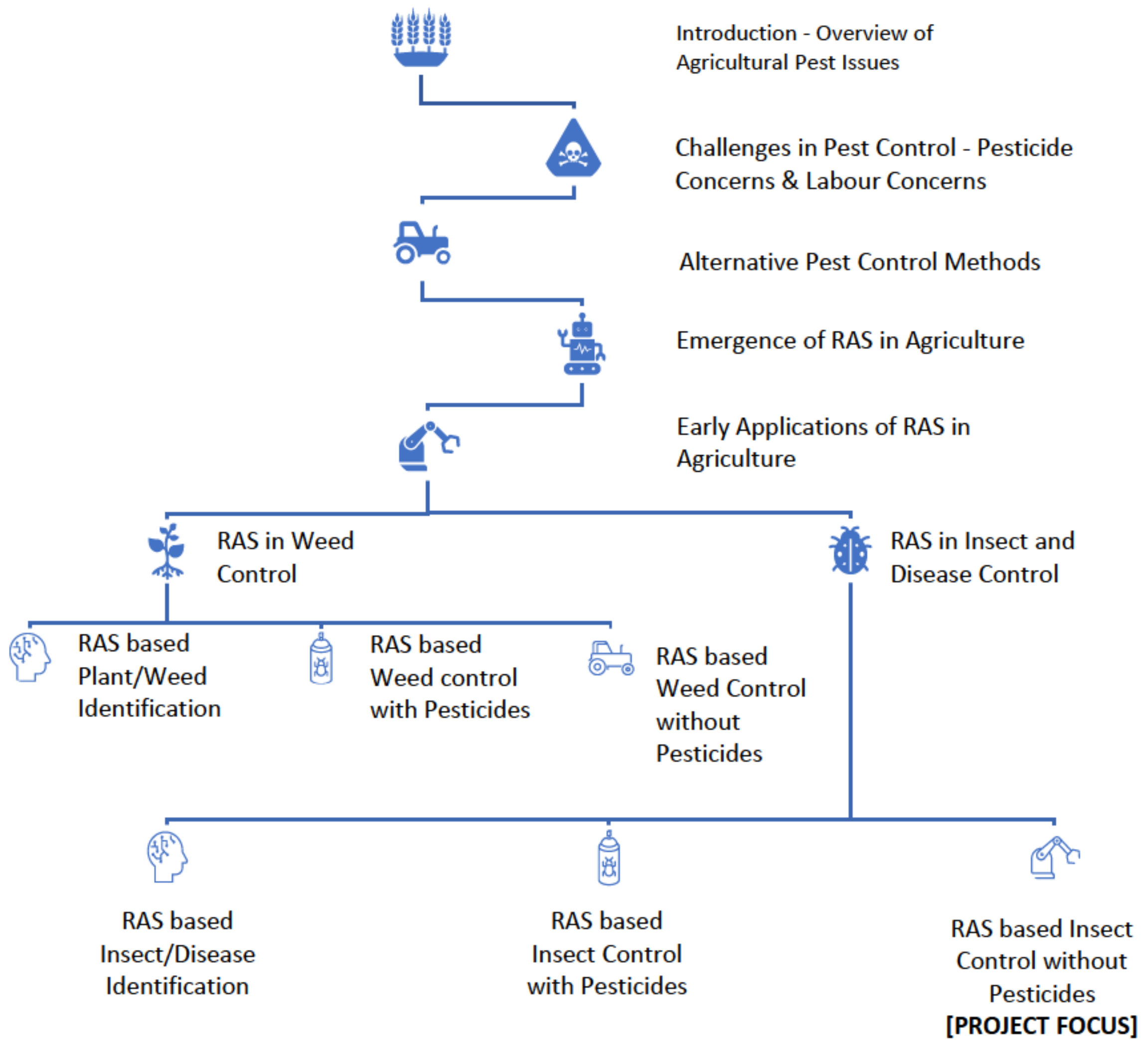


Figure 1. Literature Review Concept Development Flow Chart

2.1 Agricultural Pests and Pest Control Considerations

With pests estimated as being responsible for up to just over 40% of production losses from major crops around the world, and these losses estimated as potentially being double this without the use of pesticides (Lippmann & Leikauf 2020), the importance of pesticides is without question. However, pesticides are also increasingly being seen as placing considerable and unsustainable stresses upon our biosphere (Gonzalez-de-Santos et al. 2016; Oliveira, Moreira & Silva 2021). Their lack of specificity is of particular concern, typically killing other unintended species as a side effect of their application. This can lead to immediate disruptions in impacted ecosystems, removing the natural predators of the pest species, along with other beneficial insects such as pollinators. Follow-on impacts may include quicker recovery of the pest species soon after pesticide application, disruptions in food chains (negatively impacting food sources for higher order species such as birds, bats, amphibians, and reptiles), and reduced crop yields as a result of reduced pollination (EEA 2023). Furthermore, it has long been known pesticide use may result in residual toxicity within the environment that can have long-term disruptive effects upon ecosystems, including soil systems, with impacts upon the ability of soils to support life. The accumulation of these chemicals within the environment, and within lower order species (such as plants and insects), through the process of bioaccumulation, may also pose further risks to higher order species, potentially resulting in toxic impacts upon these organisms (Iyaniwura 1991).

In the last fifteen years, there has been a growing body of evidence indicating pesticide usage is having detrimental impacts upon human health, being clearly linked with a range of chronic diseases and disorders (Mostafalou & Abdollahi 2013; Davies 2022; Limb 2023; EEA 2023, Schlindwein 2023). Of note, are links between pesticide use and DNA damage, with evidence suggesting pesticide exposure in agricultural workers has resulted in increased incidence of diseases including: Alzheimer's; Parkinson's; and cancer, along with higher rates of birth defects and reproductive disorders (Kaur & Kaur 2018). In recent years, a number of pesticides are noted to have been banned in the United States by the EPA, due to health concerns, with dimethyle tetrachloroterephthalate (DCPA) having been recently banned (August 2024), due to concerns around its potential to harm human foetuses (Foster 2024). Of further concern, journalists are reporting chemicals now banned in some countries (due to their known detrimental impacts upon the environment and human health), are still being used in many parts of the world, including in Australia (Davies 2022), and actively being exported from the very countries that have banned them (Limb 2023; Schlindwein 2023). Within this list are pesticides linked to cancer, reproductive issues, hormone disruption, and neurological damage. The significant use of chemicals for the purposes of pest control can be more clearly seen in Figure 2, showing the prevalence of this usage across the world during 2020. Of further concern are studies indicating some pesticide levels in surface water and ground water are being seen to exceed water quality thresholds (EEA 2023), as seen in Figure 2. It is thus evident pesticide usage is an issue of great significance, with a demonstrable need for the introduction of alternative pest control measures.

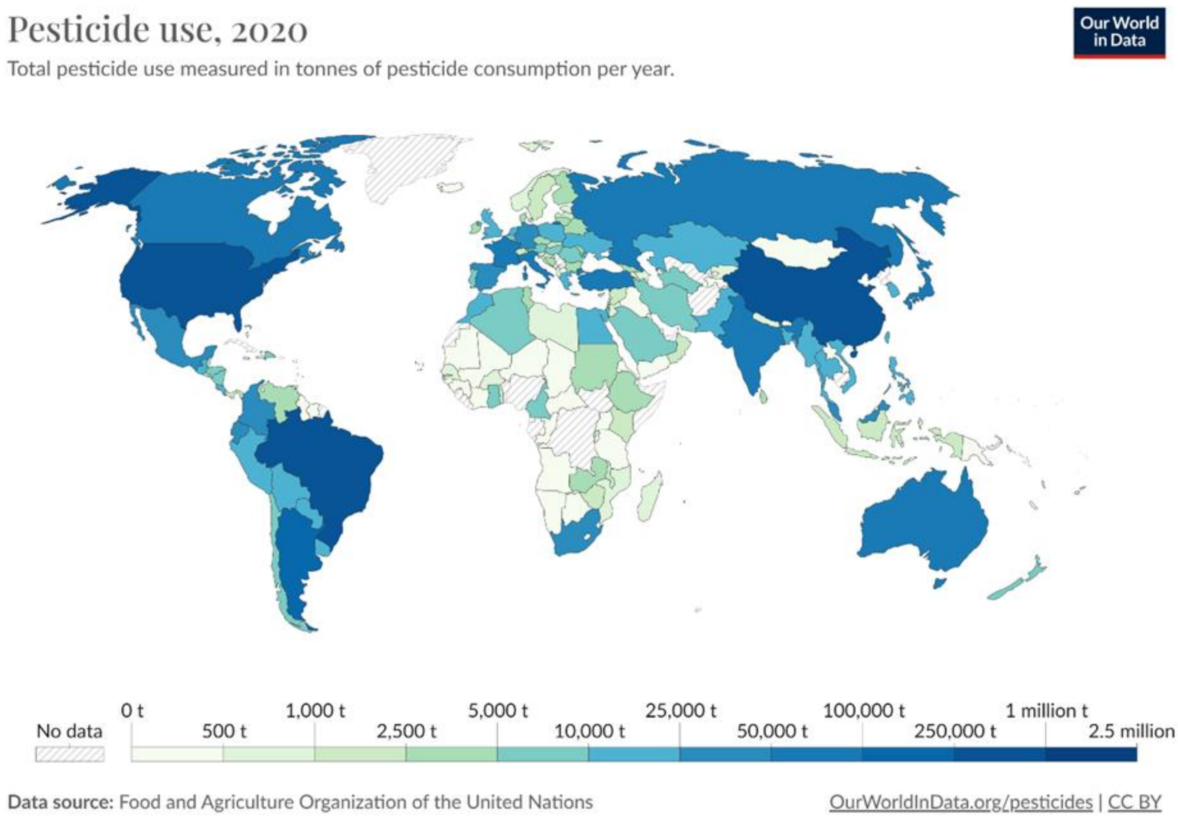


Figure 2. World Pesticide Use 2020 (Richie, Roser & Rosado 2022, p. 1)

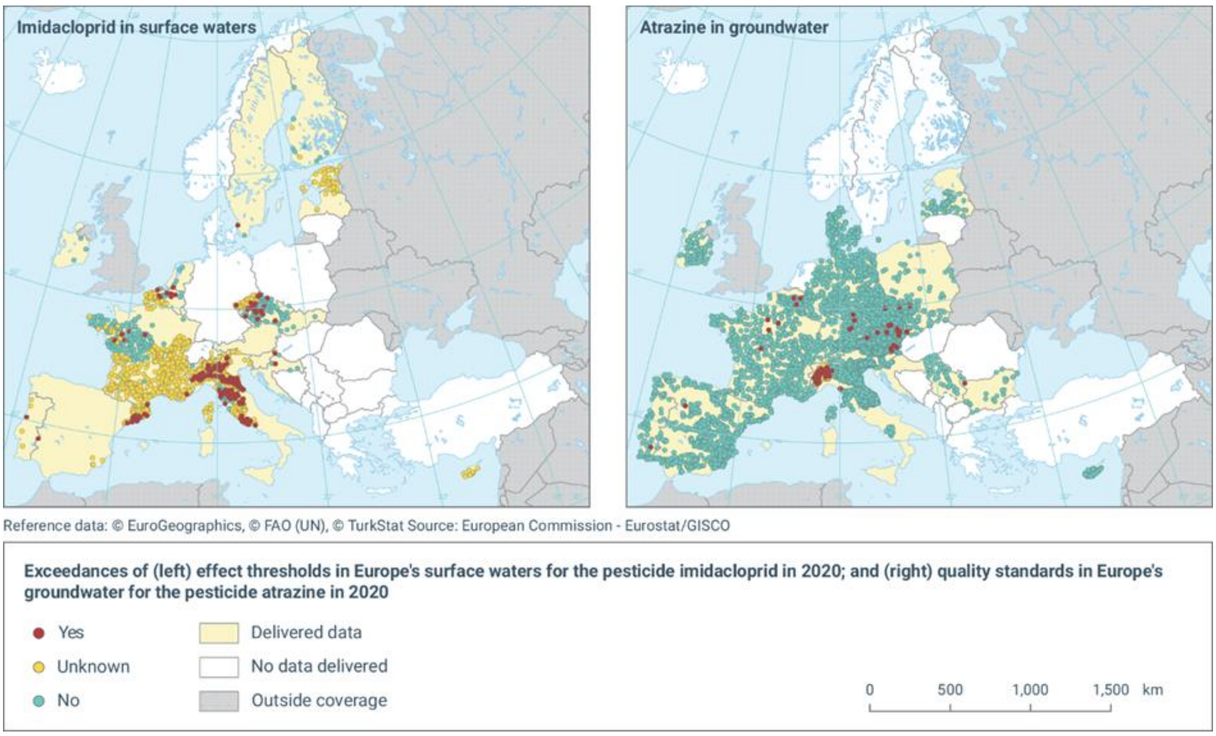


Figure 3. Exceedance of Thresholds in European Surface Waters and Groundwater (EEA 2023, Fig. 3)

One such alternative is the use of biological control systems. Such systems rely on the use of living organisms to control pest species (one of the most famous examples being the introduction of the Cactoblastis Moth to control Tree Pear in Australia). These systems, however, can be difficult to establish, can be very expensive, are usually slow to deploy (meaning damage may already be significant before these more natural systems are able to have an impact), do not always have a viable biological control agent available for a specific pest, do not always target the intended pest exclusively, and typically do not completely destroy or remove the pest (DPIRD 2017). One of the more successful ways in which these types of systems do work, is when combined with other control systems, through what is known as Integrated Pest Management, or IPM. While IPM has had proven success over many years, it too can struggle with efficacy where pesticides continued to be used, as a result of these pesticides killing the beneficial organisms being introduced by biological control systems (Overton et al. 2021). Furthermore, IPM requires a significant need for good habitat management to maintain the biological control agents, through improving their long-term survivability within the ecosystem (Koul, Dhaliwal & Cuperus 2004). In summary, while a relevant and important method of pest control, on their own, biological control systems are unable to meet the needs of modern agriculture, especially in controlling large or sudden outbreaks in pest species, or where pesticide application is also in existence.

Another pesticide-free alternative to pest control, is to manually remove and, where appropriate, destroy the pest species. While employed in many agricultural settings (e.g. hand removal of grubs from backyard crops, hand pulling/chipping of weeds, and small to large-scale cultivation using machinery), there are significant labour requirements and associated costs involved. It is also noted options such as cultivation via mechanised means are not always viable (e.g. intra-row cultivation, and cultivation around some horticultural crops), or may in-turn, create further issues that may adversely affect the soil (e.g. soil compaction), or the environment (e.g. agricultural diesel emissions from use of diesel tractors). Furthermore, agricultural enterprises are finding it increasingly difficult to source experienced and/or willing workers (Tian, Yi & Yu 2020; Downham & Litchfield 2022; NFF 2022), especially for work which may be labour intensive, and/or highly repetitive. Whilst other mechanical based control approaches also exist, including use of traps and barriers, these also typically have significant labour requirements around construction and maintenance, and so suffer the same issues as the manual removal approach.

2.2 Use of Robotics and Autonomous Systems in Agriculture & Pest Control

While the problems are many, and there seems no clear way to move past our need for pesticides, nor any easy way to overcome the stated labour issues, with significant advances in technology over the last thirty years, a solution potentially does exist – this being through the use of robotics and autonomous systems (RAS). In 2018 it was established by Duckett et al. that RAS within agriculture was becoming an increasingly important, large, and growing sector within the United Kingdom. Their White Paper also made it clear RAS was seen to be a solution of growing importance in helping reduce pesticide use. The use of robotics in agriculture was further identified as having significant potential in improving the efficiency, intensity and sustainability of agriculture, a concept supported by Oliveira, Moreira & Silva, in their 2021 review paper. This is noted to be of particular importance in supporting future food security, a point of growing worldwide concern, given growing populations combined with frequent adverse weather conditions (resulting from the growing impacts of climate change), are now placing significant stress on food generating enterprises. This 2018 assertion by Duckett et al. has been supported by recent comments from Degieter et al. (2023), who noted the development of these technologies, forming part of what is now increasingly referred to as "Agriculture 4.0", was being driven by increasing populations and the need for improved sustainability of agricultural production, along with a need for reducing its associated environmental pressures.

In Spain, Gonzalez-de-Santos et al. (2014), established, via their "Robot Fleet for Highly Effective Agricultural and Forestry Management" (RHEA) project, a wholistic integrated approach for the automation of pest detection was possible using robot visual systems and open-source analysis algorithms. In this study, aerial-based robots (UAVs) were co-ordinated with ground-based robots (unmanned ground vehicles or UGVs), so as to combine the technologies as a means of reducing pesticide use. The UAVs were initially used for field image and data acquisition, which was processed and fed into UGVs that were equipped with systems allowing them to navigate the field, discriminate weeds from crops in real-time, and then apply appropriate physical or chemical treatments for their control (with different actuation systems being attached to the UGVs for the different methods of control as per Figure 4). The first actuation system used was the weed patch spraying system, which controlled spray application with solenoid operated valves, and was able to select one of three flow rates, based upon whether the system had detected low, medium or high weed/crop ratios (it being noted the ground detection system was unable to be used in narrow row crops). Weed detection at this time was essentially based on the system establishing the green density of locations where the crop should not have been present. This was achieved by first defining a crop line for each row, and then a density matrix which was then used to define the weed/crop ratio. The canopy sprayer included a perception system of vertically oriented ultrasonic sensors configured to establish the size of the object present in the spray zone (i.e. the trees being sprayed), and then through a combination of small motors and solenoids, focussing the spray on just the targeted area. The final actuator system was the mechanical and thermal tools. These appear to have been designed to be set to generally till the earth and to then also apply a level of flaming to areas where weeds were detected, once again being based on a three-tier system, much like the patch spraying system. While not a highly refined approach for management of pests, and some concerns exist around the transport of flammable gas and use of flame within a field situation, the study successfully demonstrated weed control via automated targeted herbicide application was possible, as was use of automated heat and blade systems.

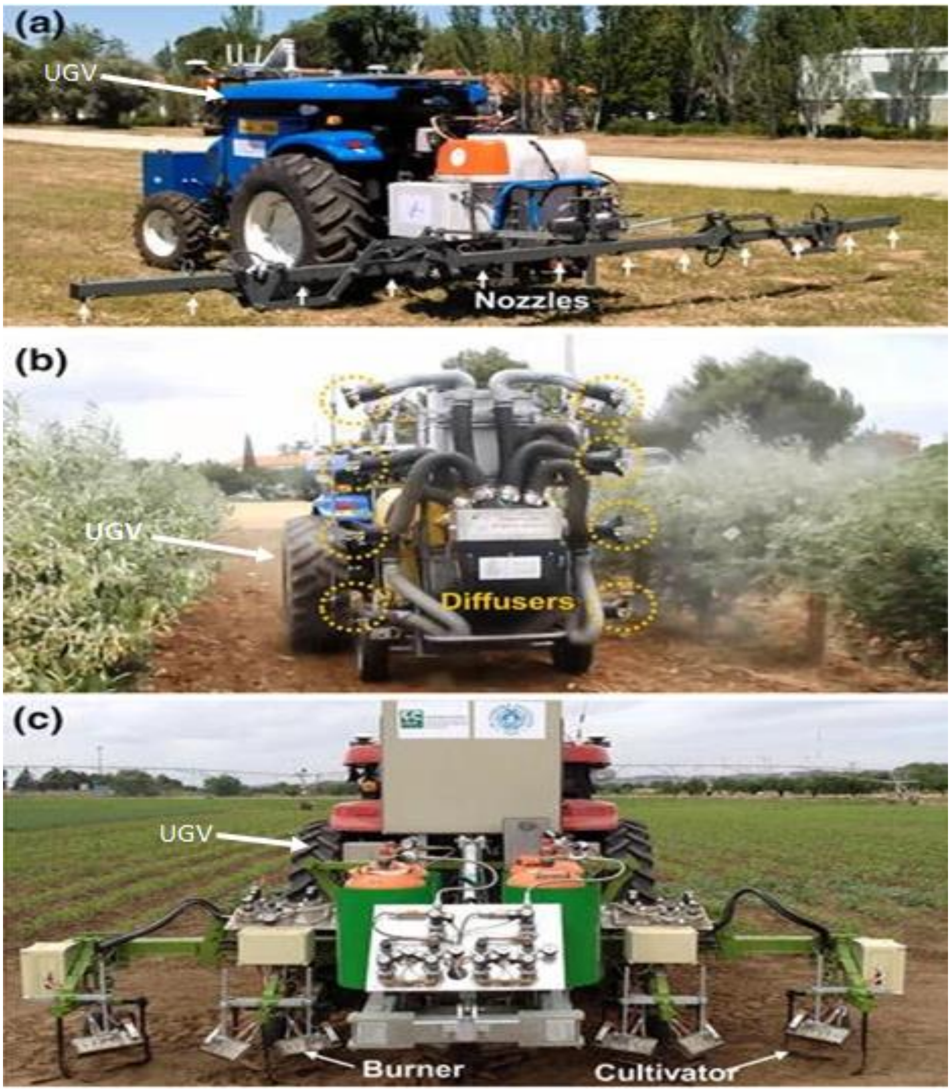


Figure 4. UGV with a) Patch Sprayer, b) Canopy Sprayer, c) Mechanical and Thermal Implement (Gonzalez-de-Santos et al. 2016, Fig. 11)

Work by Shamshiri et al. in 2018 reviewing the state of digital farming, indicated development of RAS based technology within the agricultural space had continued. In their paper, the authors noted the use of collaborative robots and drones in: fertiliser application; fruit detection; weed detection, identification, and mechanical control; and targeted application of herbicides across a range of agricultural industries. While a broad range of activities and areas were examined, the authors specifically noted development of RAS within field scouting and data collection robots, weed control and targeted spraying robots, and harvesting robots. With field scouting and data collection robots, use of advanced sensors for navigation, obstacle avoidance and manipulator control, was noted to have successfully managed such things as mapping, autonomous navigation, yield estimation, plant detection, health monitoring, vegetable detection and classification, and the manipulation of small objects (including trimming, pruning and fruit picking). Weed control and targeted spraying robots were identified as being one of the most in demand application of agricultural field robots, due to the need for accuracy, uniformity, and efficiency within this area. Findings identified a range of such robots were already in existence and well represented within the literature, with a 90% reduction in herbicide use commonly observed when applied via RAS based systems. It is thus noted such approaches clearly offer large financial and environmental benefits over existing application approaches. With respect to robotic harvesting, the authors observed demand for such systems arising from the desire to shift from tedious and repetitive manual approaches to one that was automated and continuous. Whilst such approaches have clear benefits from a labour perspective, benefits in terms of efficiency, competitiveness, and yield also exist. Despite significant research and development in the field, difficulties were still observed to be occurring around the detection, localisation and harvesting processes. Improvements were, however, still noted to be occurring, with better visual recognition, greater ability to detect and localise fruit (even in dense foliage), and customisation of end-effectors to be more fit-for-purpose. Of note within this area, was the authors having identified use of an autonomous framework utilising a number of simple axis manipulators had the potential to be faster and more efficient than the use of more expensive "professional" manipulators. Ultimately, while noting significant advances, and specifically observing research around robotic weeding and harvesting was seeing increasing attention over recent years, the 2018 Shamshiri et al. review identified there still being a need for improved sensory systems within RAS. The authors also identified there to be a need for further development of simple manipulators for agricultural purposes, and their associated control systems, with robots still unable to compete with human operators. These observations have also been noted in other works, including those of Duckett et al. (2018), clearly indicating a gap in these areas within agricultural RAS.

From a review of the literature in 2020, Fountas et al. established while there was significant work being done around harvesting and weed control using RAS, as previously indicated by Shamshiri et al. in 2018 there was still little being done around other areas including disease control and planting. This is supported by Figure 5, showing the number of robots in each specified type of field operation identified by the authors during their review. In this figure it is observed harvesting, weeding, and scouting robots dominate the field and that there is significant development within the commercial space around both weeding and harvesting. Specifically, within their review Fountas et al. made it apparent there was minimal evidence of robotic insect pest control having occurred within the last 20 years, suggestive of there being a significant gap within this research space. Within disease and insect detection robots the authors observed three core issues existed: a lack of image databases; slow image processing; and non-uniformity in lighting conditions. The authors also noted, however, these issues were gradually being addressed. In concluding their review, Fountas et al. recognised there was need for further work to occur within the areas of agricultural RAS communication and sensing systems, in particular, better vision systems to help with crop and pest detection and identification. The need for the development of Deep Learning methods to improve end-effector performance, with particular focus on improvements in hand-eye coordination, was also noted.

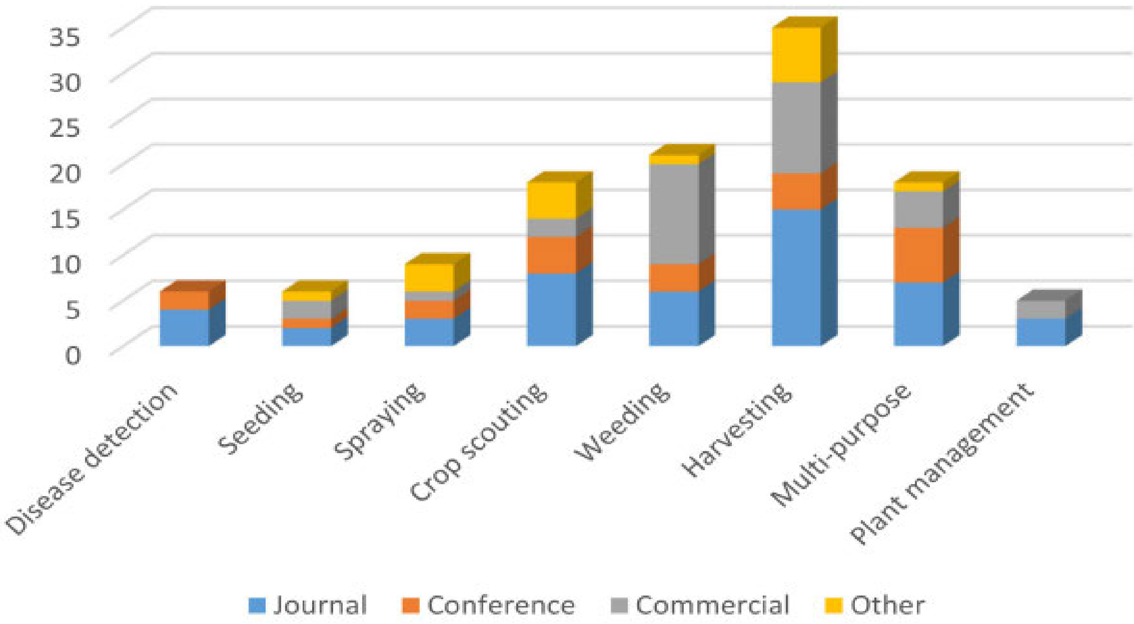


Figure 5. Number of Reviewed Robots Identified per Field Operation Type (Fountas et al. 2020, Fig. 4)

The Fountas et al. 2020 findings were supported by a later 2021 review by Oliveira, Moreira & Silva, who established while significant developments in agricultural robotic applications were occurring (with examples provided around land preparation, planting, plant treatment and harvesting through use of RAS), insect identification and control showed little evidence of research or development. Similar support for these findings was noted as being described ed by Gawade et al. in 2022, though the authors further identified RAS as successfully having used: machine learning; implementation of support vector machines (SVMs); and blob analysis, to identify specific weeds and disease. Looking more closely at the 2021 Oliveira, Moreira & Silva study, it is noted that weed detection and removal has been occurring across numerous studies, over a number of years, and showing steady signs of improvement, with RAS based recognition of lettuce and broccoli by newer visual systems exceeding an accuracy of 90%. The presence of commercially available autonomous weed control robots, including three French Robots (Oz, Dino and Ted) designed for market farmers (see Figure 5), lends further support to the degree of development occurring within this field. It is noted all three robots mentioned are autonomous, battery powered, and use mechanical tools for weed elimination. Other countries such as Japan, Italy, Australia, and the USA were shown to have developed, or be in the process of developing, similar technologies, though with a greater focus on the precise control of pesticides, rather than use of mechanical based end-effectors. The authors of this review furthermore identified there were advances being observed within the area of plant disease detection, with a reviewed study by Schor et al. (2016), establishing RAS systems were able to detect powdery mildew and tomato spotted wilt virus within a greenhouse environment. Robotic harvesting technology was another field that the review demonstrated as having considerable work occurring around it, with numerous countries heavily involved with this work, due to the recognition of the large labour demand, growing difficulty in sourcing such labour, and associated cost of such work. Examples of such technology noted in the review included the Spanish developed Agrobot E-series robot (Figure 7), made of stainless steel and military grade Aluminium, utilising 24 independent robot arms and associated end-effectors able to pick strawberries, and the American Berry 5 robot, capable of harvesting eight acres of strawberries per day. Of particular significance in these developments, with respect to use of RAS in Agriculture, is the steady improvements within robotic visual perception, and development of systems able to better manage hand-eye co-ordination type activities. The need for improved simplicity of construction and efficiencies within robotic systems are, however, noted as needing further work.

Figure 6. French Weeding Robots - Oz, Dino and Ted (Oliveira, Moreira & Silva 2021, Fig. 6)

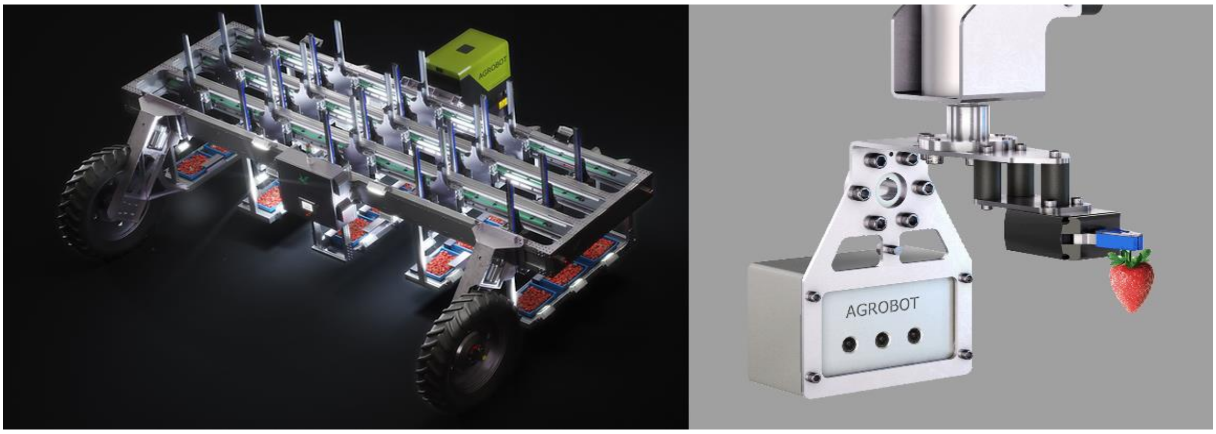


Figure 7. Agrobot E-Series (Adapted from Agrobot 2020, para. 3 & para. 5)

2.2.1 RAS in Weed Control

In support of the 2020 Fountas et al. and 2021 Oliveira, Moreira & Silva claims around weed control, there is much evidence both within the literature and commercially, to support significant advances having continued to have occurred within the robotic weed control space. This is particularly apparent in a 2023 review by Vijayakumar et al., who observed over 100 recent articles written around smart sprayers and precision weed management. In their review the authors also noted marked development in the fields of image processing, machine vision, machine learning, Deep Learning (DL) and robotic spraying systems over the prior 25 years, with the number of papers published per year recorded as trending upwards on average. In the review, weed control was noted as being divided into that achieved with herbicides, and that achieved without herbicides. Weed control achieved without herbicides included development of mechanical systems typically involving direct contact with weeds, application of lasers, or heat. Those using herbicides were instead noted as being dominated by precision spraying technologies.

2.2.1.1 RAS Based Weed Control Using Pesticides

From a precision spraying research perspective, in 2021 Terra et al. noted while the existence of autonomous tractors and agricultural vehicles were already well documented within the literature, efficiency of pesticide application indicated that it could be further improved through the use of robotics. Noting a number of related works by other researchers also occurring around the development of improved pesticide application through use of robotics over the previous five years, the authors proceeded to establish how sprayers could be automated relatively easily to improve spray delivery, through use of low-cost robotic systems. This type of work appears to have gained commercial interest quite early, with the company "Ecorobotix" noted to have been working on developing robots that performed autonomous weed control as far back as 2018 (Ben-Ari & Mondala). Of note, this same company is currently marketing a precision sprayer able to perform highly targeted spray application of herbicides, fungicides, and insecticides. Ecorobotix claims their market ready "ARA" sprayer (Figure 8) is able to significantly reduce the use of pesticide application (with reductions stated as being in excess of 90%), through use of visual recognition systems allowing plant-by-plant spraying. Their machine is also stated to have the ability to recognise dozens of different crops as well as numerous weeds (Ecorobotix 2024). It is also noted that within Queensland, the company "Agtronics" has now commercialised a similar technology, with what they refer to as their WEED-IT weed detection and elimination technology, which they claim is able to identify and then spray only the weeds, reducing chemical usage by up to 90% (Agtronics 2023). While both the above mentioned commercially available forms of this type of technology are still towed or vehicle mounted, many agricultural vehicles are now utilising automated control systems for their steering which combined with the observations made by Terra et al. (2021), around significant work already occurring within the autonomous vehicle space, seemingly indicates the path to full automation of such systems to be a short one. While offering significant benefits over tradition herbicide application approaches, concern still exists with this use of herbicides, in that they are still entering the environment and still exposing workers, consumers and any other living organisms within that environment, to the toxins within them.

Figure 8. ARA Precision Sprayer (Ecorobotix n.d. p. 1)

2.2.1.2 RAS Based Weed Control Without Pesticides

Research performed by Visentin et al. (2023), provides further support of the nature of the recent advancement of robotics within the weed control space, but this time based around herbicide elimination, rather than herbicide reduction. In this study the authors noted autonomous weed identification and physical removal (both inter-row and intra-row), as having successfully been achieved. Of relevance to future pest identification studies, was their highly successful identification of plants (both weeds and crops) under varying lighting conditions, through use of a pre-trained Deep Neural Network, which achieved identification success rates in excess of 95%. Within this study a robotic gripper was used to remove the weeds, in association with an RGB-D vision system, which after pulling the weeds, placed them into an associated temporary storage container. Pairs of cameras were used to achieve this, with the first mounted high above the gantry robot, to identify and locate the weeds, with the second higher resolution camera mounted aside the gripper and used to correct the position and classification of the weeds prior to their removal. While the work successfully demonstrated the feasibility of autonomous robotic weeding systems, it also importantly noted that there had been numerous recent developments within the area of agricultural robotics (agri-robotics) research over the last ten years, with successful mechanical-based solutions having been used to remove both inter-row and intra-row weeds, supporting previous claims that work in this field was well represented within the literature.

Further evidence supporting the advancement in mechanical based weed control via RAS comes from within the commercial space, where it is observed the company "Carbon Robotics", based in the US, have been successfully marketing their LASERWEEDER™ implement (Figure 9) since 2022. This device uses high resolution cameras, along with advanced computing and AI to help recognise and then destroy weeds in real time using an array of high-power lasers (Carbon Robotics 2024). The automation of traditional field tillage methods by companies such as "Pellenc", is another commercialised example of a mechanical based RAS weed control approach, with this company recently releasing an autonomous inter-row crawler, for use in the cultivation of vineyards (Pellenc n.d.).

Figure 9. LaserWeeder (Carbon Robotics 2024, p. 1)

Clearly addressing many of the identified issues around pesticide usage, mechanical based technologies incorporating RAS offer significant advantages over pesticide-based RAS approaches. This said, indications are the high initial capital costs of such technologies, may be limiting or at the very least slowing, their adoption. From a research perspective, however, it is apparent there has been, and continues to be, a great deal of research occurring within the robotic weed control space, with the primary need now being to make such technologies cheaper and more accessible.

2.2.2 RAS in Insect Control

In contrast to the previously mentioned works of Fountas et al. (2020), Oliveira, Moreira & Silva (2021) and Gawade et al. (2022), regarding there being limited work occurring within the RAS space around insects, it is interesting to note that prior to all these papers having been published, research was already occurring in the area of insect pest identification. Seemingly an obvious pre-cursor to any form of future robotic insect control, the specific study in question, carried out by Dawei et al. (2019), claims to have successfully used a transference learning model, called "AlexNet" to train an image recognition system to identify 10 different types of insect pests. With the trial establishing the image recognition ability of the system as being comparable to human experts, as per Figure 10, the authors stated the trial as being highly successful, also making mention of the adaptability of their approach for other systems. The authors never-the-less acknowledged that there was much work needed within this field.

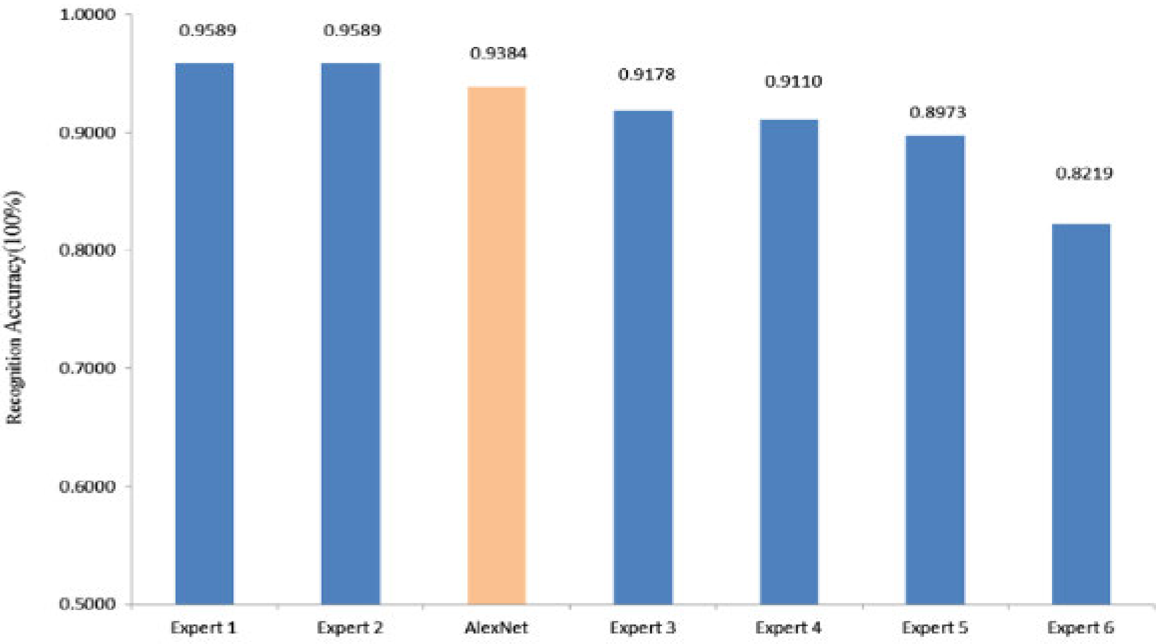


Figure 10. Accuracy of AlexNet Compared to Human Experts (Dawei et al. 2019, Fig. 5)

Another paper disagreeing with the assertion of Fountas et al. (2020), Oliveira, Moreira & Silva (2021) and Gawade et al. (2022) surrounding robotic control of insect pests was published in 2021, by Barnes et al. This paper, looking at the use of RAS in cotton, clearly identified work around insect control using robotic systems was, at that time, being considered in the United States of America (USA). As well as developments in RAS across many areas of cotton operations, the authors reported that robotic systems were being considered as an option for identifying insect pests, this being consistent with the earlier 2019 work performed by Dawei et al. In their paper, Barnes et al., stated that work with targeted insect pesticide application, along with other alternate insect control methods though the use of RAS, was in the process of being investigated. The authors furthermore noted that the use of open-source libraries, such as the Robotic Operating Systems (ROS) middleware library, were being used to facilitate developments within the agri-robotics research space. Though recognising the potential benefits of ROS in helping to speed up the development of RAS in many areas of agriculture, Barnes et al. also acknowledged the need for further advances in deep learning architecture, with the identification of specific pests still presenting significant challenges. However, the authors also made it clear that avenues of pest identification through: visual inspection of damage; detection of specific insect chemical signatures; and DNA sampling, were already being considered as alternative mechanisms of identification, potentially helping with this process.

Despite being largely focussed on RAS based weed control, of related relevance to the field of insect control, was Gawade et al.'s (2022) mention of the successful use of a Supervised Learning Process (SLP) through Random Forest (RF) algorithms, to assist in weed detection. It seems plausible a similar approach could be considered with insect identification in future research, potentially tying in with systems such as those proposed by Dawei et al. (2019) and Barnes et al. (2021), in combination with the use of Deep Learning architectures (as now successfully being used within other areas of agriculture), to generate more accurate and robust insect identifications systems. In short, while yet to be fully resolved, there appears to be much work in related fields occurring around the pest identification space, giving confidence to this being an issue likely to be resolved for insects within the near future. With such developments well underway, the next logical step is the application of such technologies to the control of insect pests.

2.2.2.1 RAS Based Insect Control Using Pesticides

With respect to developments in RAS based insecticide application, there is evidence of this having successfully occurred in recent work by Chen et al. (2021). In their study, the authors examined the use of laser guided intelligent spray technology applied to a fruit farm and two ornamental nurseries over a three-year period. While based on a similar approach to the technologies described in the Gonzalez-de-Santos et al. 2014 study, this study instead used lasers, speed sensors, a PWM flow control valve, embedded computer and associated algoriths, along with a digital flow controller (see Figure 11), to help better manage insects and disease within a fruit farm and two ornamental nurseries. The detection and spray regime used in the study focussed on five different insect pests and six different diseases of the crops, with the lasers used to establish tree canopy presence, size and shape leaf density, while the spped sensor established the sprayer ground speed, which was then processed by the embedded computer, to establish and apply the necessary rates of pesticides and foliar products in real-time. While utilising traps and visual observations to monitor pests and disease, the study shows clear advances in the work compared to the prior Gonzalez-de-Santos study, with a greater number of parameters being included within the calculations, along with greater refinement of the pesticide application. Consistent with other RAS based pesticide based control systems, the authors concluded over the length of their study, their approach had not only significantly reduced pesticide usage, but also proved more successful in controlling the targeted insect pests. It is observed that though an improvement over traditional spray approaches, this approach fails to take into consideration the impacts of killing non-target species, supporting there being a need for greater control over the pest destruction process than what systems such as this are currently capable of offering.

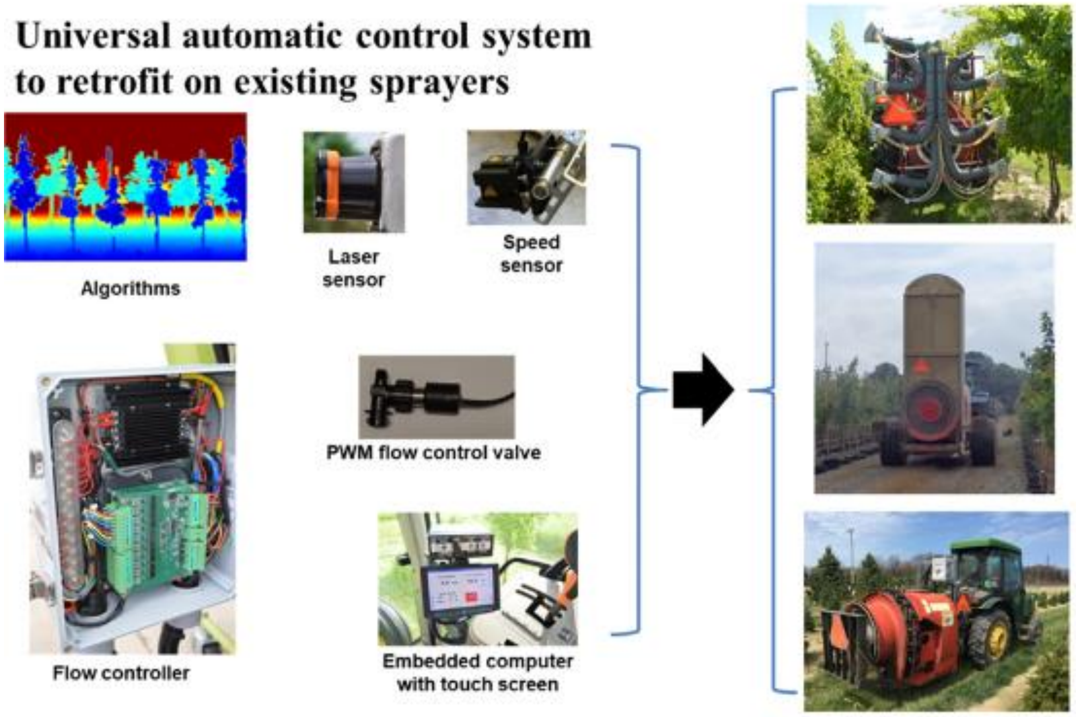


Figure 11. Intelligent Spray System Used for Fruit Farm Testing (Chen et al. 2021, Fig. 1)

In a more elaborate 2021 study, with a much greater focus on automation, Martin et al. developed and applied what they termed their "Robotframework"- an autonomous ROS based architechture integrating navigation, perception and manipulation, with the aim of enhancing early pest detection within complex environments (such as greenhouses). In this work, the authors used a mobile platform with: an onboard PC, 3D laser scanner, two saftey laser scanners, along with an absolute localisation unit (collectively used for obstacle detection, mapping and navigation); a 3D RealSense RGB-D camera and IDS RGB autofocus camera (for finding leaves and acquiring high quality images of the pests); and an electric spray unit whose nozzle was mounted on the end-effector (Figure 12). Operation of the robot was a multistep approach, beginning with navigating to the plant, then autonomously performing a pest inspection task (examining tops and bottoms of leaves and taking pictures), uploading images to the cloud to be analysed by a DL module, generating a treatment plan, returning this plan to the robot, and the robot then delivering precise application of the pesticide at the desired locations. The results of the 3 year study, which included both simulations and field trials: validated the autonomous navigational abilities of the robot; proved the DL module capable of detecting and classifying some of the most common and harmful pests within the examined crops (through both recognition of the pest and of the damage caused by the pest with accuracy levels of close to 90% having been reported); and upon detecting pests or signs of pests, proved able to selectively spray only the infested areas, thus minimising spray volumes used. Of further interest within this study, it was identified by the authors that there was a need for robotic systems to be able to identify insect pest eggs. A key point mentioned in relation to this issue, was the static nature of insect eggs, which the authors suggested may result in them being a better stage of the insect life-cylce to target for robotic control. That said, it was also observed their colouring (often similar to the plant), small size, and potentially difficult to reach positioning upon a plant, may prove to be a formidable challenge for RAS based image detection.

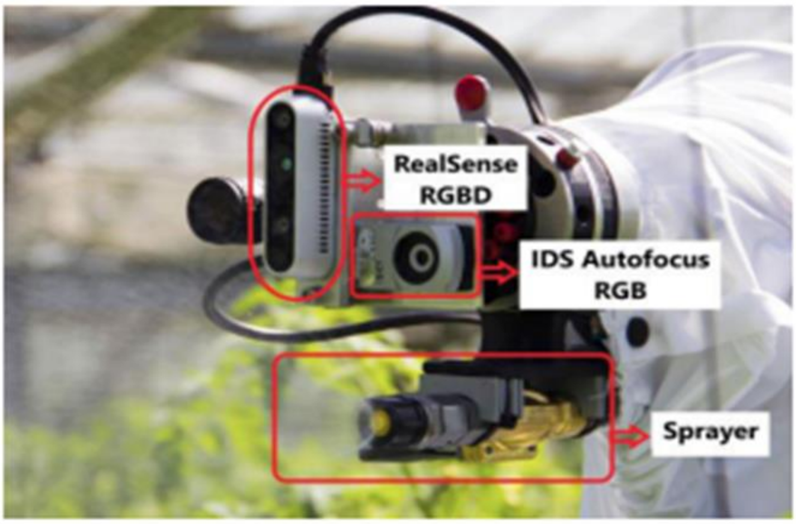


Figure 12. Pest Inspection and Treatment Tools on End-effector (Martin et al. 2021, Fig. 8)

A later study by Mustafid et al. (2022), where the authors were noted to have applied insecticides to cabbages in field conditions using an autonomous robot (Figure 13), also appears to have proved successful in the application of RAS to pesticide application, with accurate delivery of the insecticide to just the target plants having notably reduced the quantity of insecticides used (compared to blanket application). While slower than manual application, the ability of such technology to remove the worker from the process can clearly be argued as being a significant benefit of such a system. A larger, non-autonomous based study by Zanin et al. (2022) also proved successful in reducing the volume of insecticide application through the addition of real-time sensors and controllers to the insecticide spray nozzles being used for broad-acre insect control, allowing the spraying to be directed to just the plants.

While clearly such application of robotic technologies can be argued as being beneficial, both economically and environmentally, it is also apparent there is little evidence of there being specific targeting of insecticides to only the pest species, despite the advances within insect recognising technology. While recognising the improvements within RAS based insect control incorporating insecticides, this approach still fails to address many of the issues previously raised regarding the use of pesticides, including the killing of non-target species and associated spill-over effects. While addressing the lack of targeted insecticide application is a potential research gap, with clear benefits in the event this is able to be successfully accomplished, as noted with precision plant control through use of RAS and herbicides, the fact remains any use of pesticides comes with inherent risk, and if possible, is best avoided.

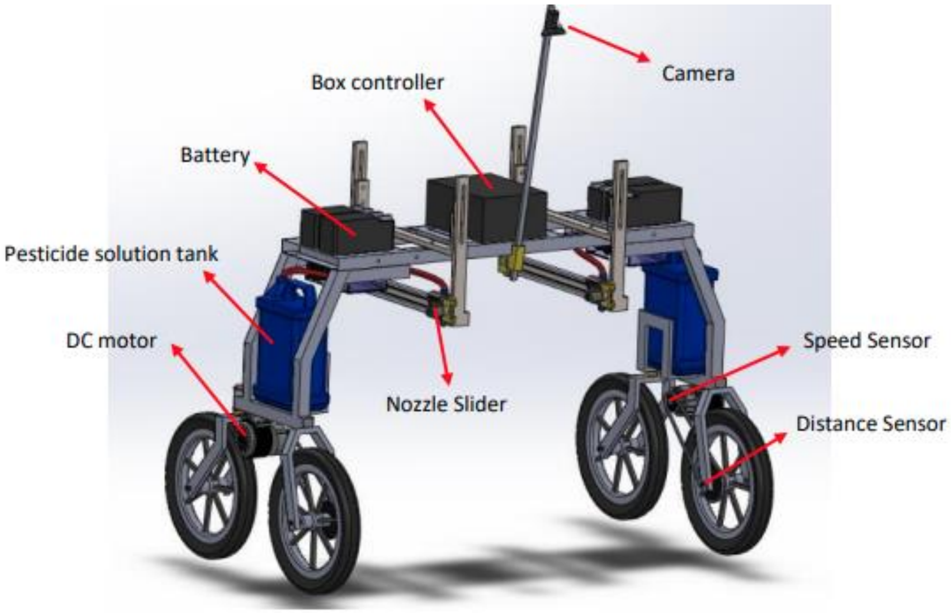


Figure 13. Insect Spraying Robot (Mustafid et al. 2022, Fig. 1)

2.2.2.2 RAS Based Insect Control Without Using Pesticides

One way of avoiding pesticide use in controlling insects with RAS is to instead focus on their control using more physical approaches. Consideration of historical, physical control of insect pests leads to the conclusion that physical approaches can, as asserted by Vincent et al. (2003), be categorised as being "Active" or "Passive" in nature. Those that are active can be in turn be classified further as being mechanical, thermal, or electromagnetic in their action, while those that are passive are primarily concerned with the use of barriers and traps (but also include the use of oils and surfactants). Apart from removing the risks associated with pesticides, the successful combination of some of these approaches with RAS clearly has the potential to alleviate the previously identified labour issues in use of manual insect control measures, removes the need for insecticide use, and if combined with insect recognition technology, provides an opportunity to selectively control specific pests, thereby producing approaches which could theoretically be incorporated within the management practices of an IPM framework.

Whilst it is acknowledged not all the previously mentioned approaches lend themselves to incorporation with RAS, those classified as active in nature, appear to be well-suited. When examining the mechanical control of insect pests, it is noted historically this has been achieved largely through a few specific practices, including tilling of the ground (to disrupt soil-based breeding cycles), manual removal and destruction of larvae and adult pest species, use of surface irrigation/washing of plants (Ofuya, Okunlola & Mbata 2023), and through the application of pressurised air (Vincent et al. 2003). With respect to robotic applications of these approaches, it has been established while automated tilling of the ground is already occurring, there is limited evidence of work being done to automate the manual removal and destruction of insect pests. With integration of RAS and fruit picking (Figure 7 & Figure 14), already an established research field (Duckett et al. 2018; Oliveira, Moreira & Silva 2021), and similar research occurring around development of end-effectors for use with picking cotton (Barnes et al. 2021), this lack seems indicative of another potential research gap, especially given the ability to modify the nature and use of gripper type end-effectors for specific and reasonably intricate agricultural purposes already proven. While there initially appears to be merit in the idea of using RAS to assist in automating the washing of pests away from plants, and potential benefits exist in the case where insect eggs are able to be removed in this way, the volumes of water likely required at large scale and water pressure potentially required to effectively dislodge these eggs, combined with the fact the pests are generally not destroyed via such an approach (so can quickly move back to the host plant), suggests this to be a less favourable approach in comparison with other available methods.

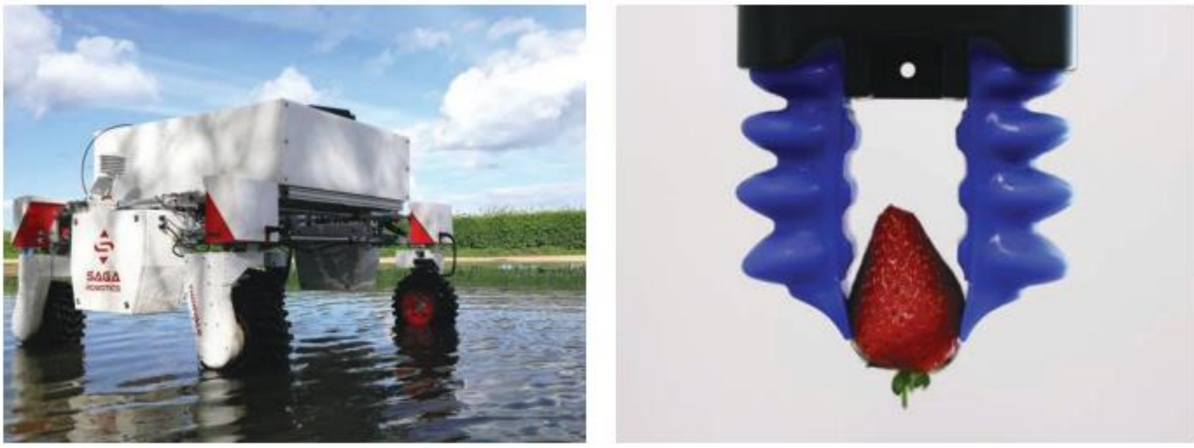


Figure 14. RAS in Fruit Picking (Duckett et al. 2018 p. 12)

With respect to the use of air pressure as a pest control mechanism, there is evidence in the literature of this already being attempted through use of negative, rather than positive air pressure, as far back as 1996, where a test bench was set up for trialling the vacuuming of insects from plants by Vincent & Chagnon (2000). Since these early experiments, despite later mention of such devices being too expensive and lacking in efficiency (Keupper 2003), work is noted to have continued, with the company "Micothon" now building commercialised vacuum systems for insect extraction in greenhouses in the Netherlands (Micothon n.d.), as shown in Figure 15. A larger manual, non-robotic field-based approach utilising this same control measure is also noted as being used by a number of farmers in California, where insect pests are sucked up to help extend the organic strawberry season (Koger 2023) via a tractor mounted, fan-based rig. While clearly already a proven method of removing insects, the nature of this approach, while evidently suited to automation, appears very specific in its use case. It is also unclear if, nor how, the insects are killed within the Micothon greenhouse system, though it is assumed the removed insects are killed as a result of moving through the blades of the field-based system. Some concern exists here whether all insects are killed, or whether those of a certain size or species are more likely to be permanently removed than others. Furthermore, all insects are noted as being removed, including beneficials, presenting some concerns about its application within IPM. These points noted, there still appears to be opportunity for further development around how such technology might be better incorporated with RAS in a field situation, and more studies around this approach thus warranted.

Figure 15. Vacuum Control of Insect Pests (Micothon n.d. p. 2)

Research around incorporation of RAS with the other two active approaches identified, thermal and electromagnetic, reveals purely thermal approaches as being largely niche, and typically involving use of hot water or controlling preparation and/or storage temperatures to help manage pests (Vincent et al. 2003), and is predominantly used as alternative to chemical fumigation. With raised temperatures likely to damage host plants if applied at levels lethal to insects, management of such approaches is expected to prove difficult. The literature also notes there is little evidence of such approaches being viable within field situation, due to issues around thermal control and heat transfer (Vincent et al. 2003), suggesting limited support for such an approach successfully lending itself to integration with RAS as a pest control measure. Conversely, the use of electromagnetic radiation, in the form of lasers, appears to have found significant interest by researchers in recent years, with integration of this method of pest control with RAS becoming increasingly common within the literature.

In support of the earlier premise (as stated in Chapter 2.2.2), around recent advances being observed in RAS based pest recognition systems, and also supporting the previous statement around use of lasers, a 2019 study was identified to have created a successful simulation using RAS based insect recognition, paired with robotic initiated insect destruction. The authors, Obasekore et al., used a unique approach inspired by cattle egret feeding techniques to develop and perform soil based simulations that were indicative of being able to identify and kill army worms in freshly tilled soil. Using a skid driven platform, manipulator, 2 RGB cameras and a 7-Watt laser as the end-effector, their robot simulation was designed to follow a cultivator, identify the presence of army worms using a purpose-built algorithm, and then locate and kill them with a short laser burst. While the simulation results showed a promising development in the control of insect pests through non-chemical RAS based technology and proved the feasibility of such a system, the authors acknowledged the need for significantly more work around the detection systems and optimisation of the laser. It is suspected, however, the use of a laser within a crop rather than on a simulated test bed, is potentially a lot more hazardous and significantly more challenging than the simulation might suggest, and its use as an end-effector in such operations may need further consideration and testing under field conditions.

In a later 2022 study, Lacotte et al. outlined how they had successfully used a robotic control system with an associated robot in their "Greenshield" project (see Figure 16), to help control aphids within a laboratory setting, also using a laser-based end-effector. The authors used DL processes to locate and neutralise aphids upon living plants, reportedly without impacting the growth of the host plants (in this case potted broad beans and wheat seedlings, grown under controlled conditions). Laser types and doses were experimentally determined prior to the main experiment to optimise the effectiveness of the end-effector laser for specific species of aphids, on specific species of plants. Key parameters examined for laser choices were the laser's ability to generate a lethal dose (to achieve a mortality rate of 90%) and ability to not damage the host plant in cases of false detection. While the experiment's positive results were clearly a significant advancement within RAS, proving development to be ongoing around this technology, the paper indicated targeting was at least partially based on the detection of movement, with the authors identifying a need for improved detection and targeting of pests before the technology would be of use within a typical farming context. The potential impact of increasing laser power or frequency to deal with larger insect pests, was not discussed. Given the small size of aphids, it is evident that while this study was a positive development within the robotic pest control field, in terms of being able to not only locate but terminate insect pests, further work to investigate the effects of laser control on a wider range of insect types and sizes would be beneficial in helping establish the broader effectiveness of this type of end-effector. The noted need to identify the right laser and power setting for even a specific species of aphid, indicates such a device may only be of use for targeting and killing of a single pest species. That said, even the selective targeting of the pest species in the presence of other species, also appears to an area requiring further work, with no mention of this having been investigated or achieved by this research. As a final point around this paper, Lacotte et al. (2022) indicated prior work on insect control using mechanical and electrical means had already been explored, thus justifying their decision to only study the impact of lasers within their design. This said, upon following up the provided references for this statement, it was noted one of these dated from 1991, with no clear link to RAS, while the other focussed primarily on the field effects of electricity used in screens to help reduce barrier penetration by small insects. This, combined with further examination of the literature, which found little evidence to support the authors' assertation, indicates both mechanical and electrical means of insect pest control, in combination with RAS, are two areas in need of further work.

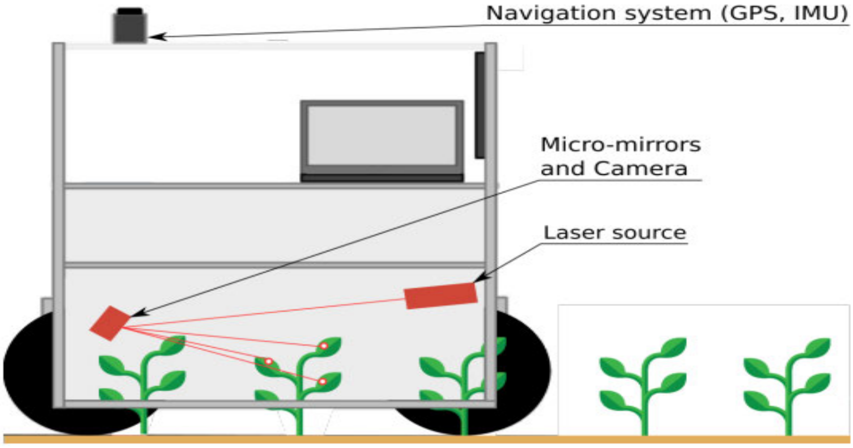


Figure 16. Greenshield Robot Prototype Design (Lacotte et al. 2022, Fig. 2)

With the merits of mechanical control and RAS integration having been discussed earlier, the previous study brings to attention one further insect control method potentially lending itself to automation, this being the use of an electric current. It is interesting to note that while this is an approach commonly used in tandem with ultra-violet (UV) light within domestic bug zappers, and one having been utilised over a significant period of time, there is little evidence of significant application of this approach in other areas. It is assumed the dominance of such domestic usage is largely a historical artifact relating to the ready availability of electricity in the home, compared to what is traditionally found within a typical agricultural environment. With RAS based devices having significant integration with current based devices, however, and thus a need for their own electrical supply, a need being met by rapid technological developments within battery power and storage capacity (particularly with respect to battery size and weight), it is expected this premise will soon no longer hold true. Of concern is that such devices are non-specific in their action, a limitation that would need to be addressed should such devices be desired for use within an IPM based control system. In terms of research around this topic, Jobe et al. (2024) recently examined how electric fields are currently used in the control of insects, as well as having outlined potential directions for the future of this technology. The findings of this study indicate that while electric fields (EFs) have been successfully used to repel, capture, and kill insects, the scientific knowledge around EF-insect interactions, and the efficacy of associated technologies, is still very early in its development. Focussing purely on the insect killing potential of EF technologies, it was recognised by the authors that although electrocuting insect traps have been successfully used for decades to help control flies and mosquitoes, as previously indicated, such traps lack target specificity, and kill significant numbers of non-target insects during their operation. In their conclusions, the authors observed that while use of EF technologies had the potential to significantly expand the range of chemical-free insect control options available, there was a need to better understand the nature of EF-insect interactions, and a need for optimisation of the technology to allow for targeting of different species in different environments, to ensure safer and more sustainable long-term usage. On this basis, and in consideration of the growing ability of RAS to recognise specific insects, there once again appears to be a research opportunity with the field of RAS based insect pest control, through combining RAS based pest recognition with electrical control methods such as electric field manipulation, in order to enhance its specificity, and its thus effectiveness.

2.3 Literature Review Findings and Conclusions

In conclusion, the literature underscores the need for advancements in robotic technology to address agricultural challenges, particularly in pest management. The integration of Robotic and Autonomous Systems (RAS) with pesticide-based approaches, while reducing some associated risks, does not fully eliminate them. Development of pesticide resistance, harm to non-target organisms, and potential for contamination of soils, food and water, still present challenges that can only be overcome through the complete phasing out of pesticide usage. By helping shift agricultural pest control towards more physical-based approaches, researchers can positively contribute towards the development of safer, effective and sustainable pest management strategies.

While automated physical based methods for weed control are advancing rapidly, there's a noticeable gap in integrating similar methods with RAS for insect pest control. Current physical devices, like fan driven vacuum systems, lack specificity, while early RAS devices using lasers show promise but require further development to better discern between insect species, and improve their application over a wider range and size of pest insects.

Progress in insect pest identification is indicative of RAS nearing the capability of selectively detecting insect species. This progress aligns with the established necessity for selective pest removal, offering both health and environmental benefits, as well as better compatibility with Integrated Pest Management (IPM) strategies. The literature, however, highlights a lack of exploration of alternative non-chemical end-effector options for the selective control of insect pests with RAS.

To bridge this gap, the literature is supportive of the need for future research to explore manual removal and electric-fields as potential end-effector options for RAS-based insect pest control. Additionally, research around the refinement of air pressure or vacuum derived control methods to be more target-specific, is expected to prove an important step in improving compatibility with IPM practices. By addressing these gaps, more effective and environmentally sustainable pest management solutions have the potential to be realised within agricultural systems.

In consideration of the rapid advancements in robotic technology, Zhang and Karkee's 2021 vision of RAS replacing labour-intensive farming and field operations seems well within reach. While embracing this future offers a pathway to a healthier environment, enhanced sustainability and increased agricultural productivity, the realisation of this vision requires a significant effort on the part of humanity to reduce their dependence on pesticide use. The development of chemical-free end-effectors for use with RAS based insect pest control would represent a significant step towards achieving such a future.

2.4 Proposed Research Questions

Considering the stated project aim, objectives and outcomes, and taking into account the literature review findings, as outlined in Chapter 2.3, a number of questions have arisen, which this current research project aims to address.

Regarding the primary aim, and in consideration of the literature review indicating there is little evidence to support much work having occurred around physical insect control approaches being integrated with RAS, along with concerns around the lack of specificity with existing control methods:
Is it possible to develop an end-effector prototype, capable of selectively removing and/or killing insect pests, that does not require the use of pesticides, and if so, what types of technologies might be suitable for achieving this?

With the literature review indicating a need to further explore manual removal, electric field based, and air pressure derived control methods, and to help in accomplishing Objectives One and Two:
How might mechanical, electrical or vacuum based non-chemical approaches be incorporated into a functional end-effector prototype with the ability to help control insect pests?

In the event such end-effector prototypes are able to be developed, then to help address Objective Three:
Does any one of the mechanical, electrical or vacuum based approaches, have better potential in controlling all insect pest types when incorporated into an end-effector prototype, or are particular end-effector prototype approaches better suited to particular insect pest types?

More specifically, with a view to addressing Objective Four, where one or more of the aforementioned approaches are able to be developed into a prototype end-effector (and established as offering a viable path towards achieving the project aim):
How can pesticide-free, insect controlling end-effector prototypes be optimised to improve their insect pest removing and/or killing performance?

Finally, in consideration of the identified need to develop both safe and simple manipulators for use with RAS in agriculture whilst also helping to enable the addressal of Objective Five:
Is it possible for a pesticide free, insect controlling end-effector prototype to be developed and built relatively cheaply, utilising readily available components, tools and technologies, and if so, how might this be achieved in a safe manner?

CHAPTER 3: METHODOLOGY

The methodology utilised by this research project endeavoured to use experimental investigation as a means of achieving design refinement. With a primary aim of progressing the development of robotic end-effectors able to eliminate insect pests without the use of pesticides, the methodology used adopted a systematic approach of conceptualisation, prototyping, stimulatory testing, analysis and prototype refinement, in order to develop fully functional and partially optimised end-effector prototypes. Through this approach, the methodology not only demonstrated the practical application of mechanical design principles, but also emphasised the importance of the iterative nature of engineering design, in that insights gained from stimulatory testing of one design, were used to inform changes in the next.

3.1 Project Approach and Methodology Summary/Overview

The project was largely experimental in nature, with design and construction elements embedded within it. The methodology employed encompassed a number of key phases, as per:

Phase 1. Initial Design and Build (Prototyping)

- Ideas conceptualised over the course of the literature review were first developed and transformed into three preliminary end-effector prototype designs.
- Each prototype was designed to use a different approach for non-pesticide-based removal of insect pests.
- The three approaches examined focussed on those areas identified as worthy of follow-up investigation, as per literature review findings, including: physical removal by a gripper based end-effector ("Gripper" prototype); electric field driven electrocution by a bug-zapper based end-effector ("Zapper" prototype); and air pressure driven removal through use of a vacuum based end-effector ("Sucker" prototype).
- Modelling and development of the three prototype designs was achieved through hand-sketching followed by utilisation of 3D CAD software (AutoDesk Inventor), based on initial consideration of: ability of the design to remove or kill insect pests whilst limiting damage to host plants (*Removal Performance*); material/parts availability, expected ease of manufacture, design simplicity, and expected cost effectiveness (*Build Performance*).
- Upon completion of the initial design phase, three prototype end-effectors were built, with both quantitative and qualitative data recorded around the perceived complexity of design and build, time taken to design and build, and estimated cost of the respective builds.
- The preliminary Complexity assessment was based on the following descriptors:
    - Low – simple in nature or concept / low skill necessary to utilise / common and easy to obtain / available from many locations / few simple parts

  - Med-Low – identified as having aspects of both low and medium complexity, roughly in equal parts.
  - Medium – some complexity involved in design or manufacture / some complexity with respect to concepts utilised / medium level of skill necessary to successfully utilise / available or accessible in some locations / numerous parts with limited integration required
  - Med-High – identified as having aspects of both medium and high complexity, roughly in equal parts.
  - High – complex in nature or in design / complex conceptually / high level or uncommon skill set required to effectively utilise / only available from very specialised or specific locations / numerous parts requiring high levels of integration
- A "control" prototype was also considered, to allow comparison of the respective prototypes against doing nothing (this being the basis of the control prototype considerations).

Phase 2. Preliminary Testing – Bench Testing

- Prototypes underwent preliminary performance evaluation and assessment, to establish their effectiveness in the removal of insect pests.
- Stimulus-based testing was employed, subjecting the prototypes to simplified operational conditions.
- Preliminary testing occurred within controlled conditions, testing end-effector effectiveness in removing and or eliminating a range of insect pests of different sizes from a test bench environment, along with other suitable specimens to help establish prototype operation. Insect and other test specimens were collected, placed within a plastic dish, and the end-effectors applied.
- Ability to remove and/or kill/permanently incapacitate the insect pest was recorded, and a description of the process and outcome noted for each insect. Species and size of insect was also recorded. Multiple species and life cycle stages were tested by each prototype, with an attempt to assess preliminary end-effector impact on a range of different insect types.

Phase 3. Secondary Design and Build

- Key limitations and flaws in the devices during preliminary testing were identified and noted, with the primary aim of this phase being to assess design viability and to inform the next phase of the prototype development, so as to create the next iteration of the device.
- Design change proposals were made based around how the noted limitations and flaws of the preliminary prototypes could be addressed or corrected, along with consideration of the material and budgetary constraints.

- Respective prototypes were then adapted and/or rebuilt based upon design change proposals, and quantitative and qualitative data recorded around the perceived complexity of design and build (including time taken to redesign), time take to build, estimated cost of the build and estimated ease of adapting the final build such that it could be easily connected to a robotic arm on a field robot.
- Each of these measures were allocated a value on a 5-point scale (0 - 2), as per:
  - Cost: < $50 = 2; $51 - $75 = 1.5; $76 - $100 = 1; $101 - $125 = 0.5; >$125 = 0.
  - Perceived Complexity: Low = 2; Med - Low = 1.5; Medium = 1; Med - High = 0.5; High = 0.
  - Build Time: < 8 hrs = 2; 8.1 - 12 hrs = 1.5; 12.1 - 16 hrs = 1; 16.1 - 20 hrs = 0.5; >20 hrs = 0.
  - Integration Ability: Very High = 2; High = 1.5; Medium = 1; Low = 0.5; None = 0.
- Perceived Complexity was based on the same original descriptors as used during Phase 1, being a judgement made based on the nature of the components, as well as the perceived difficulty involved in generating the design and then completing the build.
- Integration Ability was based on the following descriptors:
  - Very High – Limited to no changes or additions needed to allow connection to a robot arm.
  - High – Relatively simple changes or additions needed to allow connection to a robot arm with little further time and money needed to accomplish this.
  - Medium – a degree of complexity involved in adjusting the design to allow connection to a robot arm along with a moderate increased investment in time and money.
  - Low – some complexity involved in adjusting the design to allow connection to a robot arm along with significant further investment in time and money.
  - None – state of device is such that large amounts of time and money would be required to make integration with a robot arm feasible.
- These scores were collectively utilised to provide an indication of *Build Performance* for each prototype.
- Preliminary Testing (Phase 2) and Secondary prototype development (Phase 3) continued until three final iterations of the respective prototypes were completed, all of which were deemed as being viable (Noting that as the "Control" prototype involved doing nothing, no changes were required here).

<u>Phase 4. Primary Testing – Controlled Field Testing</u>

- Damage caused by the respective end-effectors to the host plant (Host Damage) was assessed through application of the respective prototypes to chosen host plants at different intensities with photographs of the damage taken over a period of five and a half days.

- Extent of damage, nature of damage and potential for damage from each prototype was then considered and a damage level score assigned to each prototype, to help quantify the data. A total of 7 levels of damage were utilised as per:
    - No observable damage at any point over the 5 days, extremely unlikely that damage would occur during pest removal = 3.
    - Limited to no damage noted within 24 hours of application with little to no damage still observable after 5 days and/or very low likelihood of greater levels of damage occurring during pest removal = 2.5.
    - Limited damage noted within 24 hours of application and/or low likelihood of greater levels of damage occurring during pest removal = 2.
    - Limited damage noted within 24 hours of application and/or moderate likelihood of greater levels of damage occurring during pest removal = 1.5.
    - Moderate damage noted within 24 hours of application and/or moderate likelihood of equivalent levels of damage occurring during pest removal = 1.
    - Moderate damage noted within 24 hours and/or high likelihood of moderate levels of damage occurring during pest removal = 0.5.
    - High levels of damage observed within 24 hours and/or high likelihood for high damage occurring during pest removal = 0.
- Host damage scores were utilised to provide one measure of *Removal Performance* for each prototype.
- Testing was then undertaken to examine end-effector effectiveness in removing and/or killing/permanently disabling pest insects under controlled field conditions, against two lifecycle stages of the Mealworm (*Tenebrio molitor*) - larvae and pupae.
- Effectiveness was assessed via use of a set of criteria for 1. Ability to remove the pest (Removal Ability); and 2. Ability to kill the pest (Kill Ability).
- Ability to remove pest used a three-point scale as per:
    - 0 = Not removed;
    - 1 = Removed from leaf but insect still near host plant/s;
    - 2 = Completely removed from vicinity of host plant/s.
- Ability to kill the pest used a four-point scale:
    - 0 = No obvious damage or impact observed within 24 hours;
    - 1 = Minor damage/impact to test specimen but expected to survive;
    - 2 = Significant damage and/or specimen dead/expected to die, within 24 hours;
    - 3 = Dead (within 2 hours).
- To simplify comparisons, all insects were attempted to be removed and/or killed/permanently incapacitated from the same type of plant, under the same types of conditions (acknowledging this is an oversimplification of what would happen in a true field-testing situation).

- With desired test species unavailable, and substituted species having no ability to grasp host plant, testing was performed by placing test specimens on host plant leaves on the test bench.
- Testing of removal and kill ability was carried out on 20 Mealworm larval specimens and 10 Mealworm pupae, by each of the three prototype end-effectors, against criteria as discussed above and the data recorded. (Note the rationale behind the difference in life stage specimen numbers was based on considering that not all larvae would be expected to survive through to pupal formation stage due to natural attrition, primarily through predation, parasitisation, etc.).
- Sizes and descriptions (Length, Width, Lifecycle stage, Genus and Species) of all specimens tested was noted, where achievable.
- Follow-up testing was later performed using a small sample of Cabbage White Butterfly larvae and adult ladybeetles (of any available species with sourcing of 28-spotted ladybeetles proving problematic). The purpose of this was to better understand the differences observed between the primary and preliminary testing with a change in test species, and to aid in validating the primary testing results and associated analysis. Ability to remove and ability to kill were once again noted and these results compared against earlier test results.

<u>Phase 5. Prototype Analysis and Comparison</u>

- The results for "Removal Ability", "Kill Ability" and "Host Damage" were averaged (where applicable) and combined to give an overall *Removal Performance* for each device.
- Results collected during the design and build phase for the *Build Performance*, were then used alongside the *Removal Performance* results, along with qualitative observations made during the testing phases to identify the prototype/s best meeting all identified design criteria.
- The primary, averaged score data was recorded in an Excel template as per Table 2.
- To allow for assignment of different importance to the examined parameters, different weighting multipliers were then applied to each parameter to help aid in the decision-making process via use of a weighted decision matrix, as per Table 3. This was used to compare each of the end-effectors with respect to their relative overall performance, both with each other and against the control condition.
- With respect to decision matrix weightings:
    - "Integration Ability" rating was set as having twice the contribution of the other *Build Performance* parameters, this measure being increased to allow for the fact that the project failed to reach the point where the prototypes were able to be connected to a robot arm, and thus time, complexity and cost of build were assessed as not providing a fair comparison. This also helped ensure the control result was scaled down, noting it would never be able to be adapted for use as an end effector and yet due to costing nothing, taking no time and having no complexity, it was in theory, by these measures alone, the best build.

- "Removal Ability" was scaled up by a factor of 2x to increase its relative importance in comparison to Cost, Complexity and Build Time, and to give it equal importance to the device "Integration Ability". This also allowed consideration of its importance in the meeting of project objectives.
- "Kill Ability" rating was also allocated a scale factor of 2x, so as to contribute 1.5 times as much as the other two *Removal Performance* parameters (i.e. maximum score of 6 v's maximum score of 4), with pest destruction considered the key objective of the project and thus weighted more heavily.
- The ability to minimise damage to the host "Host Damage" was scaled up slightly by a factor of 1.333, to give it equal weighting to the "Removal Ability Score", noting that any end effector that caused as much damage as it was aiming to eliminate, would serve no valid function.

- Weighted performance scores were then combined and used as a measure of the end-effector effectiveness.
- Results from the weighted decision matrix, along with qualitative data collected throughout the experiment were then used to provide insights around areas in need of improvement and taken into consideration for development of conclusions and recommendations.

Table 2. Average Score Template

	Build Performance				Removal Performance			**Overall Performance (/16)**
Parameter	Cost (0-2)	Complexity (0-2)	Build Time (0-2)	Integration Ability (0-2)	Removal Ability (0-2)	Kill Ability (0-3)	Host Damage (0-3)	
Prototype A								
Prototype B								
Prototype C								
Control								

Table 3. Weighted Decision Matrix Template

	Build Performance				Removal Performance			**Overall Performance (/24)**
Parameter	Cost (0-2)	Complexity (0-2)	Build Time (0-2)	Integration Ability (0-4)	Removal Ability (0-4)	Kill Ability (0-6)	Host Damage (0-4)	
Weighting	1	1	1	2	2	2	1.33	
Prototype A								
Prototype B								
Prototype C								
Control								

- Qualitative data was used to re-evaluate the original decision matrix weightings, along with comparison against doing nothing (i.e. the control prototype), to ensure the weighted results did not prove to be bias towards any device that was clearly unfavourable with respect to the originally stated experimental objectives.
- Consideration of the change in the species used for testing was also performed, including some observations and evaluation around how the results between the various testing phases changed (including the final cross check), along with the possible implications of this.

With multiple testing runs undertaken, results recorded, assessed, and utilised to inform ensuing designs, followed by modifications systematically implemented and tested, the chosen methodology was successfully able to help develop and optimise prototype designs. While recognising that design, testing and development phases were all crucial to the success of the methodology in achieving the primary project aim, safety and ethical considerations are also acknowledged as having been important aspects contributing towards the ultimate success of the project.

Safety during the project was considered not only from an experimental perspective, but also from an operational perspective, thus ensuring a key aspect of objective 5 (to ensure that any end-effector developed was safe, affordable, and easy to construct) was met. Ethical considerations during performance of the methodology were noted to have taken three forms: the first concerning the ethical removal and destruction of the insect pests; the second concerning the integrity and transparency of the collection, analysis, and publishing of the experimental data; & the third concerning the manner in which the findings are ultimately used. Through acknowledging and considering how the limitations and assumptions have impacted the design and performance of the research project, and thus the nature of data collected, the planned methodology aimed to mitigate bias and uncertainty through the use of well-considered experimental design and thorough documentation.

In summary, it is believed that the chosen methodology represented a considered approach in addressing the primary project aim of progressing the development of robotic end-effectors able to selectively remove insect pests without the use of pesticides. By combining experimental investigation with design optimisation, and incorporating engineering principles with scientific based experimental techniques, whilst taking consideration of limitations, safety and ethics (details as per Sections 3.3 to 3.5), this methodology endeavoured to ensure research aims were safely met, whilst also ensuring research outcomes were valid and reliable.

3.2 Materials and Equipment

With the methodology being comprised of design, build and testing stages, the materials and equipment were similarly divided, as per:

Prototyping Design and Build

Arduino UNO board; PC and C++ coding application (Arduino IDE); electric fly swatter (Mafiti); 3D modelling software (AutoDesk Inventor); breadboard, switches, buttons; 10K Ω resistor; and associated wiring; plastic bottles of various sizes; 5V power source; 9V power source; 12V power source; 12V DC 80 mm PC case fan; 12V DC 80 mm CPU fan; Micro servo; 3D printer and associated consumables; soldering iron; silver solder; silicon glue; screws (self-tapping of various sizes); adhesives; 6 mm ID PE tubing; 16 mm ID PE tubing; Digital scales (accuracy ±2 gm); 40L Air compressor; 5 m x 20 mm OD compressed air hose; air blow gun; Electric drill; various sized drill bits; small files; Stanley knife; tape measure; & small Phillips head screwdrivers.

<u>Testing</u>

3 x Constructed end-effector prototypes; Various insect for preliminary testing, including: 3 x Cabbage White Butterfly (*Pieris rapae*) adults (see Figure 20), 18 x Cabbage White Butterfly larvae (see Figure 18), 6 x Cabbage White Butterfly pupae (see Figure 19), 9 x Large Spotted Ladybeetle (*Coleomegilla maculata)* adults (see Figure 20) or similar; 2 x Large Spotted Ladybeetle larvae (see Figure 21) or similar; Various small objects for preliminary testing (Styrofoam balls, foam square, dried pea, dead insects); 30 Mealworms (*Tenebrio molitor*) per prototype for final testing, composed of: 10 x Mealworm pupae and 20 x Mealworm larvae, with group compositions containing specimens of similar size; camera; broccoli plants; digital callipers; plastic containers with lids (various sizes); growth medium for storage of Mealworm specimens after testing (raw rolled oats and slices of carrot).

Figure 17. Cabbage White Butterfly Adult

Figure 18. Cabbage White Butterfly Caterpillar

Figure 19. Cabbage White Butterfly Pupae

Figure 20. Large Spotted Ladybeetle Adult

Figure 21. Large Spotted Ladybeetle Larvae

Data Analysis and Reporting

Spreadsheeting software (MS Excel); Word-Processing software (MS Word).

3.3 Risk Assessment and Management

Whilst the nature of the experiment was such that risks were minimal; it was acknowledged that all identified risk must be effectively managed so to minimise any potential harm. Development of the initial manipulators involved the use of heat and electrical current. With low voltages (< 12V) and low current (< 1A) expected to be used in two of the initial three prototypes, concerns around shock or any form of electrical based damage were very low. It was noted, however, that the Zapper device, being based on electric bug-zapper technology, was stated as able to produce voltages of up to 3000V once constructed. Though seemingly of some concern, it was also noted this was achieved through use of a capacitor, and the device generated only a very low level of current for a very short time. As such, while care was established as needing to be taken with using this device, significant harm was assessed as being unlikely. With heat required to be well above 100ºC, due to soldering requirements during construction of the prototypes, and such heat having the potential to cause burns or ignite dry materials, soldering was identified as a potential hazard, which had to be risk assessed and managed. With soldering fumes also recognised as a potential hazard, consideration of methods to mitigate or minimise any associated risk were also identified as necessary.

A more complete breakdown and explanation of the key elements of the proposed risk assessment and management plan, developed prior to actioning the project, and then utilised to manage the risk, is outlined in the following subsections of this Chapter (Chapter 3.3).

3.3.1 Identification of Risk Sources

- Electrical Hazards: The prototype based on electric bug-zapper technology posed a risk of electrical shock due to high voltages. However, it was noted that the use of low current and short duration greatly reduced the likelihood of significant harm.
- Heat Hazards: Soldering and heating requirements during prototype construction posed a risk of burns and the potential ignition of dry materials.
- Chemical Hazards: Soldering fumes presented a potential hazard to respiratory health if not properly managed. The lead present in standard solder was considered to have health and environmental risks.
- Physical Hazards: The gripper based prototype was identified as potentially having a risk of pinching during operation. Attempts to avoid exposure to the gripper based end-effector or the electrical bug-zapper based end-effector had potential for falls, trips, or collision with objects.

3.3.2 Risk Assessment

3.3.2.1 Electrical Hazards

The likelihood of electrical shock occurring during the use of the third prototype based on electric bug-zapper technology was considered medium. While frequency of exposure had the potential to be high, use of a double switch system ensured that the device must be first turned on, and then held with a trigger depressed to activate it. All wiring apart from the very tips of the end-effector were contained within the device, and the handle insulated.

The potential consequences of electrical shock were considered low. Likelihood of harm or injury were very low given the short duration and low current produced by the device. While having the potential to cause small children or pets some level of stress, physical injury was expected to be minimal. The possibility of a secondary hazard of falling while attempting to avoid proximity to the device was considered, with the consequences of this established as being much higher than any direct injury caused by the device, including severity of harm and likelihood of injury.

The potential for the device to be misused to cause distress from electric shock, and potentially cause injury from secondary actions (whilst avoiding electric shock) was also considered.

3.3.2.2 Heat Hazards

The likelihood of ignition of dry materials during soldering was low, provided usage occurred within an appropriate environment. Similarly, likelihood of burns was low, provided care was taken, appropriate equipment used, and suitable operational procedures followed. Frequency of exposure was considered low.

The consequence of ignition of dry material had the potential to be severe, particularly where materials were present within a residential dwelling, or near other combustible materials. The consequences of burns was considered medium, depending upon length of exposure and the nature of contact.

3.3.2.3 Chemical Hazards

The likelihood of exposure (personal and environmental), to soldering fumes was low, with minimal amounts of soldering required. Frequency of exposure was also considered as being low.

The consequences of such exposure, given the very low quantities involved and short time of likely exposure, was also considered low.

3.3.2.4 Physical Hazards

The likelihood of exposure to direct physical hazards such as pinching was considered low. The likelihood of exposure to indirect physical hazards was also low, based on the very low frequency of exposure to such circumstances (there being very few people, and no small children, in the vicinity of the design build nor testing processes).

The potential for the devices to be misused to cause distress from electric shock or pinching, and potentially cause injury from secondary reactions whilst avoiding electric shock or pinching, was noted to exist. The consequence of exposure to physical hazards through these secondary reactions, such as falls or trips, was considered medium, with potential for significant, though non-life-threatening injuries to occur in such an event. Frequency and likelihood of exposure was, however, considered very low.

3.3.3 Risk Mitigation Strategies

In consideration of the hierarchy of controls, as per WorkSafe Victoria (2022), the following strategies were used, in combination with a UniSQ Risk Management plan (Appendix A), to ensure risk was low:

Elimination – Identified, and where possible, removed or avoided use of or interaction with anything potentially high risk. E.g. Avoided use of lasers given operating in relatively uncontrolled environment.

Substitution – Identified, and where possible, replaced items identified as potentially high risk with something safer. E.g. Used a battery-operated bug zapper to develop the desired electric field instead of mains-powered electric fence unit or mains powered bug zapper.

Engineering Controls – Used a dedicated area composed of heat-resistant materials during soldering to minimise heat risks. Checked and ensured use of insulation with electrical equipment and components, where feasible, to minimize electrical risks. Ensured design was such that all wiring was encased and exposed areas of voltage were kept minimal. Used silver solder rather than lead based solder in well-ventilated area to reduce associated health and environmental risks from lead. Engaged a double switch mechanism on the bug-zapper based device, one of which needed to be on, the other of which needed to be held in, before the device could be activated.

Administrative Controls – Read and acquired familiarity with any relevant University of Southern Queensland's (USQ's) experimental protocols, to ensure approaches used are consistent with, and compliant to, institutional expectations. Developed and followed a set of operational procedures for the workshop, consistent with USQ protocols, that ensured the safe handling of heat-generating and electrical equipment. Labelled devices with appropriate warnings as to their nature and consequences of misuse (as required). Stored devices securely away from children when not in use.

Personal Protective Equipment (PPE): Used appropriate PPE including heat-resistant gloves, safety goggles, clothes fully covering limbs and fully enclosed shoes during soldering.

3.3.4 Continuous Monitoring and Review

Ongoing Risk Assessment: Continuously monitored experimental procedures and environments to identify new or evolving risks during construction and testing. Adjusted risk management strategies as necessary to ensure risk remained low.

3.3.5 Risk Summary

In summary, appropriate hazard identification and risk assessments were performed, followed by the use of appropriate management strategies, thereby ensuring all hazards and associated risk were minimised during the course of the project, such that the potential for harm was reduced to acceptable levels.

3.4 Ethical Considerations

3.4.1 Animal Ethics

As the experiment involved use of living creatures, there were considerations around the way in which they were treated. Within Australia, there is a specific code for the care and use of animals for scientific purposes. It is noted within this code that animals are defined as being "*any live non-human vertebrate (that is, fish, amphibians, reptiles, birds and mammals encompassing domestic animals, purpose-bred animals, livestock, wildlife) and cephalopods*" (NHMRC 2021, p. 3). As insects are neither vertebrates nor cephalopods, these standards were noted not to apply to experiments performed upon insects in Australia. This was noted to be consistent with the Animal Care and Protection Act 2001 (Qld), meaning that there was no need to seek approval from an animal ethics committee (AEC), nor to register with Biosecurity Queensland. That said, care was still taken to not cause any unnecessary suffering.

3.4.2 Research Ethics

With respect the research ethics of the project, it is acknowledged there existed a significant need for the demonstration of professional responsibility, integrity and transparency. This was achieved through:

- Adherence to ethical and associated research guidelines, as per those described by the University of Southern Queensland (Research Code of Conduct Policy, 2019), Engineers Australia (Engineers Australia code of ethics, 2022), and the National Health and Medical Research Council (Code for the responsible conduct of research, 2018);
- The clear documentation of research methodology (including experimental procedures, data collection processes and analytical techniques utilised);
- Practicing open and honest communication with the project supervisor, including the seeking of guidance and feedback;
- The keeping of detailed records of research activities, data, observations and results;
- Respecting the intellectual property of others via appropriate recognition and crediting of all sources and contributions utilised within the project;
- Ensuring analysis methods were thorough and appropriate;
- Reporting research findings accurately and objectively;
- Behaving professionally throughout all aspects of the project;
- Identifying and acknowledging research limitations, uncertainties, and shortcomings, while at the same time making efforts to reflect upon these and being proactive in attempting to address them wherever possible.

Through doing so, it is hoped this work has upheld ethical standards, built trust, promoted accountability, preserved academic integrity, and ultimately, contributed towards the advancement of engineering knowledge.

3.4.3 Ethical Implications of Research Findings

One of the primary implications of the research findings from an ethical perspective will be the equity of access to such technologies. With costs of robotics generally out of the reach of many, consideration must be given to how those who cannot afford such technology might be impacted by its successful development. Concerns exist where in the event chemical companies begin losing market share in the pest control space, they might attempt to cheaply offload surplus chemicals, and their associated issues, to such individuals (particularly those living in poorer, less developed nations). With this in mind, it is important efforts are made to ensure the development of non-chemical RAS based pest control technologies are not monopolised, and efforts are also made to keep the costs of such technologies as low as possible, such that equitable access is ultimately achievable.

A secondary ethical consideration arises from the manufacture and disposal of any technologies that may occur as a result of the successful development of non-chemical RAS based insect destroying technologies. While clear benefits exist from the adoption of such technologies, as with all technologies, there will be resources required and waste produced during its manufacture. Similarly, at end of life, the materials used within such devices will need to be either recycled, re-used, or disposed of. As such, there is potential for the environment to be harmed, and those living in or near such environments adversely affected. With this in mind, development of the final end-effector, and any ensuing recommendations resulting from this research, should take this into account, so as to minimise any potential for harmful impacts.

3.5 Assumptions

It was assumed pest species would be able to be identified and targeted effectively by an associated sensor and manipulator system on the field robot to which any final end-effector would eventually be attached. As such, no attempt to cater for such targeting and manipulation was included within this project. It was also assumed such a robot would provide any necessary power to the end-effector via wiring through an electrical harness and appropriate hardware. As such, while ensuring devices were able to run on 24 Volts or less, inability to include the necessary power supply within the end-effector design was not a significant consideration within this project, with respect to prototype viability

The initial prototypes were deliberately of simplified design and construction, with some consideration given regarding their size or form, but not specifically how they might be attached to the robot arm. This decision was based on the assumption this would help speed up the build process, allowing greater time for testing and design development, thereby allowing a greater focus on effectiveness in the removal and/or destruction of pest insect species, so as to better establish end-effector viability.

For the purposes of preliminary prototype testing, the preferred test species was the Cabbage White Butterfly (*Pieris rapae*) a known horticultural pest. Where insufficient numbers of this species were able to be sourced, other insect species were utilised, with specimen testing for each prototype aiming to be of a similar nature for each case (in terms of the species, size and nature of the test specimens used). It was assumed that in doing so, results between the prototypes would be comparable, and thus allow fair comparison of their respective success. It was also assumed that similar sized and shaped pest species would be similarly, impacted by the prototype end-effectors. That said, it was also acknowledged that differences in size, body structure and general morphology of insects tested would likely result in variations of effectiveness, and consideration around this would also be necessary, before applying generalisations around the results. As such, preliminary testing was assumed to serve primarily as a means for establishing some level of device effectiveness, and thus allow viability determination.

Success at killing test insect species was assumed to be only one indicator of end-effector effectiveness, as was success at removing the insect from the plant. As stated in the methodology overview, other parameters were judged separately to these primary parameters, with relative importance of each parameter assigned a numeric value, to allow use of a weighted decision matrix, as also previously described. It was assumed the use of a weighted decision matrix was an acceptable mechanism for making judgements around the relative suitability of the respective end-effector prototypes. It was also assumed that weightings chosen for use in the matrix were appropriate for assessment of the success in achieving the experiment's objectives.

3.6 Experimental Setup and Procedure

3.6.1 Initial Design and Build: Phase 1

3.6.1.1 Prototype A - Gripper

- Potential gripper designs were identified that were able to be driven by a low voltage servo and having ability to be easily modified using AutoDesk Inventor, from within GrabCad library.
- A potential gripper design was located and downloaded (see Figure 22) from GrabCad (Technicontroller 2023) as a zip file. (Noting original gripper design was chosen due to its relatively simple component structure and ability to be driven by an SG90 Micro Servo).
- The zip file was extracted and an associated *.step file (in this case gripper v1.step) recovered.
- The "gripper v1.step" file was imported into AutoDesk Inventor using the "Convert Model" option in the import wizard.
- Each component from the imported model was opened and saved as a part file (*.ipt).
- Parts were opened separately within Inventor, then modified to make the gripper easier to hold for testing, as well as improving jaw accessibility to insects on plants, and their ability to grab small insects through design refinement. Part files were then saved.

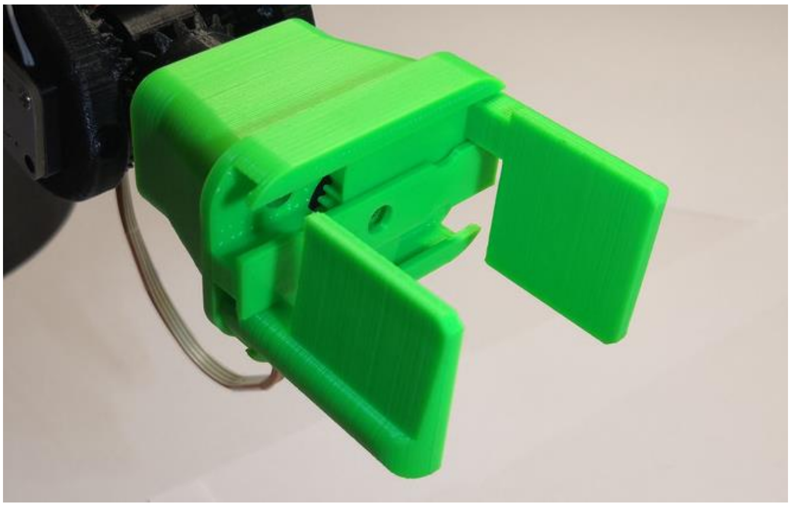


Figure 22. Original Gripper Design (Technicontroller, 2023 p. 1)

- A new assembly was created with the modified parts, with constraints reconfigured as required before checking theoretical functionality with constraints in place (see Figure 23).
- New assembly then saved as a *.asm file.
- Each part was opened separately and exported out of Inventor as an alternate CAD format file type: *.stl
- *.stl files were saved to a memory stick and each component printed (see Figure 24) using a 3D printer and associated software (various 3D printers including UP Mini 2 and Creality Endo S1 were initially trialled, with the UP Mini2 ultimately being used for most 3D printing).

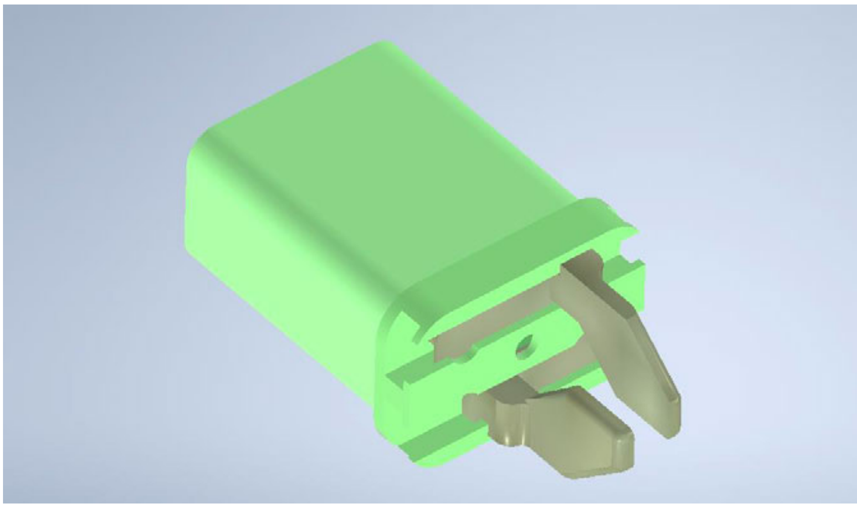


Figure 23. "Gripper" Prototype Design - 3D Render

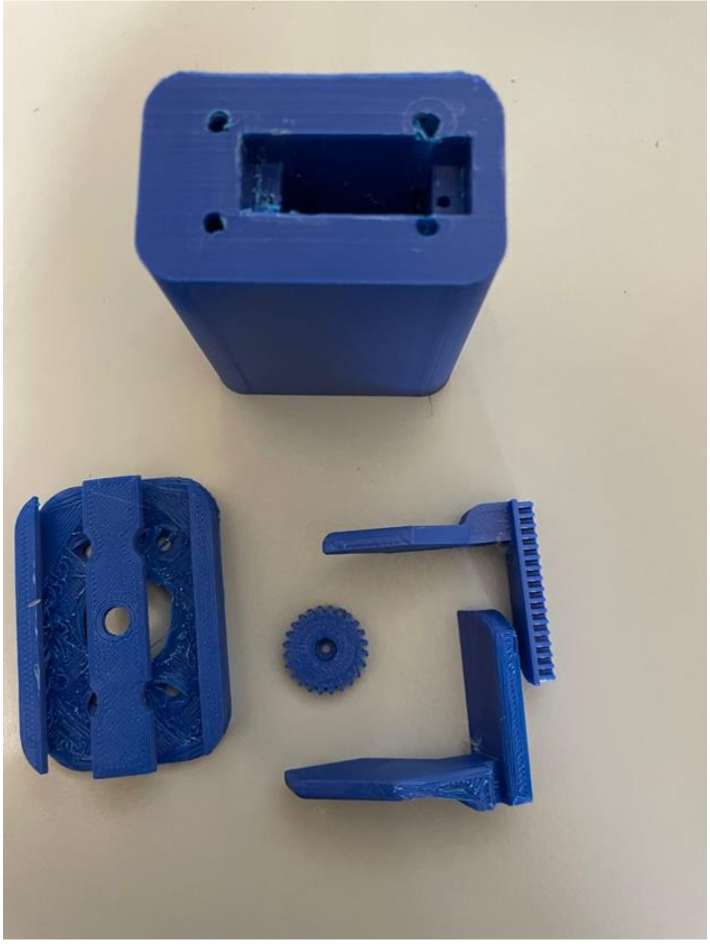


Figure 24. 3D Printed Gripper Components

- Printed parts test were assembled without the servo to ensure parts fitted together.
- Based on observations during test assembly, the gripper design was adjusted in AutoDesk Inventor to ensure parts aligned correctly once printed, with alignment issues noted due to tolerances and inaccuracy in print output. Modifications were applied as per:
    - Redesigned and reprinted the rail base, adding extra support to rail base sides to help minimise deformation of base during cooling (see Appendix B – Prototype 1 - Rail Base Final).
    - Filed back and sanded gripper arms and rail base to give and greater freedom and ease of movement in gripper arms (noting an alternative option existed to increase the tolerance of design and reprint).
- Test assembled parts with the micro servo to ensure the servo fitted into the servo base.
- Adjusted the gripper design to ensure the servo fitted correctly, applying modifications as per:
    - Added 4 mm wide x 1 mm deep internal groove to base to cater for Servo wire strap (see Appendix B – Prototype 1 - Servo Base Final).
- Assembled gripper components without fixing rail base to servo base (see Figure 25).

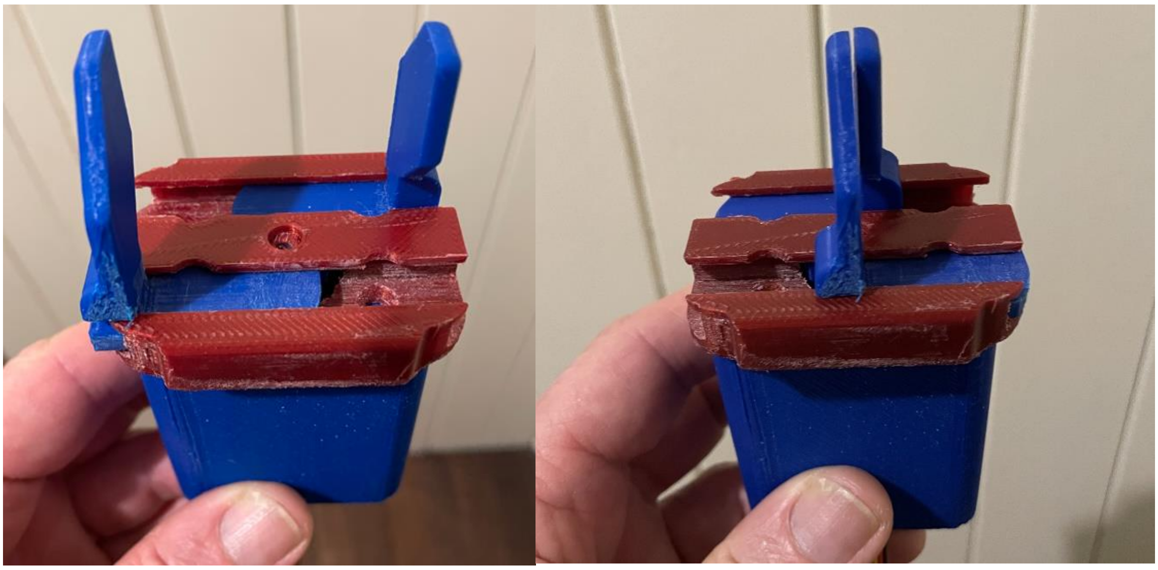


Figure 25. Assembled 3D Gripper Prototype

- Developed gripper open/close program in Arduino IDE on PC to allow single button press to activate gripper, closing gripper fully while button pressed and returning arms to fully open position when button not pressed (code as per Appendix C). Start position of servo was set at 90 degrees and the end position set at 0 degrees.
- Installed the gripper program from PC to Arduino UNO microprocessor using a USB cable and the “Upload” function from the Arduino IDE software.
- Configured the breadboard with single press switch connected to Arduino UNO to act as trigger for activation of end-effector (see Figure 26), which involved the following steps:
  - Connected a 9V battery pack to input power for Arduino UNO.
  - Connected the 3V power outlet to the switch, then connected the switch to PIN 2 on the Arduino UNO board. Then used a pull-down resistor (10K Ohm) connecting PIN 2 to ground to ensure the signal state remained at zero when the button was not pressed.
  - Connected the SG90 micro servo to 5V power, ground and trigger wire, as per manufacturer instructions. Trigger wire was connected to PIN 9 on the Arduino UNO board.
  - General circuit construction was as per the provided circuit diagram shown in Figure 27.

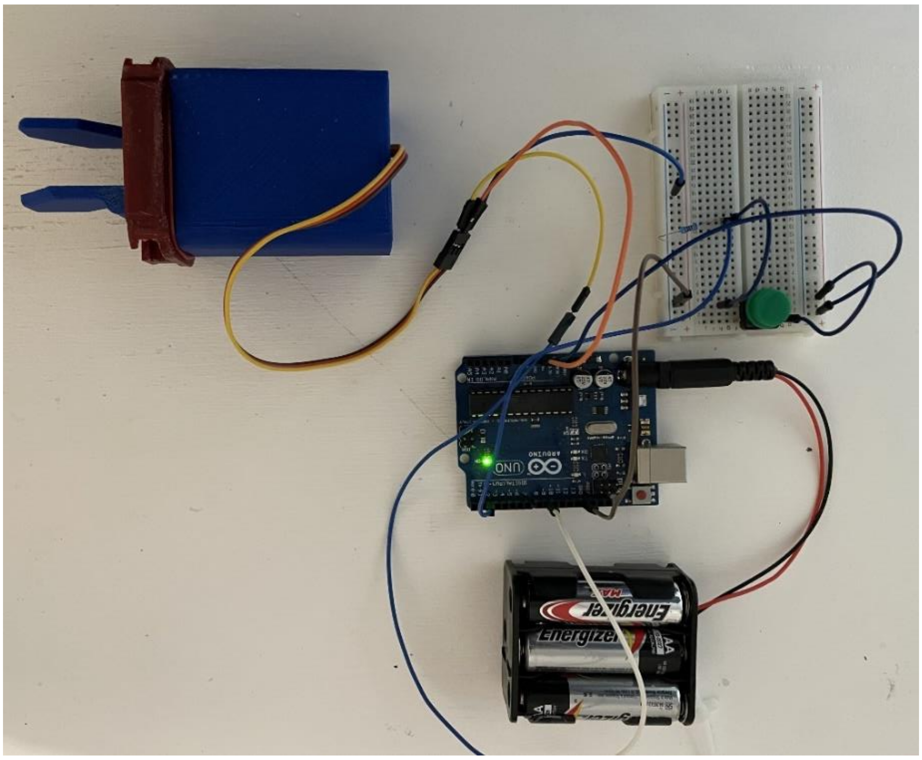


Figure 26. Assembled "Gripper" Circuit

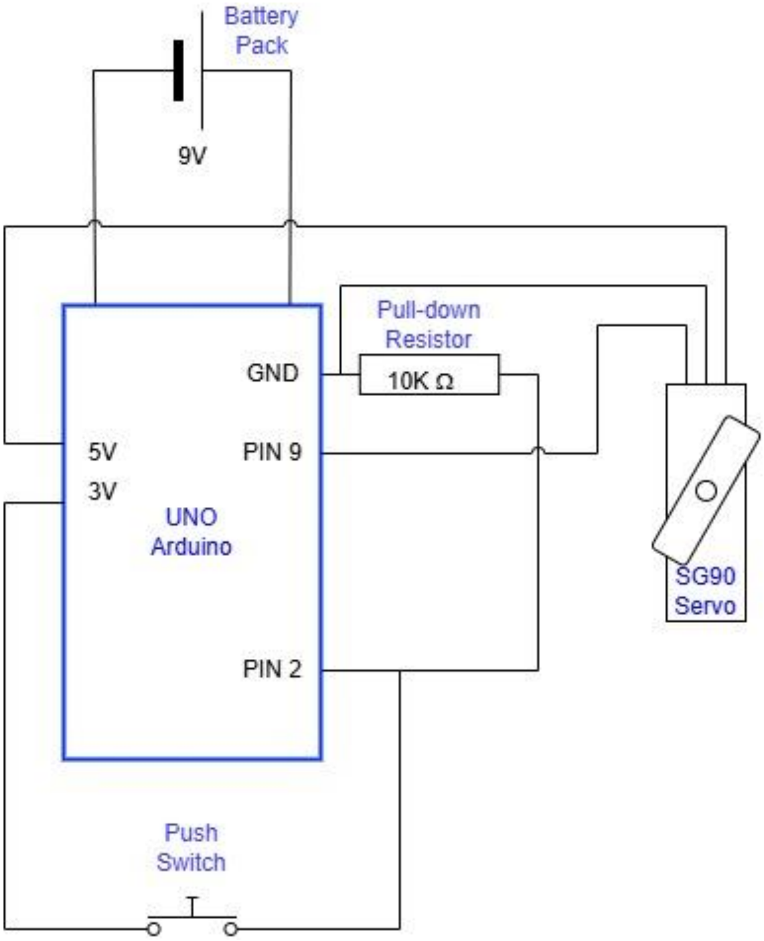


Figure 27. Gripper Circuit Diagram

- Test pressed the trigger button to confirm gripper closed when pressed, and re-opened when not pressed. Pressed trigger again and once jaws closed, keeping button held down, lifted the rail base and jaws away from the servo, centred the jaws and then repositioned over the gear so that the screw holes were aligned.
- Keeping button held in, screwed rail base firmly to servo base with minimum of 2 diagonally opposite 6g x 20 mm flat head screws, ensuring screw heads did not sit proud. Note that it was required to increase the size of the counter sinking allowance in the rail base slightly to account for screw heads being slightly larger than expected and fouling the jaws closing.
- With screws fully countersunk and inserted, tested button press with all base parts connected, noting arm locations on full open as well as general performance with opening and closing.
- Adjusted gripper design and Arduino programming based upon observations of general operation until both gripper arms slid freely, servo engaged fully on button press, and arms came completely together and separated fully upon release of trigger button.
- Applied modifications after disassembling device, as per:
    - Increased baseplate depth by 1 mm using plastic spacer to prevent mechanism jamming once screwed together (alternatively it is noted that baseplate design depth for the servo could have been increased by 1 mm and reprinted).
    - Set the starting servo angle to 90 degrees and the final angle to 180 degrees within the programming to ensure the gripper moved the correct direction on button press and release.
- Reassembled device, once again placing arms together in centre and inserting spur gear into them while button pressed, then screwed rail base to servo base with 2 x 6g x 20 mm flat head screws.
- Used gripper to attempt to pick up items, slowly increasing item size and weight.
- Adjusted gripper design and Arduino programming based upon observations during operation until gripper able to successfully grab and hold 10 gm pen, applying modifications as per:
    - Redesigned and reprinted spur gear to allow for incorporation of servo arm within spur gear creating rectangular cavity 11 mm long and 5.7 mm wide, with a depth of 1.6 mm (see Appendix B – Prototype 1 – Spur Gear Final).
    - Cut down provided SG90 servo arm and filed to size so as to fit within rectangular shaped cavity of 11 mm x 5.7 mm and inserted into redesigned spur gear (as per Figure 28).
    - Positioned servo arm onto servo and screwed down with provided screw.

Figure 28. Servo Arm and Spur Gear Modification

3.6.1.2 Prototype B - Zapper

- 1 x Mafiti electric fly swatter was purchased, as shown in Figure 29.

Figure 29. Mafiti Electric Fly Swatter

- The Mafiti electric fly swatter was then disassembled to retrieve the active wires (Figure 30) and to confirm nature of preconfigured bug-zapper circuitry (Figure 31).
- While disassembled, the handpiece was cut to 120 mm long, ensuring key elements (switch, active light and activation button), were retained and undamaged, as per Figure 32.
- The integrated battery was then removed (helping keep size down).
- Dimensioned the handpiece using digital callipers and drafted up preliminary end-effector design able to incorporate the cut-down handpiece, modifying the casing to better suit use as end-effector.
- Individual components of the casing were then modelled in Inventor (see Appendix B) to allow fitting of the Mafiti handpiece and created an associated assembly in Inventor, as shown in Figure 33.
- Applied constraints as required in order to confirm all parts fitted together and holes aligned within the theoretical model.

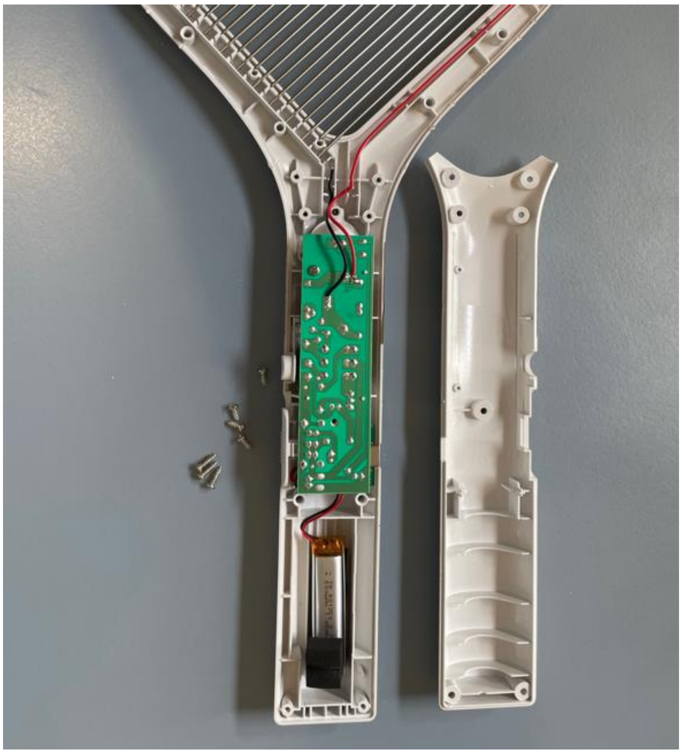


Figure 30. Disassembled Handpiece Revealing Active Wires

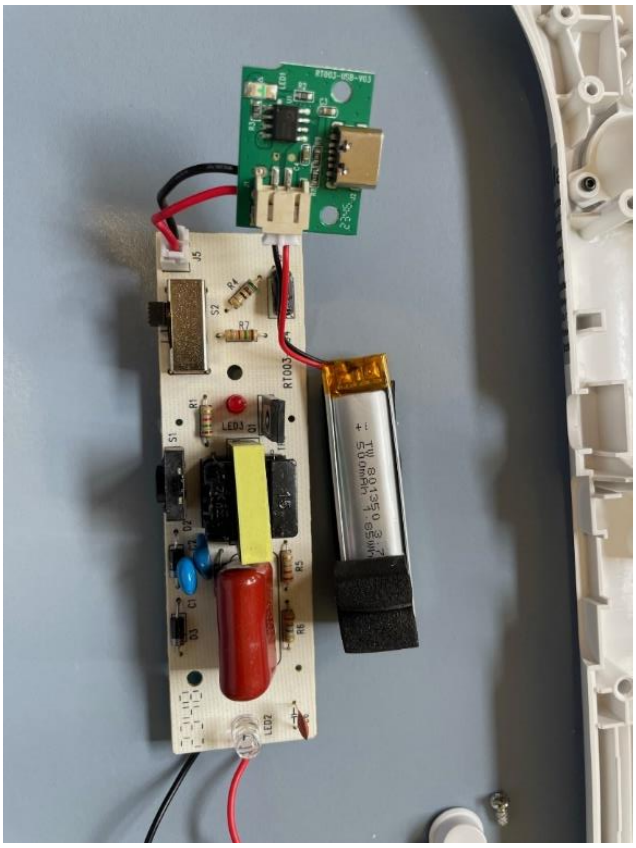


Figure 31. Mafiti Circuitry

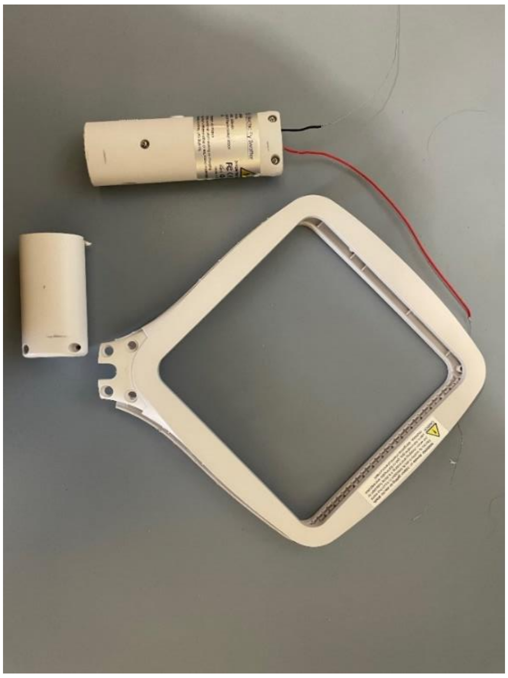


Figure 32. Mafiti Fly Swatter - Cut down

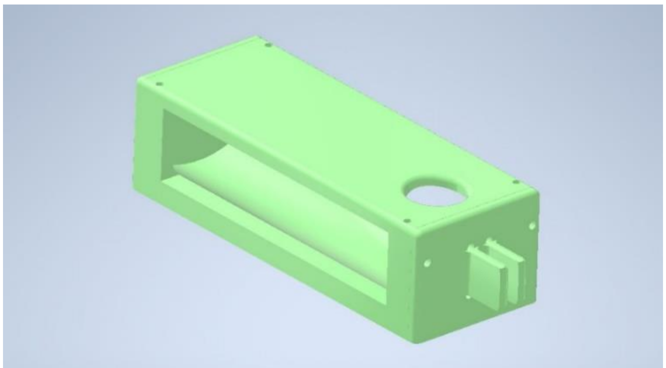


Figure 33. "Zapper" Prototype Case Design - 3D Render

- Exported out individual parts as *.stl files ready for 3D printing.
- 3D printed case components (Figure 34).

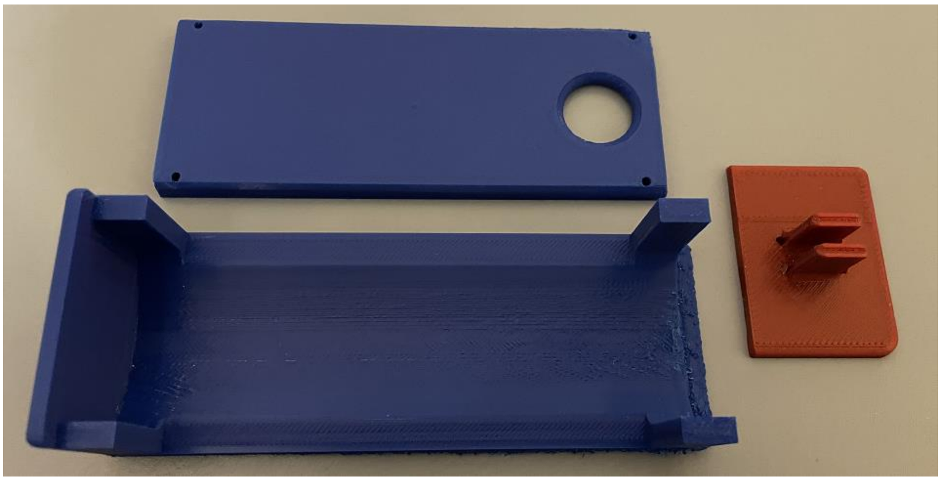


Figure 34. 3D Printed Zapper Components

- Assembled “Zapper” case incorporating circuitry from “Mafiti Electric Fly Swatter” (see Figure 35). Using a 2 mm drill, drilled 8 mm into uprights, screwing down top plate with 4 x 2.9 mm diameter (4 Gauge) x 9 mm long screws, to connect parts together.
- Inserted 1.6 mm diameter wire through end plate and passed over both end projections, bending to fit moulded shape of end projections, ensuring wires did not touch. One end of each wire was then soldered to the corresponding +ve and -ve wires coming from the original fly swatter circuit, with the other end inserted into the end plate to help secure it (as per Figure 36).
- Connections were then hot glued to the end plate to ensure no movement and no contact occurred between the +ve and -ve wires, before allowing the glue to cool and dry.
- Drilled 10 mm into end of base in 4 locations with 2 mm diameter drill before screwing end plate on using 4 x 2 mm diameter x 9 mm long screws, ensuring end plate wires did not foul the mechanism during attachment.
- Applied warning sticker regarding potential for electric shock.
- Connected USB3 power cable to the integrated power supply port.

Figure 35. Assembled “Zapper” Prototype

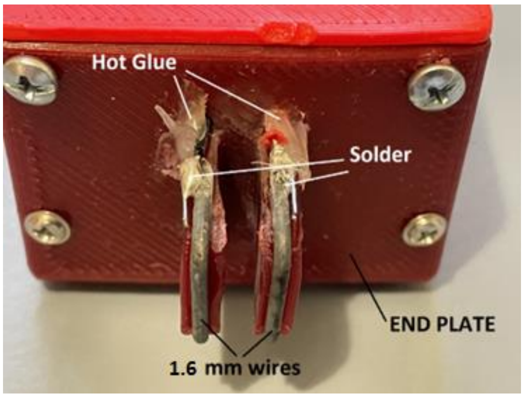


Figure 36. End Plate Connectivity Detail

- Connected device to USB power via power cable.
- Turned on the device switch and confirmed it was powering up via the built in LED *.
- With light active, pressed the activation button and tested operation by attempting to discharge across a test wire **.
- Noted operation and recorded observations.

** Where the light does not light up, check the connections. If connections are OK, disconnect from power, remove from outer casing, open device and confirm no damage to the circuit has occurred during assembly.*

*** Where device fails to discharge, check connections, including soldering between circuit and terminal wires, testing for continuity with a multi-meter. If connections are good, ensure wiring is not shorting out (in a darkened room to help observe any signs of electrical shorting)***. If not shorting out, check to see if device is discharging between terminals when button initially engaged without having to touch test wire ****.*

**** Where device appears to be shorting out, attempt to establish where shorting, then check and/or modify as per:*

- *Ensure hot glue fully dry.*
- *Remove excess hot glue from between terminals.*
- *Ensure circuit wiring soldered parallel to terminal wires and there is no excess solder on the join resulting in a smaller gap between the terminals at the joins.*
- *Remove end plate and ensure no bare wires touching or close to each other. (Take care not to pinch or break wiring when reconnecting end plate).*

***** Where device discharges between terminals without contact with test wire, then:*

- *Check wires have not become loose and that distance between them is in excess of 4 mm (being the minimum noted for the Mafiti circuit once removed from original plastic racket structure). If wires are loose, apply superglue, allow to fully dry and test again. Where wires prove difficult to fix, or excess glue results in continued discharge or shorting, consider adding grooves into sides of end plate terminal holders and shaping wire terminals to fit snugly into grooves before lightly supergluing within grooves to hold in place. (Noting this was performed to assist in holding the wires in the correct position due to wire movement and self-discharge issues).*
- *Ensure end terminal gap has not closed/reduced or opened excessively after printing (potentially may occur during cooling or later during soldering). If ends are observed to be bending inwards (see Figure 37), or outwards power down and disconnect device, then apply hot air from hair dryer to end plate until terminals begin to soften, then spread or close terminals until in desired position. Allow to cool in this position, then test device again.*

Figure 37. Closed Terminal Gap

- *Where Zapper is still discharging without contact during operation, and all other checks and changes have been made, redesign end plate and widen terminal gap at base, after testing the minimum gap requirement, then print, reassemble and retest.*

3.6.1.3 Prototype C - Sucker

- Purchased 12V, 80 mm case fan, as shown in Figure 38.

Figure 38. 12V Case Fan.

- Drafted a preliminary vacuum based end-effector design able to incorporate the 12V case fan as driving mechanism for air flow within a tube. Designed end-effector to take advantage of Venturi effect, with larger tube at fan outlet to create a low velocity air flow and smaller tube at fan inlet to generate a high velocity air flow. Used cheap, easily accessed materials for inlet tube (cut down 1.0 L "Nudie" juice bottle) and outlet tube (cut down 2.0 L "Dairy Farmers" milk bottle).
- Measured dimensions of fan casing and position of screw holes using digital callipers.
- Measured dimensions of end tube components (i.e. milk bottle and juice bottle including lid).
- Within AutoDesk Inventor used the obtained dimensions to model individual components representing the fan, inlet tube (juice bottle & lid) and outlet tube (milk bottle), (see Appendix B).

- Within AutoDesk Inventor, created join plate components to allow connection of both tubes to the case fan as well as connection of nozzle with 20 mm internal diameter (cross sectional area of 314 mm^2) to the smaller tube end to help enhance Venturi effect and thus creation of a low pressure zone at this end, as per Appendix B.
- Created an associated assembly in Inventor using all created parts, adding required constraints to confirm connectivity and alignment of screw holes, as per Figure 39.
- Designed basic switch circuitry to control start and stop of fan, and thus generation of low pressure using 12V DC power supply pack, 0.5A fuse, wiring and ON/OFF controller as per Figure 40.
- Exported out individual plate and nozzle parts as *.stl files ready for 3D printing.

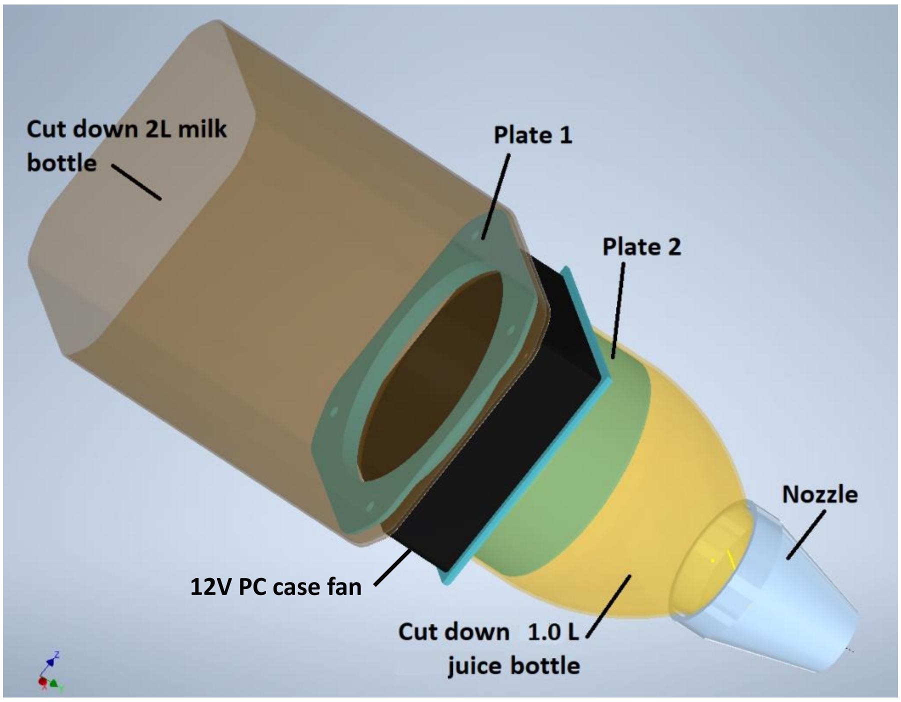


Figure 39. "Sucker" Prototype Design - 3D Render

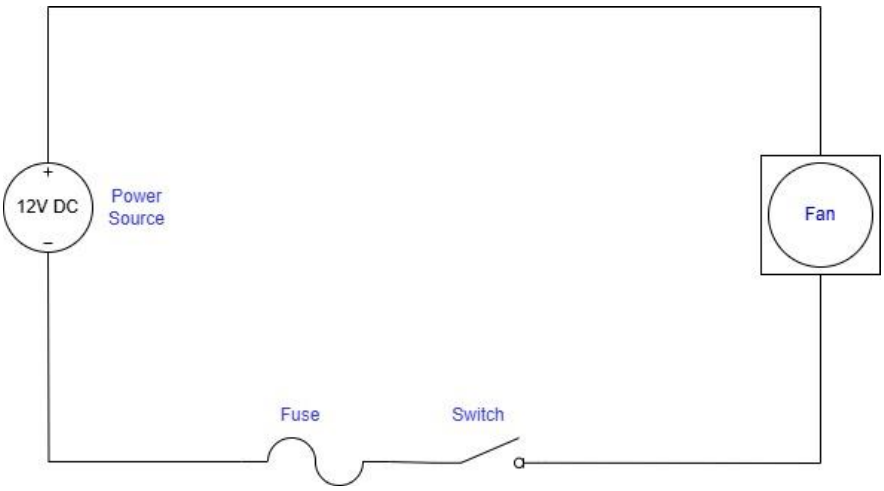


Figure 40. Switch Circuit

- 3D printed both join plates (Plate 1 and Plate 2) along with end nozzle. Used 3D print raft option to minimise issues with creation of plates (see Figure 41), which were observed when the raft was not utilised.

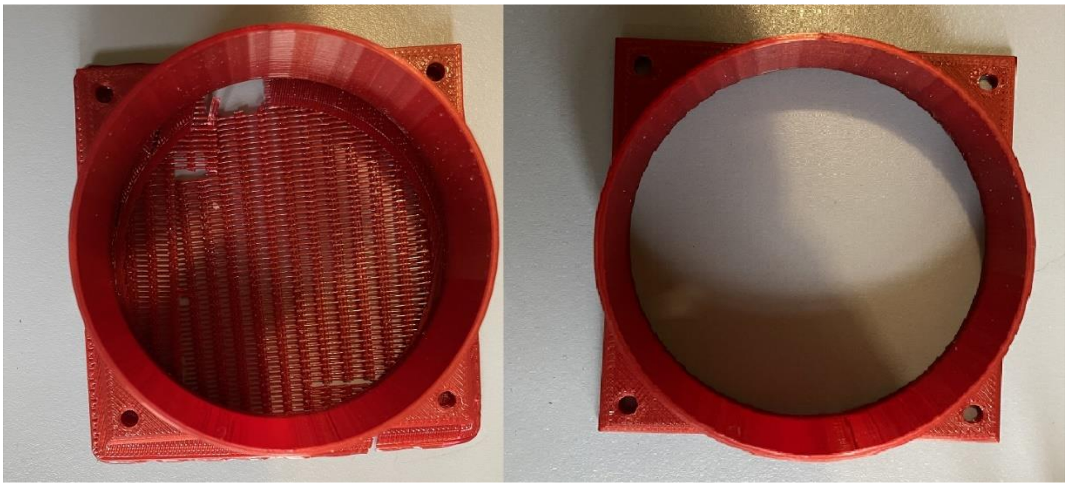


Figure 41. Join Plate 2 with Raft & Removed from Raft

- Milk bottle and juice bottle were then cut down to match model. A circular hole at the bottom end of the milk bottle was then created using a Stanley knife, to facilitate the joining process.
- Plate 1 was placed in the bottom of the milk bottle and silicon applied around edges to seal.
- Plate 2 was placed in the wide end of juice bottle and silicon applied around edges to seal.
- Removed centre of juice bottle lid and attached to nozzle to allow easy interchange of nozzle.
- Assembled cut down bottles with associated plates and fan, bolting together through case fan screw holes using 4 x 3.75 mm diameter x 38 mm long round head bolts and nuts, then screwed on nozzle as per Figure 42.

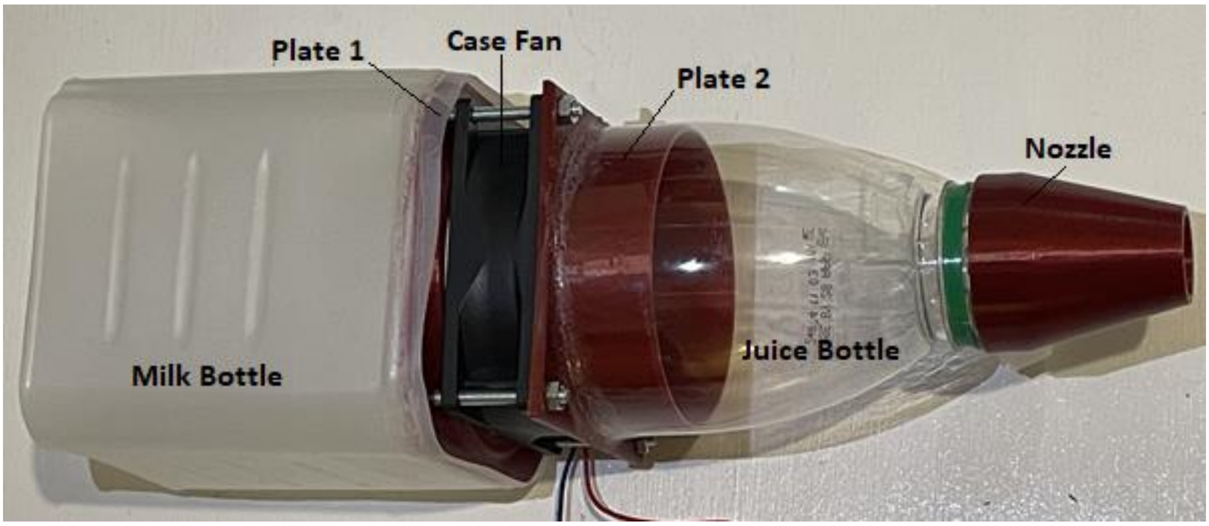


Figure 42. Assembled "Sucker" Prototype

- Connected fan wires to screw based adapter and remaining circuitry components as per circuit diagram (Figure 40) and Figure 43, ensuring wiring connections were insulated to minimise chance of short circuiting the wiring and potentially damaging the fan or the 12V power source.

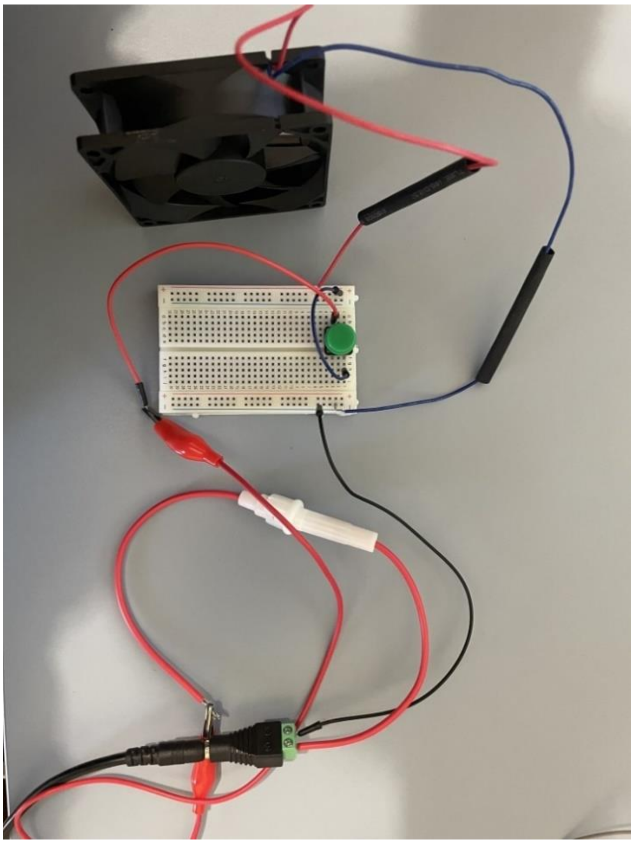


Figure 43. Sucker Wiring Test Rig

- Connected the completed device to a 12V DC power supply.
- Pressed device button and confirmed fan powered up and generating air flow in the correct direction (from smaller end to larger end).
- Tested suction effect exists by positioning device vertically with nozzle down, and placing nozzle in vicinity of 10 x small (4 - 8 mm diameter) Styrofoam balls whilst fan operating *.

** Where device unable to vacuum up Styrofoam balls:*

- *Confirm all wires still connected and fuse has not blown.*
- *Check fan working and that circuit has been configured and connected correctly.*
- *Where fan working, first confirm direction of airflow is correct, with air entering into the device via the nozzle.*
- *Where fan working but insufficient air pressure reduction created to generate suction effect: check that air is not leaking in from joins, adding silicon if required; examine alternative options for use of Case Fan of the same size with higher power rating; or consider reducing diameter of inlet nozzle incrementally until sufficient suction is generated to lift balls.*

3.6.1.4 Phase 1 Data Collection

During design, development and construction of all three prototypes, the following quantitative data was noted and recorded:

- Costs of all components requiring purchase with an overall cost total established on a per device basis. 3D printing costs were a fixed cost of $0.1 per gram, so part costs were reflective of both part size as well as the need for fill or rafts in order to complete successful printing. Where packs or kits required purchasing, relative price of the utilised components were estimated, typically on a per unit basis.
- Build Time for each device, including:
  - Design Time - time spent sketching up and then creating the parts and assemblies within Inventor;
  - Construction Time - time spent importing files, configuring the print jobs and then waiting for the successful completion of the first 5 layers on the 3D printer plus time spend assembling the device.
  - Programming Time – time spend developing and testing any necessary code.
  - 3D Printing Time – total time taken to print all necessary components (Noting while total print time was recorded, only aspects of the 3D printing time were included in the Total Build time, with these included as part of the Construction time, as previously described).

Perceived complexity was a qualitative judgement which was rated using the descriptors as outlined in Chapter 3.1 for Phase 1, based on assessing and then averaging the respective component complexity, along with consideration of how difficult it was felt that the design and construction process had been. As per the descriptors, a 5-point scale ranging from Low to High was used for this process.

Any other relevant information observed during the design and build of each device was also noted. Results were as recorded in Chapter 4.1, with Chapter 4.1.1 outlining the Gripper build results, Chapter 4.1.2 outlining the Zapper build results and Chapter 4.1.3 outlining the Sucker build results.

3.6.2 Preliminary Testing: Phase 2

3.6.2.1 Prototype A - Gripper

Preliminary testing of the Gripper's ability to remove and/or kill a range of insects was completed as per:

- Placed test specimens (2 x Cabbage White Butterfly larvae (one small, one large), 1 x large spotted Ladybeetle (medium), 1 x Cabbage White Butterfly pupae, 1 x Cabbage White Butterfly adult, and 1 x black scale (large, on leaf)), in plastic container.
- Established and recorded likely species of insects and life cycle stage (where apparent).
- Using digital callipers, measured dimensions of each insect and recorded.

- Assessed and recorded relative size of the test subject given the species and life cycle stage.
- Manipulated gripper into position over each insect in the plastic container and pressed button to activate.
- While holding button, attempted to grab and then transfer insect to plastic tray next to container using gripper closing action.
- Noted if insect incapacitated and/or killed.
- Repeated for all test insects, recording successes/failures and general observations.

3.6.2.2 Prototype B - Zapper

Preliminary testing of the Zapper's ability to remove and/or kill a range of insects was completed as per:

- Placed test specimens (2 x Cabbage White Butterfly larvae (one medium, one large), 1 x large spotted adult Ladybeetle (medium), 1 x large spotted larval Ladybeetle, 1 x Cabbage White Butterfly pupae, 1 x Cabbage White Butterfly adult, and 1 x Black Scale), in a plastic container.
- Established and recorded likely species of insects and life cycle stage (where apparent).
- Using digital callipers, measured dimensions of each insect and recorded.
- Assessed and recorded relative size of the test subject given the species and life cycle stage.
- Powered up Zapper with switch, then manipulated into position over each insect in the plastic container and pressed the activation button to discharge device against insect.
- Noted if insect incapacitated and/or killed.
- After allowing time for charge to develop, repeated for all test insects, recording successes/failures and general observations immediately and ongoing where results were unclear.

3.6.2.3 Prototype C - Sucker

Completed preliminary testing of Sucker ability to remove and/or kill a range of insects as per:

- Placed test specimens (3 x cabbage while butterfly larvae (various sizes, including one large), 2 x large spotted Ladybeetles (one medium, one large), 1 x Cabbage White Butterfly pupae, 1 x Cabbage White Butterfly adult, and 1 x Black Scale), in a plastic container.
- Established and recorded likely species of insects and life cycle stage (where apparent).
- Using digital callipers, measured dimensions of each insect and record.
- Assessed and recorded relative size of the test subject given the species and life cycle stage.
- Powered up Sucker, then manipulated into position over each insect in the plastic container and attempted to draw insect into device.
- Noted if insect successfully removed.
- Noted if insect incapacitated and/or killed.
- Repeated for all test insects, recording successes/failures and general observations immediately and ongoing where results were initially unclear.

3.6.2.4 Phase 2 Data Collection

During Phase 2, all data recorded was tabulated for each device and presented as per Chapter 4.2, with Chapter 4.2.1 outlining the Gripper preliminary testing results, Chapter 4.2.2 outlining the Zapper preliminary testing results and Chapter 4.2.3 outlining the Sucker preliminary testing results.

3.6.3 Secondary Design and Build: Phase 3

3.6.3.1 Prototype A - Gripper

- With preliminary testing indicating the Gripper prototype to be viable, and in consideration of the project already being over-budget, no further changes were initially identified as being required for the preliminary prototype design.
- The Gripper prototype was then attempted to be taken outside to initiate development of the plant damage chart.
- With unexpected difficulty in successfully transferring the prototype into a field test environment, the preliminary build was reassessed and slight modifications in the design made.
- A holder for the key components was then developed to allow successful transfer and operation of the prototype under field conditions. The process followed during the holder development was as follows:
    - Measured dimensions of battery casing, Arduino UNO board and bread board.
    - Sketched outline of each key component and created 3D sketch of possible arrangements of these items so as to: minimise sizing requirements; simplify and improve device transportability; and ensure easy modelling and 3D printing of the component holder.
    - Modelled the preferred design in AutoDesk Inventor (as per Figure 44).

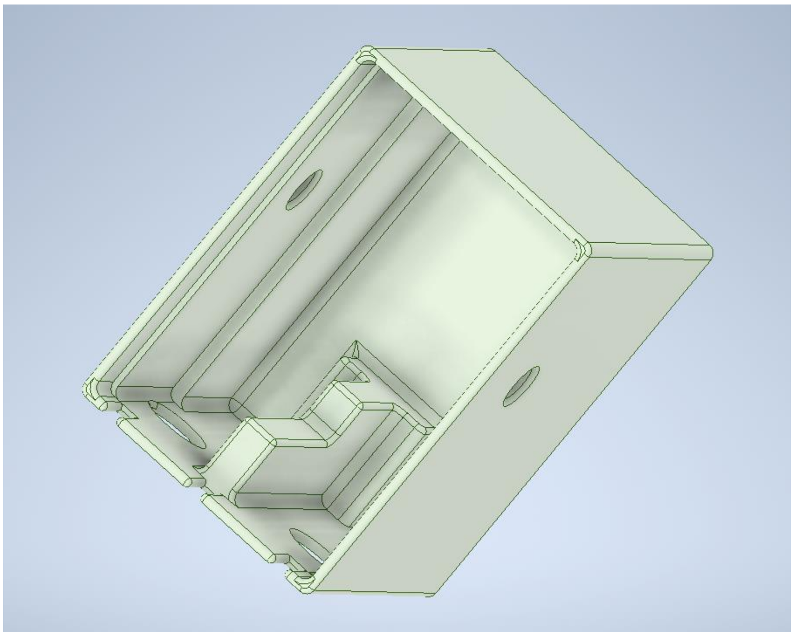


Figure 44. Gripper Component Holder

- Using the “Measure” feature in Inventor, the internal case dimensioning was cross-checked as was its internal support positioning relative to all key components.
- The design was then exported out of Inventor as a *.stl file.
- New component holder was then 3D printed (with supports but without raft).
- The battery was transferred into the newly created holder, feeding connecting power wires through the provisioned hole before connecting to the Arduino UNO power inlet.
- Transferred the Arduino UNO into the holder above the battery. Ensured lower connections did not come into contact with the batteries by inserting in a thin plastic card under it, then connected wiring as per Figure 27, feeding these out through the provisioned side holes.
- Locating the bread board above the Arduino UNO, wiring connections were then completed as per Figure 27, with the press button made clearly accessible.
- Gripper was tested to confirm it was still operational by pressing the button and confirming the jaws still opened and closed correctly.
- Finally, confirmed the Gripper prototype, including all components, was able to be easily held in two hands and could be easily transferred from the test bench environment into a field environment (as per Figure 45).

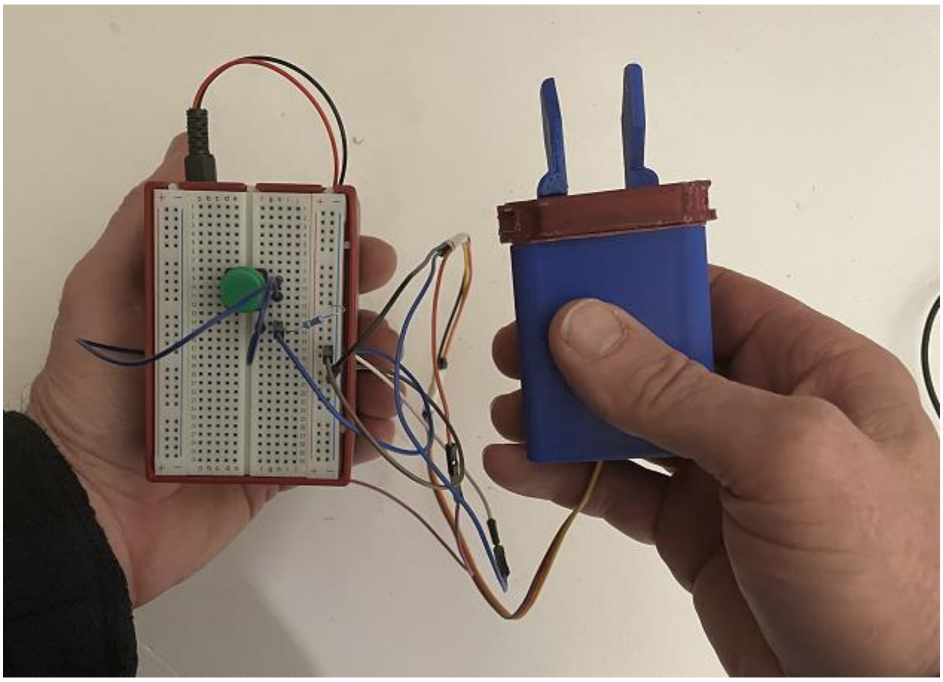


Figure 45. Gripper and Components in Holder

- An assessment was then made as to the device’s “Integration Ability”, rated against the descriptors as previously described in Chapter 3.1 (Phase 3. Secondary Design and Build), and a value between Low and High assigned (on a 5-point scale).

- Previous results for the *Build Performance* of the Gripper were adjusted accordingly, taking into account the extra time for design, development and build of the component holder, in order to produce a final *Build Performance* result for Prototype A (as per Chapter 4.3.1).

3.6.3.2 Prototype B - Zapper

- With preliminary testing indicating the Zapper prototype to be viable, and the budget being such that the purchase of a larger more powerful version of the discharge device not deemed as potentially being viable, no further changes were identified as being necessary for the preliminary Prototype B design at this stage.
- The Zapper build from Phase 1, was then attempted to be taken outside to initiate development of the plant damage chart.
- Concerns with safe transference and use of Prototype B into the field test environment, however, due to significant recent rainfall and a wet field environment, precluded use of the 240V GPO based USB adapter and extension cord, as used during bench testing. This resulted in reassessment and alteration of this aspect of the build. As such, the adapter and cord were swapped out for a transportable 5V battery with USB connectivity, as per Figure 46.
- Operation of the device was confirmed through discharging against a test wire while attached to the battery.
- With this change being minor, and not considered as relevant to the actual prototyping build, overall prototype results for *Build Performance* of the Zapper were noted as being the same as those obtained at completion of Phase 1 (see Chapter 4.1.2).

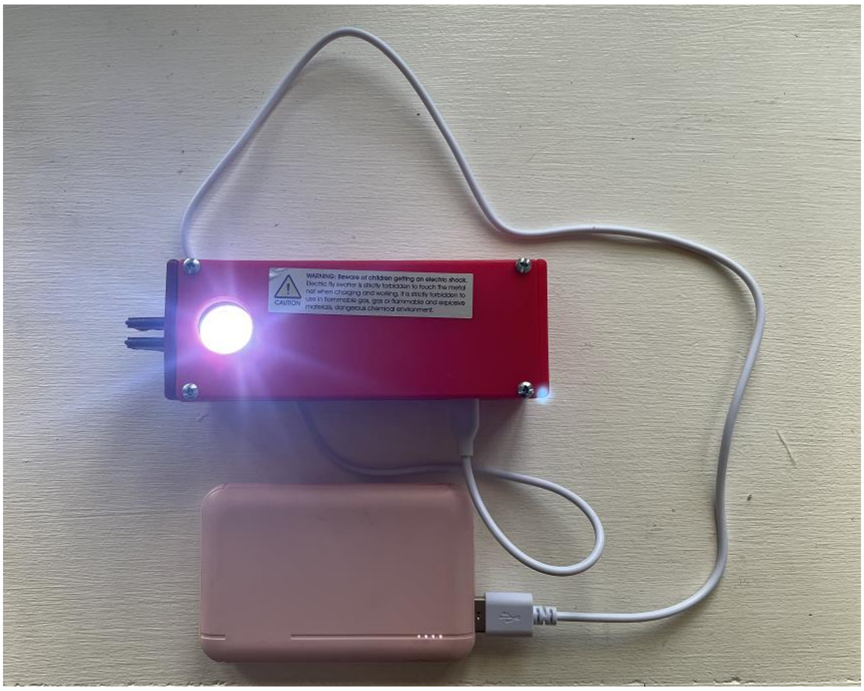


Figure 46. Zapper with 5V USB Battery

3.6.3.3 Prototype C - Sucker

- With preliminary testing indicating: the Sucker prototype to not be viable for the majority of insects tested in its current form; the project already being over-budget precluding purchase of a larger more expensive fan; and with a more powerful, reasonably priced case fan of the same size being unable to be located, changes were limited to those based on incorporation of existing materials along with modifications to the 3D printed parts and wiring harness.
- The ensuing design changes and modifications made, along with further basic testing performed to help develop the 2nd iteration of the sucker prototype, were as follows:
    - Within AutoDesk Inventor, redesigned Sucker nozzle to reduce cross sectional area, thereby increasing air velocity, thus reducing pressure and increasing suction force. Diameter of new nozzle was given a 12 mm internal diameter (cross sectional area of 113 mm^2) and the nozzle entrance length was increased to 20 mm.
    - Exported out the *.stl file of the new nozzle and then 3D printed.
    - Cut centre out of second juice bottle lid of same configuration as first juice bottle lid and attached to new nozzle to allow easy interchange of nozzles.
    - Replaced the old nozzle (Nozzle 1) with the new nozzle (Nozzle 2) (comparison as per Figure 47) by unscrewing and swapping. The original nozzle was retained for possible later use.

Figure 47. Nozzle changes - Nozzle 1 (Maroon) vs Nozzle 2 (Blue)

- Replaced breadboard and associated push button with toggle switch and more robust wiring connections to allow better manipulation of end-effector (see Figure 48).

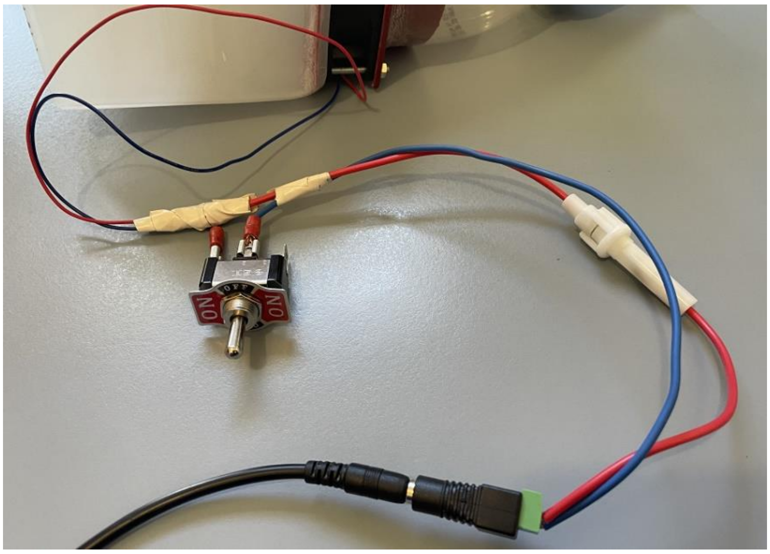


Figure 48. Modified Sucker Wiring Rig

- Retested device, as per Chapter 3.6.2.3, with the following test species examined: 1 x small Cabbage White Butterfly caterpillar (< 12 mm length), 1 x medium Cabbage White Butterfly caterpillar (> 12 mm and <18 mm length), 1 x Cabbage White Butterfly pupae, 1 x Cabbage White Butterfly adult and 1 x medium large spotted Ladybeetle (< 5 mm).

- After examining the results as per Chapter 4.3.3.1, and noting the device was still not viable, further design changes and modifications were identified and made based upon the associated analysis (i.e. increasing the cross-sectional area of the air flow output), with further basic testing performed to help further develop the prototype (3rd Iteration). The modifications and processes for this iteration were as follows:
  - Located existing 80 mm fan able to fit inside 2L milk bottle (in this case an 80 mm Intel E18764-001 CPU fan).
  - Using digital callipers, measured associated mounting bracket and noted key dimensions.
  - Sketched up drawing of new plate to allow insertion and attachment of fan into milk 2 L bottle.
  - Using AutoDesk Inventor, created new mounting plate with requisite mounting connections as per sketch and key dimensions (see Appendix B).
  - Exported out the *.stl file to USB and 3D printed the mounting plate.
  - Attached the printed mounting plate to the Intel CPU fan (Figure 49).

Figure 49. Intel CPU Fan and Associated Mounting Plate

- Inserted the Intel Fan and Plate into a 2L milk bottle with the bottom removed and then attached it via screws through the side of the bottle, to hold it in place.
- 3D printed a 2^{nd} copy of Nozzle 2.
- Attached the 2^{nd} Nozzle 2 directly to the pouring end of the 2L milk bottle.
- In AutoDesk Inventor, designed a connecting adapter (see Appendix B), allowing connection of both suction devices to a common inlet able to be attached to a 6 cm length of 16 mm ID (Inner Diameter) clear polyethylene (PE) pipe.
- Exported the adapter design out as a *.stl file.
- 3D printed the new connecting adapter (Figure 50).

Figure 50. Connecting Adapter for Sucker Prototype - Iteration 3

- Connected adapter to both Sucker devices via 28 cm length of 16 mm clear PE pipe and attached a 6 cm length of 16 mm clear PE pipe at the suction end, as per Figure 51.

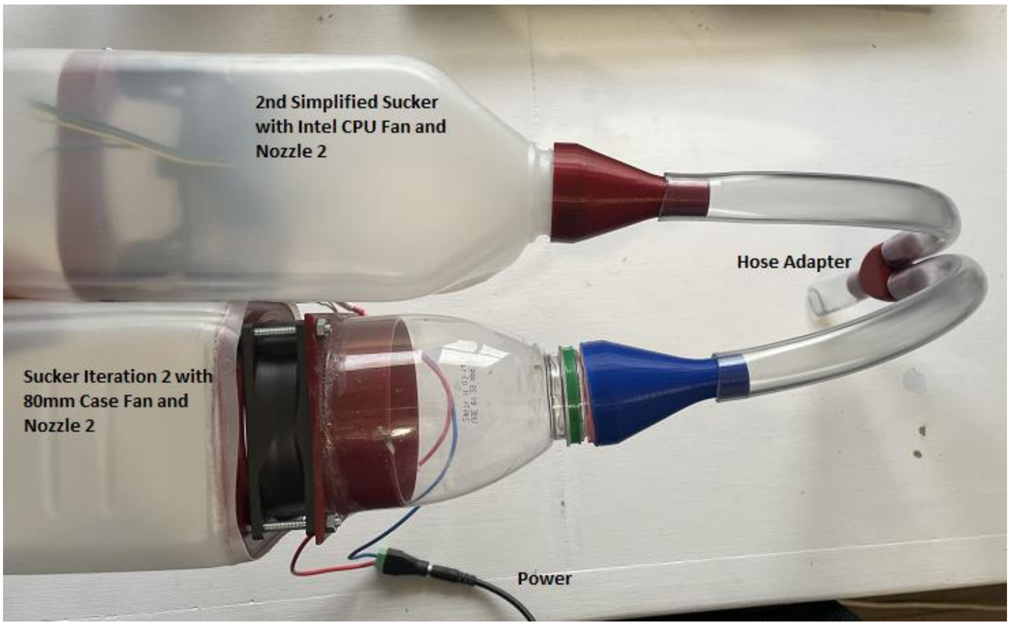


Figure 51. Sucker Prototype – Iteration 3

  - Wired power and return wires from Intel CPU fan into the existing electrical harness to allow control of both fans via a single switch.
  - Placed 6 x 5 - 8 mm Styrofoam balls into a clear plastic tray along with a ladybeetle, a dried pea, a dead medium sized caterpillar, a dead adult Cabbage White Butterfly and small foam square (5 mm x 12.5 mm x 12.5 mm), to allow testing of suction ability.
  - Connected device to power and activated switch to engage fans.
  - Applied end of hose adapter to materials in tray and attempted to suck them up.
  - Noted and recorded observations, as per results in Chapter 4.3.3.2.
  - Detached two-way adapter and applied end of connecting hose on Sucker iteration 2 to provide direct comparison against Sucker iteration 3 performance.
  - Noted and recorded observations, as per results in Chapter 4.3.3.2.
- Updated results for *Build Performance* of the Sucker as described in Chapter 4.3.3.2 to include extra time and costs involved in making the modifications as described.
- After examining the results as per Chapter 4.3.3.2, and noting the device was still not viable, further design changes and modifications were again identified and made based upon the associated analysis (this time being the addition of streams of fast air to the front end of the system), with further basic testing performed to help further develop the prototype (4th Iteration). The modifications and processes for this next iteration were as follows:
  - In AutoDesk Inventor, designed four-way air adapter (see Appendix B), allowing connection of four 6 mm ID PE tubing to a single 12 mm ID clear PE tube, through which an existing air compressor air nozzle could be attached.
  - Exported the four-way air adapter design out as a *.stl file.
  - 3D printed the four-way air adapter.

- Connected the new adapter to 2 x 25 cm lengths and 2 x 30 cm lengths of 6 mm ID clear PE tubing at the output end as well as 1 x 12 cm length of 12 mm ID clear PE tube at the input end, as per Figure 52.

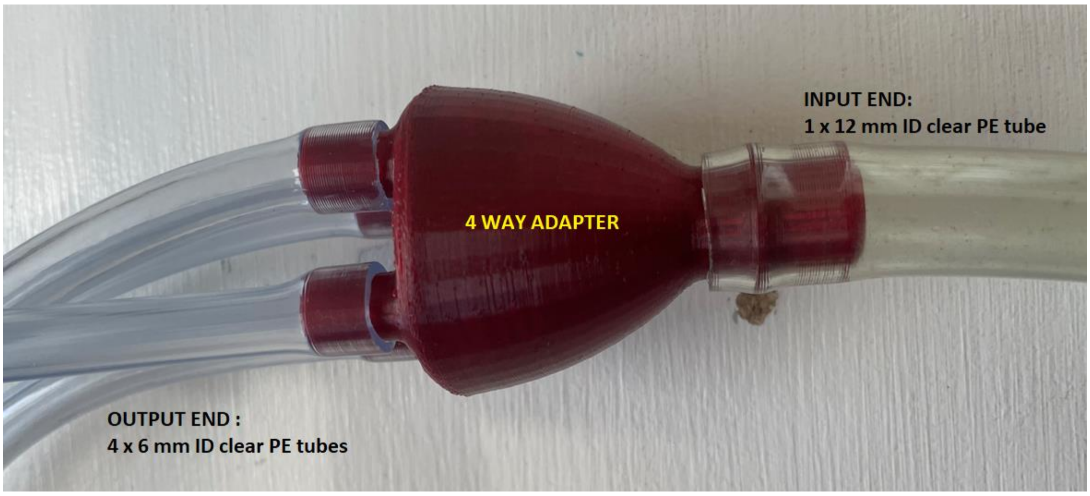


Figure 52. 4 Way Adapter and Connecting Tubes

- Heated a 16 mm long round tapered bar and pushed it through each of the top corners of the 2L milk bottle until 4 x 9 mm diameter holes were formed.
- Removed the Intel CPU fan and its associated plate from 2L bottle.
- Inserted 4 x 6 mm ID PE tube ends (from the four way adapter) through the holes into the input end of the cut down 2L milk bottle.
- In AutoDesk Inventor, designed an inner air connector plate for the input end of the 2nd Sucker device, based on the dimensioning of a standard 2L milk bottle and with the requirement to connect to 4 x 6 mm ID PE tubes (see Appendix B).
- Exported the air connector plate design out as a *.stl file.
- 3D printed the air connector plate.
- Fed the loose ends of the 4 x 6 mm ID PE tubes into 2L milk bottle through the connecting plate holes until roughly flush with the mounting plate, as per Figure 53.

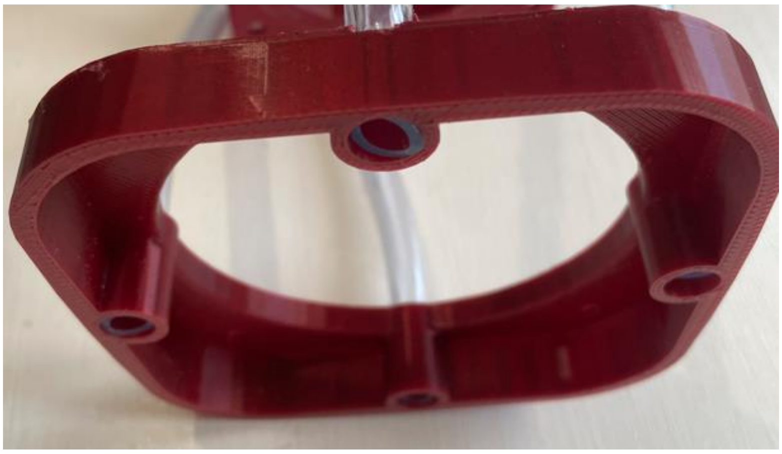


Figure 53. Air Connector Plate with Tubes Inserted

- Inserted the air connector plate into the 2L milk bottle, pulling in into the inlet end and then feeding the excess 6 mm PE back through the insertion holes, until the plate was firmly wedged in the end of the bottle.
- The CPU fan and associated plate were then inserted back into the output end of the 2L milk bottle, rotated 45 degrees to improve air flow from air connecting plate (see Figure 54), and fixed using 4 x 9 mm 4 gauge screws, to complete the construction of the 4th iteration of the Sucker prototype (see Figure 55).

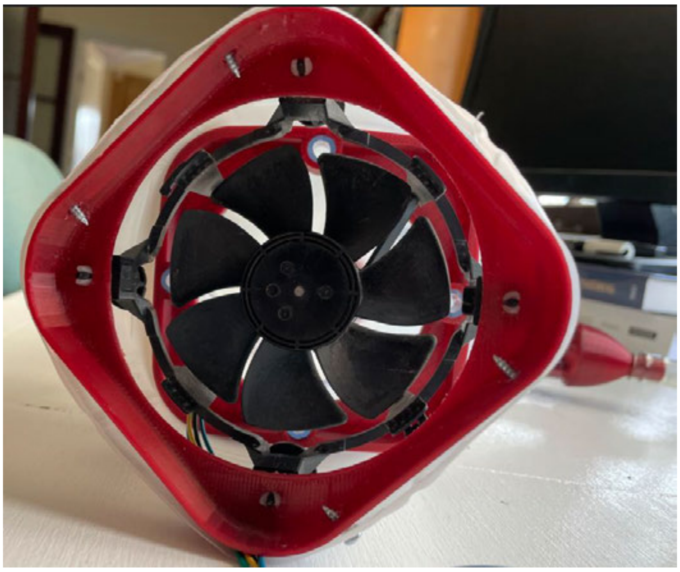


Figure 54. Offset CPU Fan and Air Connector Plate

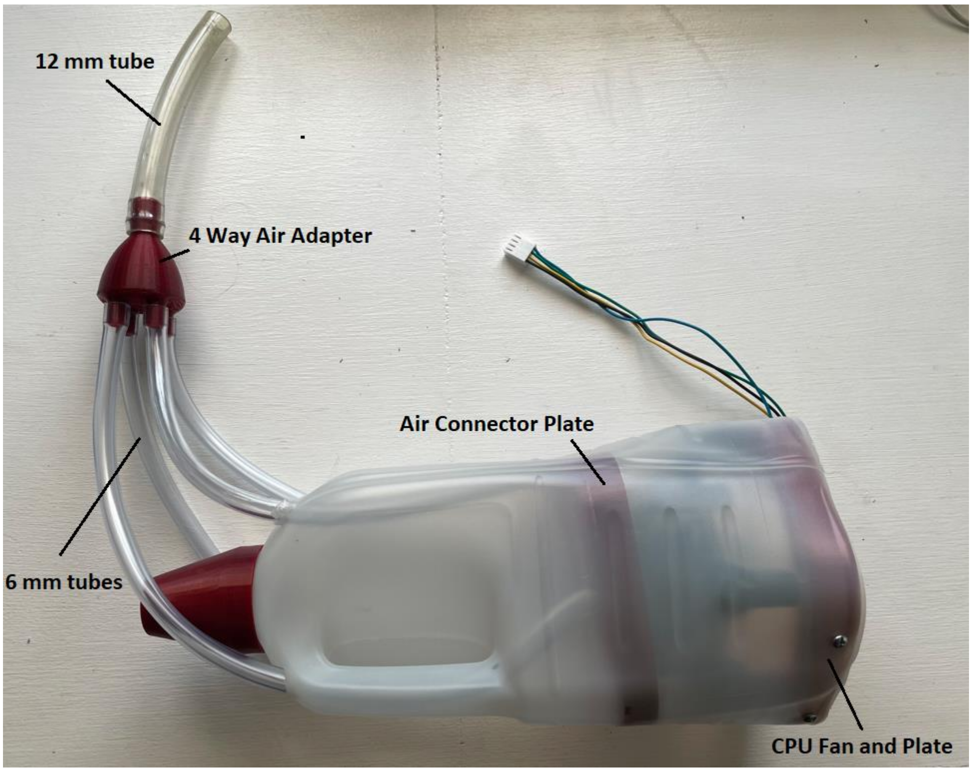


Figure 55. Sucker Prototype - Iteration 4

- Power and return wires from the Intel CPU fan were then wired into the existing electrical harness to allow control of fan via the toggle switch.
- The end of an air blower nozzle was attached to 12 mm PE tube from the 4-way adapter as per Figure 56, ensuring a good seal and no air losses when the blower trigger was depressed.

Figure 56. Air blower Nozzle Connection

- 6 x 5 - 8 mm Styrofoam balls were then placed into a clear plastic tray, along with a ladybeetle, a dried pea, a dead medium sized caterpillar, a dead adult Cabbage White Butterfly and a small foam square (5 mm x 12.5 mm x 12.5 mm), to allow testing of the prototype's suction ability.
- Activated and charged a 40L air compressor with 5 bars of air pressure.
- After which, connected the electrical harness to a 12V power adapter, connected this to a 10 Amp power lead, plugged this lead in and then powered it up, before activating the toggle switch to engage the case fan.
- A 16 mm ID clear PE tube was then inserted through Nozzle 1 of the Sucker device and its end applied to the materials in the plastic tray in attempt to suck them up, whilst at the same time depressing the air blower trigger.
- Observations were noted and recorded as per the results presented in Chapter 4.3.3.3.

- *Build Performance* results for this iteration of the Sucker were updated, as recorded in Chapter 4.3.3.3 to include extra time and costs involved in making the modifications as described.
- After examining the results (see Chapter 4.3.3.3), and noting the device was still not viable, further design changes and modifications were again identified and made based upon the associated analysis (being addition of baffles to the inlet area of the 2nd iteration of the device), with further basic testing then performed to help further develop the prototype (5th Iteration). The modifications and processes for this next iteration were as follows:
  - Using the shadow of the inlet tube (to help establish the nature of the curve in the inlet area), designed four baffle panels able to fit inside the inlet, as per Figure 57.

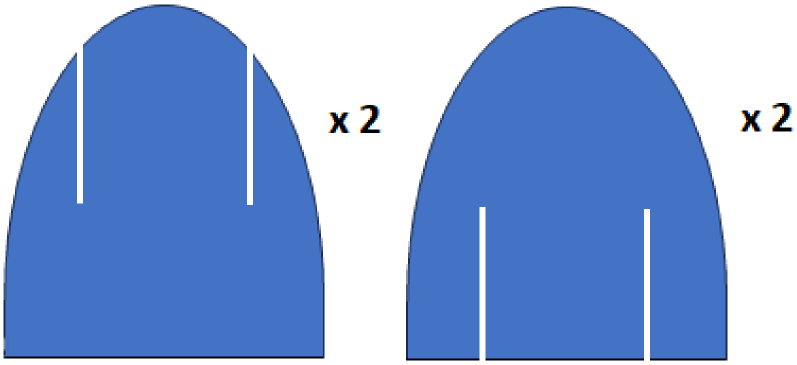


Figure 57. Baffle Templates

- Using flat sections from the sides of a 2L milk bottle, cut four baffle walls out based on the design as per the baffle templates (Figure 57), including cutting and removing thin slots in each panel to allow them to be easily connected together, ensuring the desired 3 dimensional shape was able to be maintained during device operation.
- The inlet tube Connecting Plate was then removed from the Case Fan mount by undoing the nuts on the connecting bolts and separating these components.
- The baffle was assembled and inserted into the inlet end of Prototype C – Iteration 2, as per Figure 58.

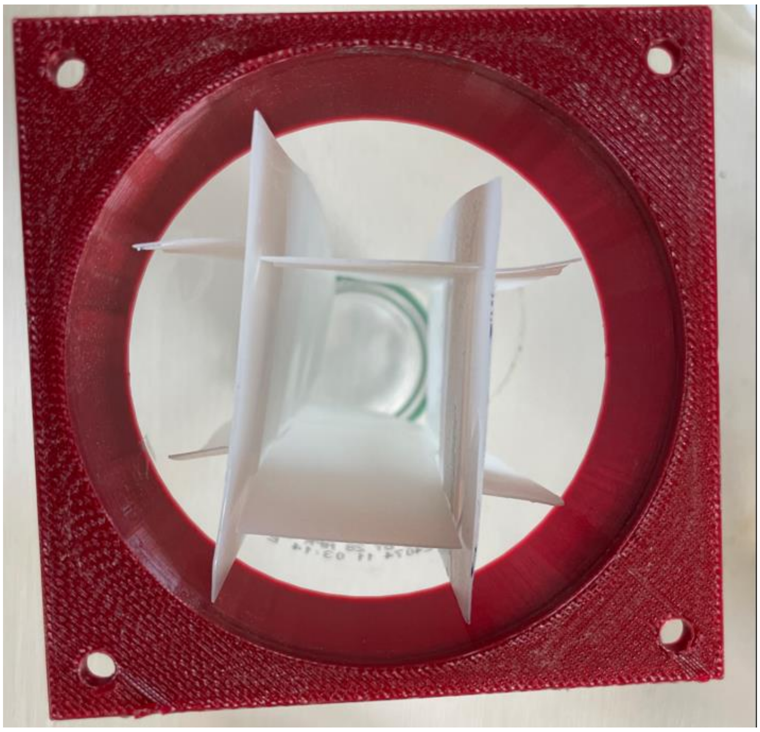


Figure 58. Baffles in Sucker Iteration 2 Inlet

  - Top and bottom corners of the baffle were glued to the inlet tube using Selley's Liquid Nails (noting Silicon could also have been used), to hold it firmly in place.
  - The inlet tube, now with baffles, was then connected back to the Case Fan using the previously removed connecting bolts and nuts, as shown in Figure 59.

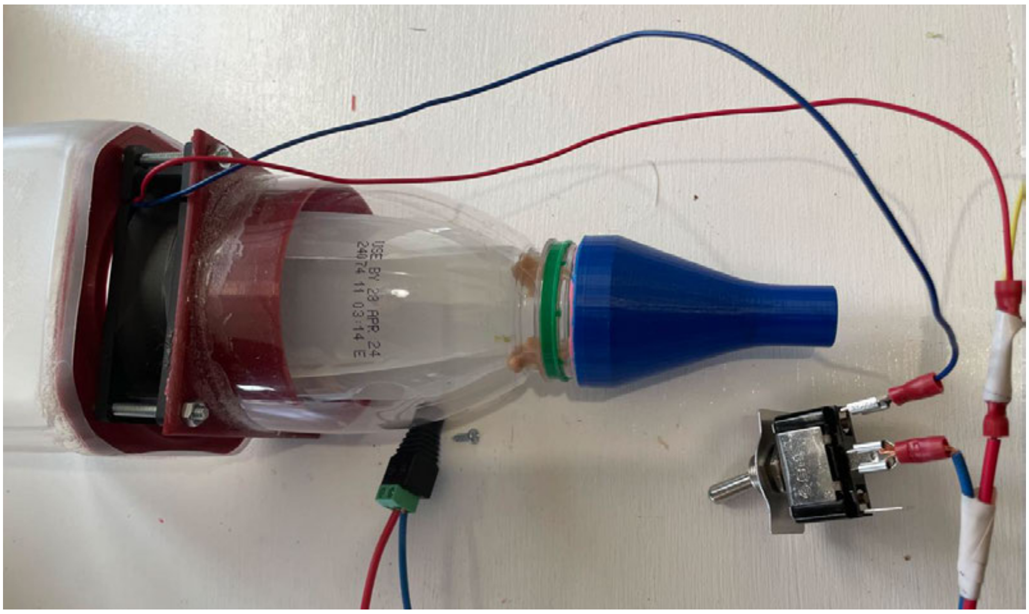


Figure 59. Sucker Prototype - Iteration 5

  - As with previous iterations, the electrical harness was connected to power and the toggle switch activated to engage the case fan.
  - 6 x 5 - 8 mm Styrofoam balls were once again placed into the clear plastic tray along with a ladybeetle, a dried pea, a dead medium sized caterpillar and a small foam square (5 mm x 12.5 mm x 12.5 mm), to allow testing of the device's suction ability.
  - Nozzle 2 was then attached to the Sucker device and applied to the materials in the plastic tray in attempt to suck them up.
  - Observations were noted and recorded, as per the results in Chapter 4.3.3.4.
- *Build Performance* results for the 5th Sucker iteration were then updated, as recorded in Chapter 4.3.3.4, to include extra time and costs involved in making the modifications as described.
- After examining the results (as per Chapter 4.3.3.4) and noting this iteration of the device, though improved, was still not viable, further design changes and modifications were again identified and made based upon the associated analysis (being addition of a high speed air flow to the inlet area of the 5th iteration of the device), with basic testing again performed to help further develop the prototype (6th Iteration). The modifications and testing processes for this next iteration were as follows:
  - Removed Nozzle 2 from Sucker device.

- Cut 30 cm of 16 mm ID clear PE tubing, wrapped one end in electrical table until OD increased by 0.5 mm and then inserted through Nozzle 1, pulling it through until the nozzle sealed over the taped end (noting that the design of nozzle could also have been changed to reduce nozzle ID so as to create a tighter seal and thereby negate the need for electrical tape, or alternatively this could have been achieved via application of a bead of silicon to the inside of the nozzle around the PE tubing).
- Using sharp pointed device, speared hole through one side of PE tubing on one side only.
- Inserted a Jamec-PEM air blow gun with a medium tube attachment through the side of the 16 mm PE tubing, facing in the direction of the Sucker outlet, as per Figure 60.
- Heated a 10 mm round steel bar and applied to either side of the PE tubing end to create air spaces as per Figure 61 (to prevent sealing off of sucker end when applied to leaf – noting this was added at a later stage after observing this occurring during preliminary testing).

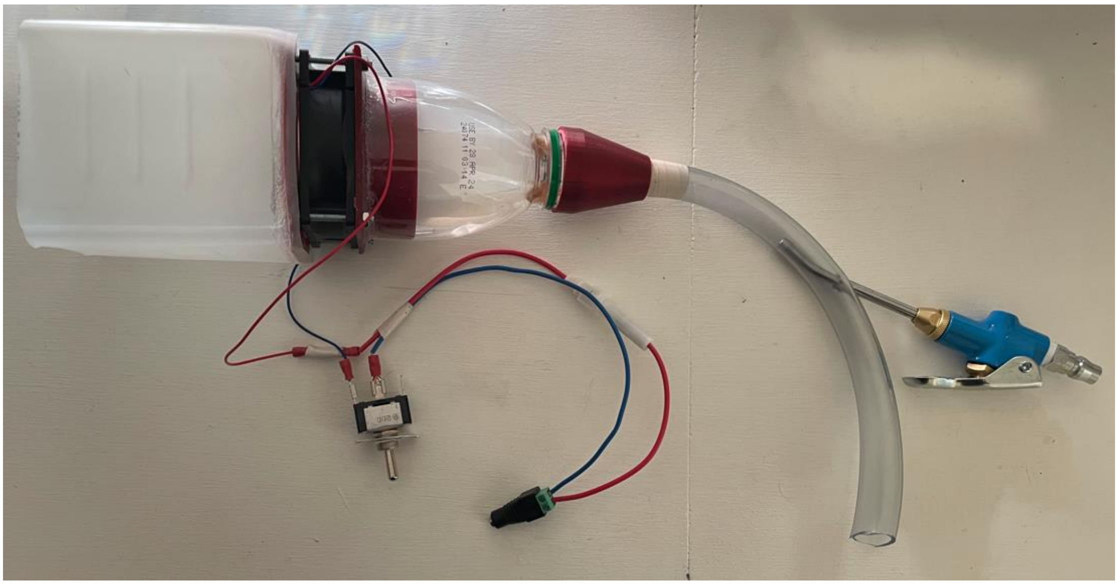


Figure 60. Sucker Prototype - Iteration 6

Figure 61. Sucker Iteration 6 PE Tube Air Gap

  - Connected the compressor air hose to the air blow gun, before activating the air compressor and allowing it to fully charge (noting compressor cut-out pressure set to 8 bar and cut-in pressure set to 5 bar to give a minimum pressure of 5 bar).
  - Connected the electrical harness to power and toggled the switch to activate the case fan.
  - Placed 6 x 5 - 8 mm Styrofoam balls into the plastic tray, along with a ladybeetle, a dried pea, a dead medium sized caterpillar, and a small foam square (5 mm x 12.5 mm x 12.5 mm), to allow testing of the prototype's suction ability.
  - The end of the PE tube of the Sucker device was then applied to the materials in the tray.
  - Depressing the air blow gun trigger, the end of PE tube was then moved around the tray in an attempt to pick up each of the items.
  - Observations were noted and recorded, as per the results in Chapter 4.3.3.5.
- *Build Performance* for the 6th iteration of the Sucker prototype was then updated (as described in Chapter 4.3.3.5), to include the extra time and costs involved in making the stated modifications.
- Examining the results (as per Chapter 4.3.3.5), and noting this iteration was now viable, no further design changes were identified as being required. This made the 6th iteration of the device the final version of the Sucker prototype, allowing progression to the next Phase of the experimental process.

3.6.3.4 Phase 3 Data Collection

During Phase 3, all data recorded was tabulated for each device and presented as per Chapter 4.3. Chapter 4.3.1 outlines the Gripper secondary build results and associated analysis, while Chapter 4.3.3 outlines the Sucker secondary build and testing results for each iteration, along with associated analysis, detailing the primary reasoning behind the implemented changes between each iteration.

3.6.4 Primary Testing: Phase 4

3.6.4.1 Plant Damage

Plant damage was assessed through first establishing a likely plant species against which the prototypes might be tested against. This was followed by direct application of each of the final iterations of the prototypes directly to the young plant leaves (henceforth referred to as "treatments"), and observations made. The process undertaken was as follows.

Established test plants:

- Prepared garden bed area appropriate for approximately 15 adult broccoli plants.
- Purchased approximately fifteen sprouting broccoli seedlings (*Brassica oleracea*), removed seedlings from punnet, carefully disentangled roots and planted into previously prepared garden bed (pressing in around base firmly, watering and mulching planted area).
- Allowed plants to grow for approximately 14 days, ensuring roots did not dry out during this time.

- Once established, selected four similar sized seedlings and identified with unique labels.
- Took photograph of the plot and seedlings, as per Figure 62, to help identify the associated plant locations and labels.
- Took photographs of all plants and treated leaves prior to treatment at time zero (T_0).

Figure 62. Established Broccoli Seedling Plot

Damage testing was then carried out as per:

- Plant 1 was selected as being the control plant, with no treatment applied.
- Plant 2 had 1 application of each of the prototype treatment applied to each of 3 separate leaves as per:
  - The leftmost leaf had the Gripper jaws placed either side, the button depressed, and the leaf squeezed between the jaws of Prototype A for 3 seconds, as per Figure 63.
  - The rightmost leaf of plant 2 had the Zapper placed near its out rim and the button depressed, discharging the electrode of Prototype B against the plant on a single occasion as indicated by Figure 64.

Figure 63. Application of Gripper to Plant 2

Figure 64. Application of Zapper to Plant 2

- The bottom most leaf of Plant 2 then had Prototype C (the Sucker), applied to it, with the fan running and the air blow gun activated for a 2 second burst (with a source pressure of approx. 5 bar), to create a suction force of approximately 2.5 kN*, as per Figure 65.

* *Note that suction force was established through applying the suction device to a balloon attached to weights and the maximum weight able to be lifted measured, (with source pressure for the Air blower nozzle set between 5 and 8 bar). The cross-sectional area of the sucker application end was then calculated (assuming the shape to be approximately oval), to establish pressure, as per Appendix E.*

Figure 65. Application of Sucker to Plant 2

  - Images of leaves were taken after treatment and all leaves then visually inspected for signs of damage.
- Plant 3 was treated similarly, however, this time with two applications per leaf as per:
  - The bottom left most leaf had the gripper placed either side and the button depressed, and the leaf squeezed between the jaws of Prototype A in the same place twice (as per Figure 66), each time for 3 seconds.

Figure 66. Application of Gripper to Plant 3

- The uppermost leaf of plant 3 had the Zapper placed near its outer rim and the button depressed, discharging the electrode of Prototype B against the plant on two occasions, each to the same location, as indicated by Figure 67.

Figure 67. Application of Zapper to Plant 3

- The bottom leftmost leaf of Plant 3 then had Prototype C (the Sucker), applied to it, with the fan running and the air blow gun activated for a 2 second burst, with a source pressure of approximately 5 bar, to create a suction force of approximately 2.5 kN (as previously described). This was repeated twice at the same location, as per Figure 68.

Figure 68. Application of Sucker to Plant 3

- Images of leaves were taken after treatment and all leaves then visually inspected for signs of damage.

- Plant 4 was treated similarly, however this time with four applications per leaf as per:
  - The left most leaf had the gripper placed either side, the button depressed, and the leaf squeezed between the jaws of Prototype A in the same place four times, as per Figure 66.

Figure 69. Application of Gripper to Plant 4

- The uppermost leaf of plant 4 had the Zapper placed near its outer rim and the button depressed, discharging the electrode of Prototype B against it. This was repeated four times at the same location, as per Figure 70.

Figure 70. Application of Zapper to Plant 4

- The bottom leftmost leaf of Plant 4 then had Prototype C (the Sucker), applied to it, with the fan running and the air blower nozzle activated for a 2 second burst, with a source pressure of 4.5 bar, to create a suction force of approximately 2.5 kN (as previously described). This was repeated four times at the same location, as per Figure 71.

Figure 71. Application of Sucker to Plant 4

- Images of treated plants and leaves were taken after treatment (T_1) and all leaves then visually inspected for signs of damage.
- Images of treated plants and leaves were taken 24 hours after treatment (T_2), 3.5 days after treatment (T_3), and 5.5 days after treatment (T_4).
- Results were then collated and presented as per Chapter 4.4.1, with ratings assigned as described in Chapter 3.1 – Phase 4, with all data then being tabulated in an Excel Spreadsheet.

3.6.4.2 Insect Removal

Insect removal testing was achieved through first obtaining sufficient quantities of insect test subjects, of the same species, for life cycle stages deemed most easily targeted by robotic end-effectors (these being larvae and the pupae). For the purposes of testing, due to ease of acquisition, and ability to obtain large quantities at the point in time of testing, Mealworms (*Tenebrio molitor*), were utilised. A 50 gram tub was purchased, and thirty pupae randomly removed from the tub, before being visually arranged in 3 equal groups of similar sizes. Sixty larval Mealworms were then removed and similarly arranged. One group of each was then transferred to a plastic container (see Figure 72), to give a total of 30 test subjects per prototype. During transfer, specimens were measured across their broadest and their longest aspects, to allow identification of major size discrepancies, to help ensure sample variation was relatively evenly distributed across the three trials, and to help establish any impact size might have upon results. Measuring was performed using digital callipers, as per Figure 73 through to Figure 76.

Figure 72. Mealworm Larvae and Pupae being Transferred into a Plastic Container

Figure 73. Measuring Mealworm Larvae Width

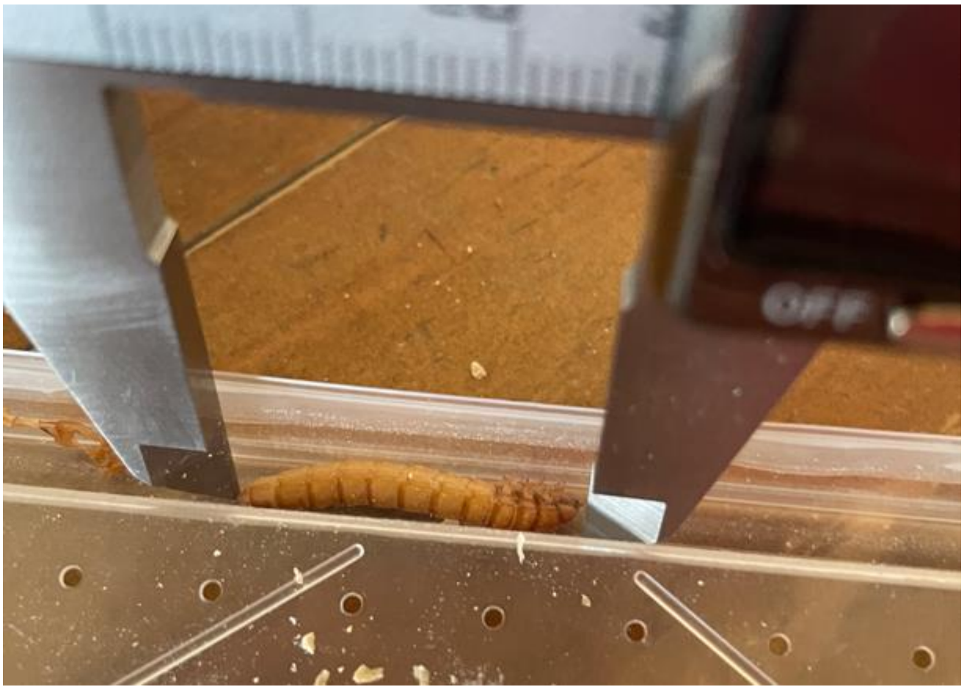


Figure 74. Measuring Mealworm Larvae Length

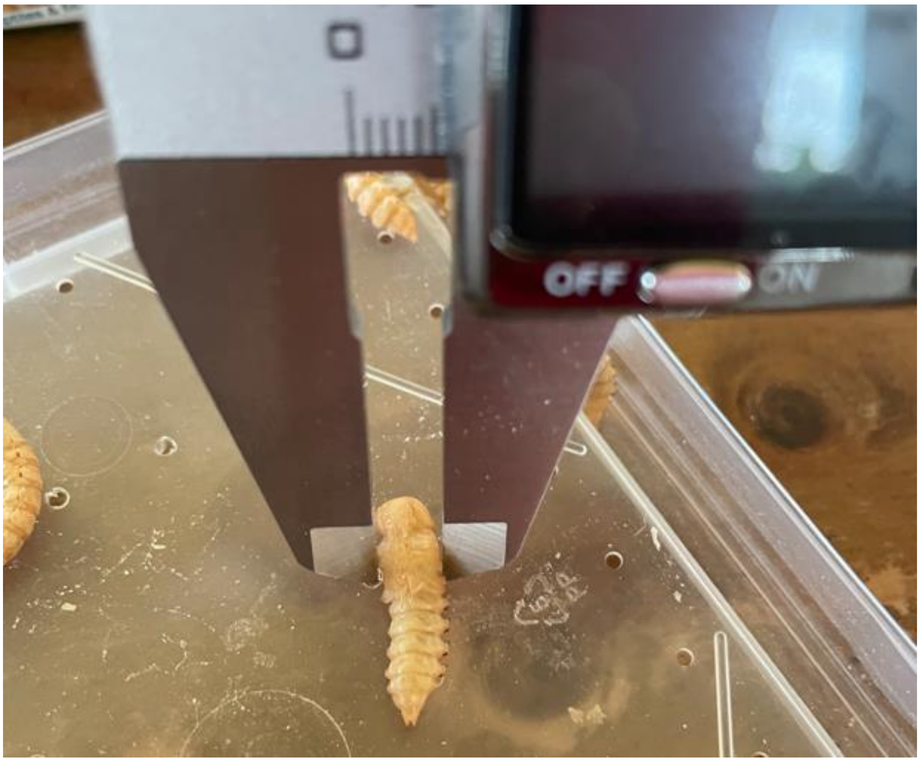


Figure 75. Measuring Mealworm Pupae Width

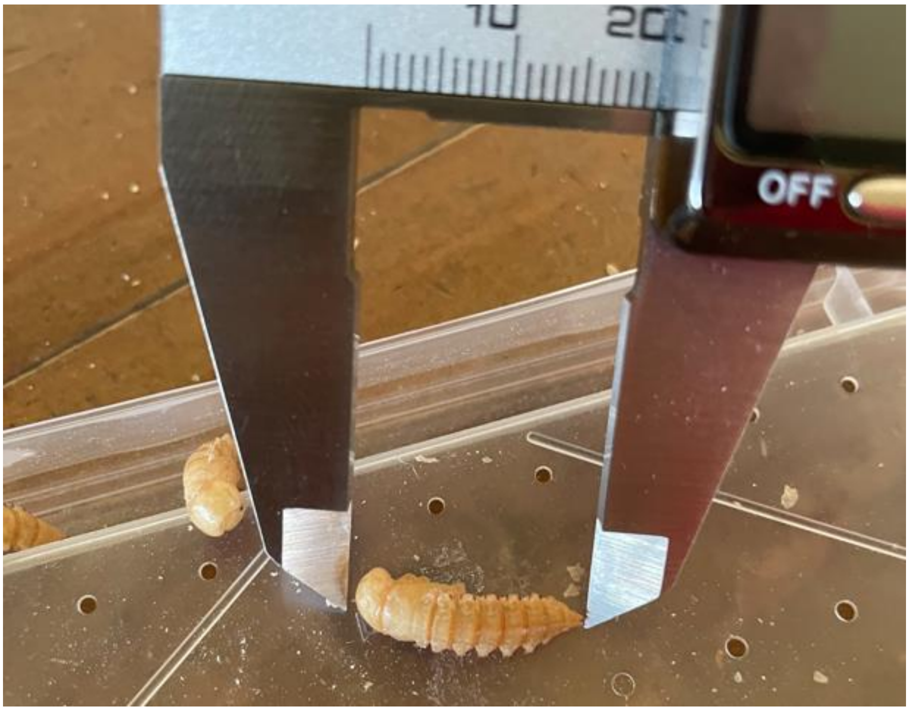


Figure 76. Measuring Mealworm Pupae Length

This was followed by configuration and application of each of the final iterations of the prototypes directly to the test specimens (henceforth referred to as “treatments”), observations made and recorded. The process for testing each of the prototypes was as follows:

Gripper Testing

- All test specimens were removed from the container and placed upon a single broccoli leaf.
- Specimens were attempted to be picked up on a one-by-one basis through placing the gripper jaws either side of each specimen, then pressing and holding the activation button, lifting from the leaf, and transferring back into the holding container (see Figure 77).

Figure 77. Removing Test Specimens with Gripper

- Where specimens were clustered, forceps were used to gently separate out individuals to allow singular selection. Specimens were otherwise allowed to move freely over the leaf (being placed back upon it where they moved off it completely).
- Observations were then made and recorded around ability to successfully remove and transfer the specimen, the state of specimen after transfer, along with any other details believed pertinent.
- A lidded plastic container was then prepared with a medium of raw rolled oats and slices of carrot placed inside. Approximately 20 small holes (~ 2 mm) were then made in the container lid using a standard cordless drill and 2 mm drill bit.
- All treated test subjects were transferred to the container, the lid secured, and the container labelled as "Prototype A", along with the time and date.
- Observation of larvae and pupae status and condition was performed approximately 2 hours after initial treatment. This was achieved by transferring all specimens out of the medium, one-by-one, into a clear plastic container. Non-active specimens were lightly squeezed with forceps after transfer to check for response to stimulus and to thus ascertain likely life status.
- Specimens were then measured using Digital Callipers, and attempts made to cross-reference specimens against the originally recorded notes. As alignment of measurements proved to be

extremely difficult (with few measurements proving to align and most specimens now appearing shorter than originally observed), matching was based on those most closely aligned within the two data sets.

- Results were recorded and all specimens transferred back into the rolled-oat medium.
- Observation of larvae and pupae status and condition was again performed approximately 24 hours after initial treatment, with the transfer, response check and measure process repeated.
- Results were recorded, as per Appendix F.1, and all specimens transferred back into the rolled-oat medium.
- All results were then collated, summarised and presented as per Chapter 4.4.2, with judgements made around *Removal Performance*, and ratings assigned as previously described in Chapter 3.1 – Phase 4, with all data then being tabulated in an Excel Spreadsheet.

Zapper Testing

- All test specimens were, as with the Gripper testing, removed from the container and placed upon a single broccoli leaf.
- Specimens were attempted to be electrocuted on a one-by-one basis through placing the Zapper terminals in close proximity to each specimen, whilst not touching (see Figure 78), then pressing and holding the activation button until discharge occurred. Where discharge failed, or shorted, further attempts were made until discharge against the specimen was observed, thus ensuring all specimens received at least one treatment from the Zapper device.

Figure 78. Application of Zapper to Test Specimens

- Where specimens were clustered, forceps were used to gently separate out individuals to allow singular selection. Specimens were otherwise allowed to move freely over the leaf (being placed back upon it where they moved off it completely).
- Observations were made and recorded around ability to successfully "remove" the specimen, the state of specimen after treatment, along with any other details believed pertinent.
- A lidded plastic container was prepared with a medium of raw rolled oats and slices of carrot placed inside. Approximately 20 small holes (~ 2 mm) were made in the container lid using a standard cordless drill and 2 mm drill bit.
- All treated test subjects were transferred to the container, the lid secured, and the container labelled as "Prototype B", along with the time and date.
- Observation of larvae and pupae status and condition was performed approximately 2 hours after initial treatment. This was achieved by transferring all specimens out of the medium, one-by-one, into a clear plastic container. Non-active specimens were lightly squeezed with forceps after transfer to check for response to stimulus and to thus ascertain likely life status.
- Specimens were then measured using digital callipers, and attempts made to cross-reference specimens against the originally recorded notes. As alignment of measurements proved to be extremely difficult (with few measurements proving to align and most specimens now appearing shorter than originally observed), matching was based on those most closely aligned within the two data sets.
- Results were recorded, as per Appendix F.2, and all specimens transferred back into the rolled-oat medium.
- Observation of larvae and pupae status and condition was again performed approximately 24 hours after initial treatment, with the transfer, response check and measure process repeated.
- Results were recorded and all specimens transferred back into the rolled-oat medium.
- Results were collated, summarised and presented as per Chapter 4.4.3, with judgements made around *Removal Performance*, and ratings assigned as previously described in Chapter 3.1 – Phase 4, with all data then being tabulated in an Excel Spreadsheet.

Sucker Testing

- All 30 test specimens were, as with the prior testing, removed from the container and placed upon a single broccoli leaf.
- The sucker fan was then activated, the air compressor charged, and the air blow gun connected. A small net was then placed over the outlet tube, to catch any specimens ejected past the boundary of the outlet tube (see Figure 79).
- Specimens were attempted to be removed on a one-by-one basis through placing the Sucker inlet within close proximity of each specimen, then activating the air blow gun for approximately 3 seconds.

- Upon successfully removal, the next specimen was then treated in a similar manner until an attempt to remove all specimens had been made.

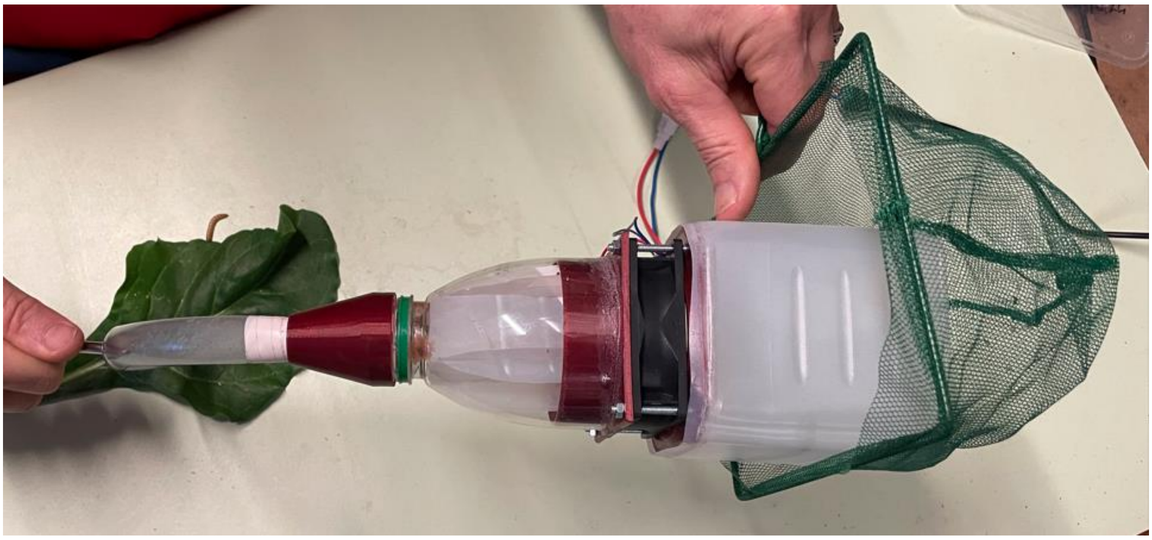


Figure 79. Sucker in Test Position with Net

- Where specimens were clustered, forceps were used to gently separate out individuals to allow singular selection. Specimens were otherwise allowed to move freely over the leaf (being placed back upon it where they moved off it completely).
- Observations were made and recorded around ability to successfully "remove" the specimen, the state of specimen after treatment, along with any other details believed pertinent.
- A lidded plastic container was prepared with a medium of raw rolled oats and slices of carrot placed inside. Approximately 20 small holes (~ 2 mm) were made in the container lid using a standard cordless drill and 2 mm drill bit.
- All surviving subjects were transferred to the container, the lid secured, and the container labelled as "Prototype C", along with the time and date.
- Observation of larvae and pupae status and condition was performed approximately 2 hours after initial treatment. This was achieved by transferring all specimens out of the medium, one-by-one, into a clear plastic container. Non-active specimens were lightly squeezed with forceps after transfer to check for response to stimulus and to thus ascertain likely life status.
- Specimens were then measured using digital callipers, and attempts made to cross-reference specimens against the originally recorded notes. As alignment of measurements proved to be extremely difficult (with few measurements proving to align and most specimens now appearing shorter than originally observed), matching was based on those most closely aligned within the two data sets.
- Results were recorded and all specimens transferred back into the rolled-oat medium.

- Observation of larvae status and condition was again performed approximately 24 hours after initial treatment with those previously noted inactive/suspected dead, again checked to confirm status was unchanged.
- Results were recorded, as per Appendix F.3.
- Results were collated, summarised and presented as per Chapter 4.4.4, with judgements made around *Removal Performance*, and ratings assigned as previously described in Chapter 3.1 – Phase 4, with all data then being tabulated in an Excel Spreadsheet.

Control

- To confirm that specimens being transferred into the rolled-oat medium was not responsible for later specimen death, 20 larvae and 10 pupae were placed within a container of the same size and shape as those being utilised for the Gripper and Zapper specimen storage, and the same rolled-oat medium (along with slices of carrot), added.
- Observation of specimen status and condition was then performed approximately 24 hours later, and the results recorded, as per Appendix F.4. Summarised results are as per Chapter 4.4.5.

3.6.5 Follow-up Testing: Phase 4

With the preferred test species having not been available in sufficient numbers to perform primary testing against, and noting differences between the results observed during preliminary testing and primary testing, further testing upon other species, including the original target species, was undertaken.

Follow-up pest removal testing for each device specifically targeted Cabbage White Butterfly larvae and ladybeetle adults. This was achieved through first allowing a small Cabbage White Butterfly population to establish in the test plant plot (as described in Chapter 3.6.4.1). Twelve *Pieris rapae* specimens, all larvae, were visually identified within the plot, six being large caterpillars (exceeding 30 mm in length with a diameter of approximately 4 mm), six being small caterpillars (10 - 15 mm in length, with a diameter of approximately 2 mm). These were divided into three groups of four, with two large and two small specimens in each. Twelve ladybeetles from a range of species, were also identified across various locations (primarily sourced from citrus trees), and similarly divided into three groups of four, with an effort made to ensure equal distribution of beetle sizes in each group. The prototypes were then applied to the respective groups, in an attempt to remove/kill the test specimens. Application occurred under field conditions where possible, with all caterpillars being left in their originally located positions on the test plants as per Figure 80 and Figure 81, and ladybeetles similarly left in their original locations but only for prototype A and prototype B application, as per Figure 82 and Figure 83. Due to the nature of the prototype C construction (needing compressed air and power), ladybeetles in this group were collected and temporarily stored in a plastic container, before bench testing the Sucker device against them. Surviving ladybeetles for all prototype testing were collected after treatment and observed over

24 hours before being released back to their original locations (where identified as having survived and not fallen from the plant after treatment and attacked by ants within 15 minutes).

As with primary testing, results for all device testing were collated, summarised and presented as per Chapter 4.5, with judgements made around *Removal Performance*, and ratings assigned as previously described in Chapter 3.1 – Phase 4. All data was then tabulated in an Excel Spreadsheet with raw results recorded and reported as per Appendix G.

Figure 80. Application of Gripper to Caterpillar in Test Plot

Figure 81. Application of Zapper to Caterpillar in Test Plot

Figure 82. Application of Gripper to Ladybeetle in Field Testing

Figure 83. Application of Zapper to Ladybeetle in Field Testing

To confirm that specimens not treated were not dying of natural causes, four caterpillars located on four different test plants were noted and observed over a 24 hour period. While attempting to also do so for four ladybeetles, their highly mobile nature prevented this. As such, four medium sized ladybeetles from various species were collected and placed in a clear plastic container with a few host leaves over a period of 24 hours. Observation of ladybeetle specimen status and condition was performed at 24 hours, before releasing specimens back onto the original host plants. The results were then recorded, as per Appendix G.4, with summarised results as per Chapter 4.5.4.

3.6.6 Prototype Analysis & Comparison: Phase 5

After collecting results for primary testing and follow-up testing, assigning values as per the descriptors presented in Chapter 3.1 – Phase 4 for "Removal Ability" and "Kill Ability" for each specimen tested, and tabulating all scores in an Excel Spreadsheet, the values were averaged for each device, and the Standard Deviations calculated using the inbuilt Excel formula for a population sample (STDEV.S). "Host Damage" values were then tabulated (as described above in Chapter 3.7), to complete the *Removal Performance* for each device, as presented in Chapter 4.6.

Build Performance results collected during the design and build phase were tabulated alongside the *Removal Performance* results, to create averaged prototype performance tables, as per Table 2 (Chapter 3.1), for both primary testing and follow-up testing, with all values for each criteria summed to generate an overall performance score out of 16. This was completed for all three prototypes with a control performance score also generated to allow comparison and device assessment. Weightings, as described in Chapter 3.1- Phase 5, were applied to each criterion to create a secondary set of tables, as per the format previously outlined in Table 3 (Chapter 3.1). Qualitative observations made during the testing phases were then examined and used to cross-check both the averaged overall performance scores and the weighted overall performance scores to confirm the appropriateness of the weightings chosen. Weighted performance scores for primary testing and follow-up testing were then plotted to allow visual comparison of device performance and to better establish trends within the data (see Chapter 4.6.1).

Data from the primary testing and the follow-up testing was later separated based upon the nature of the specimens tested, to create a summary of relative device effectiveness against different specimens, with the respective scores then presented as a percentage of the maximum possible score. This summary was then plotted and visually assessed to help establish trends in performance for devices against pest types (see Chapter 4.6.2).

3.7 Data Collection Overview

Data collection was in the form of both quantitative and qualitative results collected throughout phases 1 - 4 of the project.

Quantitative data was taken with respect to cost (in $AU) and build time (in hours) for *Build Performance* during phases 1 and 3. Perceived complexity, being subjective, was by its nature noted to be qualitative, so was be judged on a 5-point scale and assessed against a predefined list of criteria, in an effort to quantify this data to help make later comparisons and judgements. Preliminary descriptions, aligning with the complexity categories previously detailed in Chapter 3.1 – Phase 1 & Phase 3, were prepared prior to prototype construction, with a reasonably prescriptive set of "standards" assigned against each rating, to help validate and ensure consistency across these judgements. Consideration of difficulties encountered during the design and build were also incorporated into these descriptions, resulting in changes from those originally proposed, and as such, contributed towards this judgement.

With *Removal Performance*, the data was noted to be slightly more nuanced, in that while the test insect was either removed or not removed, killed or not killed, and the host plant damaged or not damaged, potential was noted to exist for results that were outside of these strict definitions, making the data non-binary in nature. As with perceived complexity, in order to better utilise this data, these measures were rated with a points system, against a set of descriptors, to help quantify them, as previously outlined in Chapter 3.1. This data was collected during Phase 2 purely for preliminary viability assessment, and again during Phase 4 primary testing and follow-up testing, with this later data forming the basis of the experiment data and associated analysis.

Ability to remove the test specimen was judged on a 3-point scale. Judgement of this ability was relatively straight-forward (as described in Chapter 3.1 – Phase 4), due to the prescriptive nature of the respective score descriptions. Ability to kill the pest was judged on a 4-point scale, with further levels included between the major classifications (further detail as per Chapter 3.1 – Phase 4). This judgement of the intermediate classifications was noted as being quite subjective in nature, therefore documentation of actual damage observed was necessary, as was provision of some rationale around classification decisions made here.

Damage caused to the host plant by the end-effectors ("Host Damage"), was also assessed with a 3-point scale, based upon the degree of damage (as described in Chapter 3.1 – Phase 4). With data once again being subjective, a mechanism to help quantify this data was noted to be necessary. This was achieved through use of photography and visual observation over time. Each device was deliberately used with intent to replicate likely damage the host plant caused by treatment of any specimens located upon it, and images recorded of the damage made after application. With little to no obvious damage noted directly after treatment, scores were assessed against degree of damage noted over a period of 5.5 days. Host plants were allowed to continue growing after the initial damage was applied, and given time to recover, with follow-up images recorded of damaged areas. Potential for damage resulting from treatment application, was then used to assess the "Host Plant Damage" score from each device, with this score applied to each prototype.

Assessment of minimum and maximum size of pest insects successfully dispatched were also noted, with these results primarily used to establish the operational limitations observed for each device (noting this was impacted by available insect size and thus does not necessarily represent actual upper or lower operational limits of each device).

3.8 Data Validation

Testing and data collection procedures were standardised and kept constant across all devices so as to maximise data consistency and accuracy.

Data quality was ensured through thorough back-checking of hand-written notes against data entered and recorded digitally for the final report. Inconsistencies in data were examined to check for cases of error including checking for data lacking congruency with experimental observations.

Detailed records documenting all actual experimental procedures undertaken, data collection protocols, along with any deviation from the originally outlined procedures and protocols, were also taken, with these then updated accordingly. All raw data was then presented within the Appendices (see Appendix D, Appendix F and Appendix G).

Discussions with the project supervisor were also undertaken to ensure experimental design, including data collection methods, and basic data analysis approaches used throughout the course of the project were appropriate, with approval obtained prior to commencement of testing.

CHAPTER 4: RESULTS AND ANALYSIS

4.1 Build Performance: Phase 1

4.1.1 Gripper

Results for the preliminary *Build Performance* of the Gripper, as per Phase 1 of the project, are as summarised in Table 4. Perceived complexity, as previously noted, was based on the author's perception as to the nature and the development of the parts and build, so is acknowledged as being highly subjective. Further notes were included regarding the preliminary build phase, including assumptions, decisions and considerations relating to the collected results.

Table 4. Phase 1 Gripper Preliminary Build Performance Results

Preliminary Build - Initial	Cost	Perceived Complexity	Build Time (Hrs)
Tower Pro Micro Servo	$ 15.95	High	0
3D printed parts	$ 6.00	Medium	10
Screws	$ 0.40	Low	0
Arduino UNO	$ 34.95	High	0
Breadboard + components	$ 8.95	Medium-Low	0
Design	$ -	Med-High	4
Construction	$ -	High	4
Programming	$ -	Medium	2
TOTAL	**$ 68.35**	**Med-High**	**10**

Notes:

- Tower Pro Micro Servo readily available from JayCar store or online – pricing varies.
- 3D printing – cost 10c/gm from local library, size limited to 10 x 10 cm print platform.
- Print Build Time is actual time taken to print all parts. Actual time spent printing has been ignored apart from configuration and setup time (importing file, arranging, setting print parameters and establishing that printing had successfully completed the first 5 layers). Configuration and setup time has been included as part of the construction time. Time to learn the software and complete necessary inductions in order to gain access to and use the publicly available 3D printer has not been included.
- Arduino UNO readily available from JayCar store or online – pricing varies.
- Components (press button, cap, wiring, resistor) estimated at $2.

- Cost of power supply has been ignored, as it is assumed that this would be able to be easily provisioned via the robotic arm the device would ultimately be attached to.
- Design time assumes that AutoDesk Inventor has already been loaded to the design device and that the user already has basic familiarity with use of the software.
- Cost of the software licensing for AutoDesk Inventor has not been included in the costing of the device build. It is assumed that it, or something similar would be readily available to any Mechanical Engineer or University student studying Mechanical Engineering (furthermore noting that a one-year free license to its use is available for all students).
- The nature, size and composition of the device was indicative of it being relatively easy to adapt for connection through to a robotic arm, requiring only slight modifications to the main body and development of an interconnecting part to allow physical attachment, along with a small cable harness for the servo wiring.

Extra costs and time to make the necessary modifications to produce a working prototype are included and summarised as per Table 5, which furthermore includes a summary of the final cost, perceived complexity and build time for the Gripper based end-effector at the end of Phase 1.

Table 5. Phase 1 Gripper Preliminary Build Performance Results after Modification

Preliminary Build - Final	Cost	Perceived Complexity	Build Time (Hrs)
Tower Pro MicroServo	$ 15.95	High	0
3D printed parts	$ 12.00	Medium	20
Screws	$ 0.40	Low	0
Arduino UNO	$ 34.95	High	0
Breadboard & components	$ 8.95	Medium-Low	0
Design + Redesign	$ -	Medium-High	6
Construction	$ -	High	5.5
Programming	$ -	Medium	2.5
TOTAL	**$ 69.30**	**Med-High**	**14**

4.1.2 Zapper

Results for the preliminary *Build Performance* of the Zapper, as per Phase 1 of the project, are as summarised in Table 6. As with the Gripper, perceived complexity was based on the author's perception as to the nature and the development of the parts and build, so is acknowledged as being highly subjective. Further notes have been included regarding the preliminary build phase, including assumptions, decisions and considerations relating to the collected results.

Table 6. Phase 1 Zapper Preliminary Build Performance Results

Preliminary Build - Initial	Cost	Perceived Complexity	Build Time (Hrs)
Mafiti Bug Zapper	$ 29.99	Med-High	0
3D printed parts	$ 4.80	Medium	8
Screws and wiring	$ 0.60	Low	0
Design	$ -	Medium	3
Construction	$ -	Medium	4
TOTAL	**$ 35.39**	**Medium**	**7**

Notes:

- Mafiti bug zapper readily available online – pricing varies.
- 3D printing – performed by USQ engineering department. Cost estimated at 10c/gm based on local library costs to ensure costing consistency over project. Local library 3D printer limited to 10 x 10 cm print platform which was too small for the required print job.
- Print Build Time is actual time taken to print all parts. Actual time spent printing has been ignored apart from configuration and setup time (importing file, arranging, setting print parameters and establishing that printing had successfully completed the first 5 layers). Configuration and setup time has been included as part of the construction time. Time to learn the software and complete necessary inductions in order to gain access to and use the publicly available 3D printer has not been included.
- Cost of power supply has been ignored, as it is assumed that this would be able to be easily provisioned via the robotic arm the device would ultimately be attached to.
- Design time assumes that AutoDesk Inventor has already been loaded to the design device and that the user already has basic familiarity with use of the software.
- Cost of the software licensing for AutoDesk Inventor has not been included in the costing of the device build. It is assumed that it, or something similar would be readily available to any Mechanical Engineer or University student studying Mechanical Engineering (furthermore noting that a one-year free license to its use is available for all students).
- The nature, size and composition of the device was indicative of a medium amount of further work being required to adapt it so as to allow connection through to a robotic arm. Specifically, this would require slight modification of the main case and development of an interconnecting part to allow physical attachment to the arm, along with rerouting the switch and trigger to a controller in the main robot, along with a small cable harness for the power and trigger wiring.

Extra costs and time to make the necessary modifications to produce a working prototype are included and summarised as per Table 7, which furthermore includes a summary of the final cost, perceived complexity and build time for the Zapper based end-effector at the end of Phase 1.

Table 7. Phase 1 Zapper Preliminary Build Performance Results after Modification

Preliminary Build - Final	Cost	Perceived Complexity	Build Time (Hrs)
Mafiti Bug Zapper	$ 29.99	Med-High	0
3D printed parts	$ 4.50	Medium	8.75
Screws and wiring	$ 0.60	Low	0
Design	$ -	Medium	4
Construction	$ -	Medium	5.5
TOTAL	**$ 35.99**	**Medium**	**9.5**

4.1.3 Sucker

Results for the preliminary *Build Performance* of the Sucker, as per Phase 1 of the project, are summarised in Table 8. As with the Gripper, perceived complexity was based on the author's perception as to the nature and the development of the parts and build, so is acknowledged as being highly subjective. Further notes have been included regarding the preliminary build phase, including assumptions, decisions and considerations relating to the collected results.

Table 8. Phase 1 Sucker Preliminary Build Performance Results

Preliminary Build - Initial	Cost	Perceived Complexity	Build Time (Hrs)
80 mm Case Fan	$ 19.95	Medium	0
3D printed parts	$ 7.80	Medium	8
Breadboard & components	$ 8.45	Medium-Low	0
Screws	$ 0.60	Low	0
Design	$ -	Medium	3
Construction	$ -	Low	3
TOTAL	**$ 36.80**	**Medium**	**6**

Notes:

- 80 mm Case Fan readily available from JayCar and online – pricing varies.
- 3D printing – cost 10c/gm from local library, size limited to 10 x 10 cm print platform.
- Print Build Time is actual time taken to print all parts. Actual time spent printing has been ignored apart from configuration and setup time (importing file, arranging, setting print parameters and establishing that printing had successfully completed the first 5 layers). Configuration and setup time has been included as part of the construction time. Time to learn the software and complete necessary inductions in order to gain access to and use the publicly available 3D printer has not been included.
- Cost of inline fuse ignored. It is assumed any power supply to the manipulator would have a fuse already in place.
- Cost of power supply has been ignored, as it is assumed that this would be able to be easily provisioned via the robotic arm the device would ultimately be attached to.
- Design time assumes that AutoDesk Inventor has already been loaded to the design device and that the user already has basic familiarity with use of the software.
- Cost of the software licensing for AutoDesk Inventor has not been included in the costing of the device build. It is assumed that it, or something similar would be readily available to any Mechanical Engineer or University student studying Mechanical Engineering (furthermore noting that a one-year free license to its use is available for all students).
- The nature, size and composition of the device was indicative of a significant amount of further work being required to adapt it so as to allow connection through to a robotic arm. Specifically, this would require complete modification of the tube design to be smaller, as well as potentially replacement of the fan with something smaller and more powerful. As with the other devices, rerouting of the trigger to a controller in the main robot, likely involving need for a small cable harness for the power and trigger wiring, would be required.

With initial testing indicating the sucker end-effector to be at least partially functional, no further modifications were identified as being required at this stage, thus leaving initial *Build Performance* for the device being as per Table 8 above.

4.2 Preliminary Testing: Phase 2

4.2.1 Gripper

Results for preliminary testing of the Gripper end-effector were as per Table 9.

Table 9. Gripper Preliminary Test Results

Test Specimen	Life Cycle Stage	Relative Size	Removed	Incapacitated	Killed
Cabbage White Butterfly	Larvae	Small	Yes	Yes	Yes - Immediately
Cabbage White Butterfly	Larvae	Large	Yes	Yes	Yes - Immediately
Cabbage White Butterfly	Pupae	Average	Yes	Yes	Yes - Immediately
Cabbage White Butterfly	Adult	Average	Eventually	Temporarily	Yes - Eventually
Large Spotted Ladybeetle	Adult	Medium	Eventually	Yes	Yes - Immediately
Black Scale	Adult	Large	No	Yes	Yes - Eventually

Further details and notes are as per Appendix D.

4.2.2 Zapper

Results for preliminary testing of the Zapper end-effector were as per Table 10.

Table 10. Zapper Preliminary Test Results

Test Specimen	Life Cycle Stage	Relative Size	Removed	Incapacitated	Killed
Cabbage White Butterfly	Larvae	Medium	No	Yes	Yes - Immediately
Cabbage White Butterfly	Larvae	Large	No	Temporarily	Yes - Eventually
Cabbage White Butterfly	Larvae	Very large	No	Temporarily	Yes - Eventually
Cabbage White Butterfly	Pupae	Average	No	Yes	No
Cabbage White Butterfly	Adult	Average	No	Temporarily	No
Large Spotted Ladybeetle	Adult	Medium	No	Yes	No
Large Spotted Ladybeetle	Larvae	Average	No	Yes	Yes - Eventually
Black Scale	Adult	Large	No	Yes	Unknown

Further details and notes are as per Appendix D.

4.2.3 Sucker

Results for preliminary testing of the Sucker end-effector were as per Table 11.

Table 11. Sucker Preliminary Test Results

Test Specimen	Life Cycle Stage	Relative Size	Removed	Incapacitated	Killed
Cabbage White Butterfly	Larvae	Small	Temporarily	No	No
Cabbage White Butterfly	Larvae	Medium	No	No	No
Cabbage White Butterfly	Pupae	Average	No	No	No
Cabbage White Butterfly	Adult	Average	No	Yes	Yes - Eventually
Cabbage White Butterfly	Adult	Average	No	No	No
Large Spotted Ladybeetle	Adult	Medium	No	No	No
Large Spotted Ladybeetle	Adult	Large	No	No	No
Black Scale	Adult	Large	No	No	No

Wiring harness noted as unreliable in current format. Further details and notes are as per Appendix D.

4.2.4 Summary and Analysis

From the results of the preliminary Gripper testing (Table 9), it was apparent that the Gripper end-effector had good promise with respect to its ability to remove and kill a range of insects from within a highly controlled test environment. Ability to remove and kill insects of a range of sizes, though be it those with low mobility, appeared very high. Ability against more mobile insects appeared questionable at this stage. Initial testing was, however, supportive of the device in its current iteration being suitable to use for undertaking more rigorous testing. The smallest specimen successfully removed and killed was noted to be an adult large spotted ladybeetle, with a size of 3.8 mm x 2.7 mm. The largest specimen successfully removed and killed was an adult Cabbage White Butterfly, with a size of 60 mm x 28 mm.

In contrast, the results from the preliminary Zapper testing (Table 10), were indicative of the Zapper end-effector having some, though limited, effectiveness. Firstly, by the nature of its design, it was noted to have no ability to remove insect pests unless said the pest was to fall off the plant after its electrocution. Secondly, while showing promise in at least temporarily incapacitating a range of insects, its ability to kill a range of pest insect species, life cycle stages, and sizes was very much inconclusive. With some success in killing insect pests, however, there was sufficient evidence to support the further testing of the device in its current form. The smallest specimen successfully killed was noted to be a larval form of the large spotted ladybeetle, with a size of 6 mm x 3.5 mm. The largest specimen successfully killed was a Cabbage White Butterfly caterpillar, with a size of 22 mm x 3.8 mm. In both cases death was not immediate.

The results of the preliminary Sucker testing (Table 11) were indicative of the Sucker end-effector having insufficient performance capability to undergo further testing in its current form. The data suggested limited ability to remove insect pests, results indicative of this being restricted to very small insects or winged insects, and only in situations where the insects had limited purchase. Overall removal ability was also noted as being limited, with only the adult butterfly being fully removed during the testing, and only after multiple attempts. Kill ability also appeared very poor, with only the adult butterfly being damaged sufficiently such that it eventually died, giving both a minimum and maximum kill size of 60 mm x 28 mm. It was observed that the wiring harness resulted in circuit disconnection when attempting to capture the escaped butterfly. Further modification was thus identified as being needed. Results were such that significantly greater air velocity/decreased entrance pressure appears necessary in order to improve device effectiveness.

In consideration of volumetric flow (Q) being equal to inlet cross sectional area (A_1) x inlet velocity (V_1) and this being equal to outlet cross sectional area (A_2) x outlet velocity (V_2) as per:

$$Q = A_1 V_1 = A_2 V_2$$

Equation 1.

It can be concluded that by maintaining outlet cross-sectional area and velocity, while reducing inlet cross-sectional area (A_1) should in theory increase inlet air velocity (V_1), assuming the fan has sufficient power to overcome the increased system resistance created by reducing this area. By Bernoulli's Principle, which effectively indicates that increasing the speed of a fluid will, by the conservation of energy, result in a simultaneous reduction in the pressure of that fluid (Çengel et al. 2017), it would be expected that inlet air pressure should be reduced as a result of this increased velocity, thus enhancing the suction effect experienced.

4.3 Secondary Build (and Test): Phase 3

4.3.1 Gripper

With issues identified in the ability of the prototype to be transferred into a field environment when attempting to develop a preliminary plant damage chart, additional design and build was required to hold the various components (as described in Chapter 3.6.2.1), increasing build time and costs. Extra considerations for these factors were included and summarised in Table 12. This table includes a summary of the final cost, perceived complexity and build time for the Gripper based end-effector through to the end of Phase 3 of the project.

Table 12. Phase 3 Gripper Preliminary Build Performance Results after Modification

Preliminary Build - Final	Cost		Perceived Complexity	Build Time (Hrs)
Tower Pro MicroServo	$	15.95	High	0
3D printed parts	$	22.00	Medium	28
Screws	$	0.40	Low	0
Arduino UNO	$	34.95	High	0
Breadboard & components	$	8.95	Medium-Low	0
Design + Redesign	$	-	Medium-High	8
Construction	$	-	High	6.5
Programming	$	-	Medium	2.5
TOTAL	**$**	**79.30**	**Med-High**	**17**

Examination of the size and structure of the final Gripper prototype were indicative of further work required before it could be attached to a robot arm, conceivably only requiring adaptations to the base component. It was therefore rated as having a High integration ability.

4.3.2 Zapper

No significant modifications affecting *Build Performance* were identified as being required after the Phase 2 analysis, therefore, no significant changes were made, with cost, complexity and time results thus as previously presented in Chapter 4.1.2. Examination of the size and nature of the final Zapper prototype were indicative of it also requiring further work to the case design, before it could be easily attached to a robot arm. Being only slightly longer and not too dissimilar in its dimensions to the Gripper, it was also rated as having a High integration ability.

4.3.3 Sucker

With issues identified in the viability of the Sucker device after preliminary analysis of the Phase 2 results, further modifications were required (as described in Chapter 3.6.3.3), thereby impacting *Build Performance* at each iteration. Results for the various Sucker iterations are as follows:

4.3.3.1 Sucker 2nd Iteration

Extra costs and time to make the necessary modifications to produce the first functional prototype are summarised as per Table 13 below, which includes a summary of the cost, perceived complexity and build time for the Sucker based end-effector at the early stages of Phase 3 of the project.

Table 13. Sucker 2nd Iteration Build Performance Results

Preliminary Build - Initial	Cost		Perceived Complexity	Build Time (Hrs)
80 mm Case Fan	$	19.95	Medium	0
3D printed parts	$	9.40	Medium	9
Switch and wiring	$	8.99	Medium-Low	0
Screws	$	0.60	Low	0
Design & Redesign	$	-	Medium-Low	3.75
Construction	$	-	Low	3.75
TOTAL	**$**	**38.94**	**Medium-Low**	**7.5**

Retesting of the device to establish viability after preliminary Stage 3 modifications produced results as per Table 14 below.

Table 14. Sucker Preliminary Test Results after Modification

Test Specimen	Life Cycle Stage	Relative Size	Removed	Incapacitated	Killed
Cabbage White Butterfly	Larvae	Small	Yes	No	No
Cabbage White Butterfly	Larvae	Medium	Yes	No	No
Cabbage White Butterfly	Larvae	Large	Yes	No	No
Cabbage White Butterfly	Pupae	Average	No	No	No
Cabbage White Butterfly	Adult	Average	Eventually	No	No
28 Spotted Ladybeetle	Adult	Medium	No	No	No

Further details and notes as per Appendix D.

While Table 14 indicated the 2nd iteration of the Sucker end-effector still performed poorly, with the reduced nozzle cross sectional area and improved wiring harness, it was observed to have gained a slightly improved ability to successfully remove insects. Kill ability was, however, noted to be non-existent, with the adult butterfly sucked up by the smaller nozzle blocking the nozzle and preventing it being pulled through the fan (see Figure 84), rendering the device useless, and failing to kill the pest insect.

Figure 84. Nozzle 2 Blocked by Butterfly

Its inability to incapacitate or kill insect pests established the viability of the device to be highly questionable at this point in its development, indicating further development of the design was still required. From observational notes, data was indicative of still more suction being needed in order to improve device viability. It was identified that sufficient suction needed to be generated in order to draw insects all the way through the case fan, so as to have some potential to damage/kill the insect pests after their removal. This established that in order to be viable, the prototype required the design to be adjusted until capable of pulling objects of greater size and mass through the case fan.

In consideration of Equation 1, as previously discussed, theory indicated that provided outlet air velocity is kept constant, doubling the cross-sectional area of the Outlet, should double the velocity of the air at the Inlet, as per:

$$A_1 \times \mathbf{2} \times V_1 = \mathbf{2} \times A_2 \times V_2 \qquad \text{Equation 2.}$$

thus resulting in a corresponding reduction in Inlet air pressure, as per the Bernoulli principle. Based on this theory, it was proposed that the next iteration should involve doubling the outlet area (as well as total air flow), through making a second device, and connecting it with the original sucker device to a common inlet. To keep costs and development time down, and match the existing air flow, it was proposed to use a similar fan of the same size and speed with a simplified tube design, and a primary aim of increasing outlet area whilst providing inlet connectivity. Note here that it was assumed the second fan produced a similar total air flow to the original fan.

4.3.3.2 Sucker 3rd Iteration

Incorporation of extra costs and time to make the necessary modifications to produce the 3rd iteration of the prototype gave the *Build Performance* results as shown in Table 15

Table 15. Sucker 3rd Iteration Build Performance Results

Preliminary Build - Initial	Cost	Perceived Complexity	Build Time (Hrs)
80 mm Case Fan	$ 19.95	Medium	0
80 mm CPU Fan	$ 25.00	Medium	0
3D printed parts	$ 15.00	Medium	14
Switch and wiring	$ 8.99	Medium-Low	0
Screws	$ 0.60	Low	0
Design & Redesign	$ -	Medium	4.75
Construction	$ -	Medium-Low	4.25
TOTAL	**$ 69.54**	**Medium**	**9**

Application of the suction end of the 3rd iteration of the device to the items in the plastic tray during viability testing gave results as per Table 16.

Table 16. Sucker Iteration 3 Test Results

Item/s	Item Lifted?	Final Position	Observations
6 x Styrofoam balls (5 – 8 mm)	Yes	4 in Prototype 2 inlet; 2 in tube to 2nd sucker device.	Balls in Prototype 2 inlet swirling in circular motion.
1 x Lady Beetle (Medium)	Yes	Inside Adapter.	
1 x Caterpillar (Medium - Dead)	Yes	Held in mouth of inlet tube.	As dead, no ability to resist suction.
1 x Foam Square	Yes	Stuck to inlet tube opening.	Too big to pass through tube opening.
1 x Adult Butterfly (Dead)	Yes	Stuck to inlet tube opening.	As dead, no ability to resist suction. Too big to pass through tube opening.
1 x Dried Pea	No	Still in tray	

Initial observations of Table 16 data suggested little, if any, improvement over iteration 2. This said, with results being against different test specimens, it was noted that direct comparison of the iterations was not possible. Therefore, analysis of the results indicated there being a need to test iteration 2 against the same test specimens as iteration 3, so as to allow confirmation of the hypothesis regarding the lack of improvement.

Application of the 2nd iteration nozzle to the same tray of items tested with iteration 3 gave results as per Table 17.

Table 17. Sucker Iteration 2 Comparative Test Results

Item/s	Item Lifted?	Final Position	Observations
6 x Styrofoam balls (5 – 8 mm)	Yes	In lower part of inlet bottle, before fan.	Balls swirling in circular motion around inlet bottle.
1 x Lady Beetle (Medium)	Yes	In lower part of inlet bottle, before fan.	Beetle swirling in circular motion around inlet bottle.
1 x Caterpillar (Medium - Dead)	Yes	In lower part of inlet bottle, just above entrance.	As dead, no ability to resist suction. Only just held in entrance of bottle.
1 x Foam Square	Yes	Stuck to inlet tube opening	Too big to pass through tube opening.
1 x Adult Butterfly (Dead)	Yes	Stuck to inlet tube opening	As dead, no ability to resist suction. Too big to pass through tube opening.
1 x Dried Pea	No	Still in tray	

Comparison of the results in Table 16 and Table 17 was supportive there being no improvement in the 3rd iteration of the Sucker device through the addition of the increased output area. Whilst still being able to pick up an adult butterfly, a medium sized caterpillar and a medium sized lady beetle, these results were virtually identical to those of the second iteration, when tested against the same specimens. It was also observed that none of the objects successfully suctioned up progressed far enough through the system to be able to pass through the fans. The increased resistance from the extra tubing and fittings appeared to reduce suction ability, with the sucked-up caterpillar and lady beetle travelling less distance through the system than what was observed during the iteration 2 testing.

During observation of the operation of prototype B, it was noted that fitting the nozzles to the suction devices while the fans were running resulted in a reduction in the fan speed. Connection of the adapter and single short piece of tube to the two devices was also noted to result in further speed reduction of the fans (evidenced by change in fan sound/pitch). From these observations, it was hypothesised that the fans, being designed for PCs and open-air environments, lacked sufficient power to overcome the system resistance; this resulting in loss of fan speed, and thus a corresponding reduction in the air velocity, thereby increasing the comparative air pressure at the input end of the device and reducing its suction ability.

Examination of results for the *Build Performance* of the two iterations showed that iteration 3 cost almost twice as much to build, slightly increased device complexity and also slightly increased time taken to build. Despite this, test results showed the new build failed to produce any improvement in performance, so was deemed as being not only unviable, but a poorer build than iteration 2, and thus indicative of a different approach being required. Noting the lack of power in the existing fans was likely contributing to the lack of suction ability in the Sucker device, led to consideration of several potential mechanisms of improving air speed, and thus pressure reduction, at the suction end of the device.

The first of these considerations was to purchase an 80 mm case fan with greater power, with the second being to purchase and utilise a larger single fan to enhance output area and thus volumetric flow rate. With project spend already exceeding the original project brief, however, these approaches were ruled out. While arrangement of the two existing fans in series was also briefly considered, theory indicated this would behave similar to pumps in series, which are known to only improve pump head (which in this situation was not the problem needing addressing). As such, the decision was made to instead use available equipment and materials to emulate improved power, through the addition energy to the front end of the system via use of compressed air.

Through release of compressed air through nozzles located in front of the case fan, it was believed that the kinetic energy in the air being pushed through the nozzle, when added behind the fan, should help counter the loss of energy (i.e. head loss) being experienced at the input end of the system, thus improving velocity of the air at the input end of the Sucker prototype. It was therefore proposed to incorporate the addition of 4 small streams of air, provided by an air compressor and delivered through an adapter and small PE tubes, within one of the two existing Sucker devices. Noting the arrangement of the fan in the Sucker device developed for the 3rd iteration offered easier incorporation of such tubes, it was recommended that testing of the addition of compressed air to the front end of the system be trialled in this device.

4.3.3.3 Sucker 4th Iteration

Incorporation of extra costs and time to make the described addition of air flow modifications (as per Chapter 3.6.3.3), to produce the 4th iteration of the prototype gave the results as shown in Table 18.

Table 18. Sucker 4th Iteration Build Performance Results

Preliminary Build - Initial	Cost	Perceived Complexity	Build Time (Hrs)
80 mm CPU Fan	$ 25.00	Medium	0
Air compressor and air blower (approx.)	$ 140.00	Medium	0
3D printed parts	$ 9.70	Medium	7
Switch and wiring	$ 8.99	Medium-Low	0
Screws	$ 0.60	Low	0
Polyethylene hose	$ 4.72	Low	0
Design & Redesign	$ -	Medium	5.5
Construction	$ -	Medium-Low	3
TOTAL	**$ 189.01**	**Medium**	**8.5**

Application of the suction end of the 4th iteration of the device to the plastic tray and contents during viability testing gave results as per Table 19.

Table 19. Sucker Iteration 4 Test Results

Item/s	Item Lifted?	Final Position	Observations
6 x Styrofoam balls (5 – 8 mm)	Yes	In sucker inlet side of bottle.	Slightly circular motion.
1 x Lady Beetle (Medium)	Yes	Inside inlet hose near entry to bottle.	
1 x Caterpillar (Medium - Dead)	Yes	Held in mouth of inlet tube.	As dead, no ability to resist suction. Not lifted unless air nozzle activated.
1 x Foam Square	Yes	Stuck to inlet tube opening.	Too big to pass through tube opening. Did not lift unless air nozzle activated
1 x Dried Pea	No	Still in tray.	

Initial observations of Table 19 data, and comparison with Table 17 data from the earlier iteration of the prototype, once again supported there being no improvement over iteration 2, even with the addition of compressed air. That said, it was noted that activation of the air blower and addition of the compressed air to the system inlet did improve the performance of this device, with larger objects being successfully lifted when the air stream was added. The lack of overall improvement in this iteration was clearly a result of the nature of the core Sucker itself, which proved to be a less effective version of the design. Examination of the fan and Sucker setup was suggestive of greater opportunity for air to be pulled in from the area near the fan output, with no cowl to control the air flow, thereby reducing the volume of air pulled through the inlet, and thus a reduction in air speed at this point. With cost, complexity and build time (see Table 18), ultimately being higher than that of iteration 2 (Table 13), it was evident that this design offered no advantages over the earlier design from either a performance or a build design perspective. However, it was observed that results were supportive of the original concepts behind the modifications, indicating that the hypothesis had support and that further work around this approach was still worth following up, though via application to the earlier Prototype C, iteration 2 build.

With observations also indicating that both the case fan used in Iteration 2, and the CPU fan used in Iteration 4 of the prototype were producing swirling air flows in the inlet area, it was hypothesized that at least some of the power from the fans was being lost through the development and maintenance of a vortex, increasing turbulence and potentially leading to increased system losses. Noting also that the Styrofoam balls rarely escaped this vortex (when the devices were held vertically), consideration was given as to how the nature of the air flow might be better arranged to reduce power loss and to ensure objects picked up were directed through the fan, rather than spun around the inlet. With baffles known to commonly be used to better direct air flow, it was hypothesised that the addition of baffles to the Prototype C Iteration 2 inlet tube area would result in more linear air flow through the system, and thereby improve likelihood of collected objects being pulled through the fan. In doing so, it is hypothesised these objects would be removed from the system and no longer be taking energy away from it (through maintenance of their movement), thus improving efficiency. It was therefore recommended that Sucker iteration 2 be redesigned to include such baffles, and its performance then retested to confirm if this hypothesis was supported.

4.3.3.4 Sucker 5th Iteration

Incorporation of the extra time to design and incorporate the described baffle modification (as per Chapter 3.6.3.4), to produce the 5th iteration of the prototype gave the results as shown in Table 20 below (which as per previous iterations, includes a summary of the cost, perceived complexity and build time for completion of this iteration of the Sucker based end-effector).

Table 20. Sucker 5th Iteration Build Performance Results

Preliminary Build - Initial	Cost	Perceived Complexity	Build Time (Hrs)
80 mm Case Fan	$ 19.95	Medium	0
3D printed parts	$ 9.40	Medium	9
Switch and wiring	$ 8.99	Medium-Low	0
Screws	$ 0.60	Low	0
Design & Redesign	$ -	Medium-Low	4.25
Construction	$ -	Low	4.0
TOTAL	**$ 38.94**	**Medium-Low**	**8.25**

Application of the suction end of the 5th iteration of the device to the plastic tray and contents during viability testing gave results as per Table 21.

Table 21. Sucker Iteration 5 Test Results

Item/s	Item Lifted?	Final Position	Observations
6 x Styrofoam balls (5 – 8 mm)	Yes	Completely pulled through fan and out outlet tube.	
1 x Lady Beetle (Medium)	Yes	Inside inlet tube just past nozzle.	
1 x Caterpillar (Medium - Dead)	Yes	Inside nozzle.	As dead, no ability to resist suction.
1 x Foam Square	Yes	Still in tray unless placed directly on nozzle.	Slight movement noted but not lifting. Nozzle supports it if held against it.
1 x Dried Pea	Yes	Lifted and held just at nozzle entry.	

Initial observations of Table 21 data, and comparison with Table 19 data from the earlier iteration of the prototype, supported there being significant improvement over the 4th iteration, with the addition of the baffles to the earlier prototype, resulting in performance better than that of the later prototype where compressed air had been added. This improved performance was consistent with the hypothesis relating to the loss of power due to the swirling air, supporting the addition of baffles for cases where computer case fans were used to generate the air stream. That said, it was noted that device still lacked sufficient power to draw even a dead caterpillar through the fan, so still not viable from an insect control perspective.

With prototype cost and build time still relatively low (especially in comparison to Prototype A as per Table 12 v's Table 20), and having noted an overall system performance enhancement from the addition of the air blower and compressed air stream as per Prototype C - Iteration 4, consideration was then given as to how such a modification could be introduced to Prototype C - Iteration 5, given the nature of its fan and associated arrangement. It was hypothesised that introducing the air flow prior to the inlet tube would be the simplest approach in achieving this and would thus require a larger inlet area to accommodate the addition of the extra air stream from an air blow gun via a thin metal tubular attachment (and associated air compressor). To minimise additional cost and build time, a decision was made to change back to the original nozzle (Nozzle 1), through which a 16 mm ID PE tube would be inserted, in order to introduce the additional air stream without fouling or further reducing the Sucker inlet entry (having noted it already being blocked during operation on several occasions). Based on prior experience in using a compressed air based vacuum system (see Figure 85), through which a rapidly moving stream of air was introduced to the middle of a pipe and pushed out through one end to create a suction effect at the other), it was furthermore hypothesised that insertion of the metal tube end of an air gun blower through the side of the PE tube, if aimed at the outlet end of the system, would significantly enhance the speed of the air pulling through inlet end of the system, and thus result in improved device performance.

Figure 85. Air Vacuum Gun

Whilst acknowledging the addition of an air compressor and associated blow gun would add significant overall cost to the end-effector, with both devices already available, and a need for better performance to make the device viable, it was recommended that these additions be made to the 5th iteration of

Prototype C to make a 6th iteration, and the performance of this iteration once again tested to confirm if the proposed hypotheses provided a valid mechanism in making the Sucker prototype viable.

4.3.3.5 Sucker 6th Iteration

Incorporation of the extra time to design and incorporate the addition of a rapidly moving air stream via an air blow gun (as per Chapter 3.6.3.5), along with estimated cost of the additional components (i.e. small 12V air compressor able to produce 5 - 8 bar of pressure and associated air blow gun with approximate pricing sourced online) to produce the 6th iteration of the prototype, gave the results as shown in Table 22.

Table 22. Sucker 6th Iteration Build Performance Results

Preliminary Build - Initial	Cost	Perceived Complexity	Build Time (Hrs)
80 mm Case Fan	$ 19.95	Medium	0
Air compressor and air blow gun (approx.)	$ 150.00	Medium	0
3D printed parts	$ 9.40	Medium	9
Switch and wiring	$ 8.99	Medium-Low	0
Screws	$ 0.60	Low	0
Design & Redesign	$ -	Medium-Low	4.75
Construction	$ -	Low	4.5
TOTAL	**$ 188.94**	**Medium-Low**	**9.25**

Application of the suction end of the 6th iteration of the device to the plastic tray and contents during viability testing gave results as per Table 23.

Table 23. Sucker Iteration 6 Test Results

Item/s	Item Lifted?	Final Position	Observations
6 x Styrofoam balls (5 – 8 mm)	YES	Completely pulled through fan and out outlet tube.	
1 x Lady Beetle (Medium)	YES	Completely pulled through fan and out outlet tube.	
1 x Caterpillar (Medium - Dead)	YES	Completely pulled through fan and out outlet tube.	As dead, no ability to resist suction. Disintegrated on way through device.
1 x Foam Square	YES	Completely pulled through fan and out outlet tube.	
1 x Dried Pea	YES	Completely pulled through fan and out outlet tube.	

Examination of Table 23 data provided a clear indication of the prototype finally being viable, with all test objects pulled through the fan and the dead caterpillar destroyed on its way through the fan. Based upon these observations, the hypotheses regarding both the changes to the inlet nozzle and the addition of the compressed air stream appeared correct and proved able to significantly improve device performance. It was thus decided that this iteration of the prototype met performance requirements, and no further modifications would be necessary. Whilst operational, examination of the size and nature of the final Sucker prototype were indicative of it requiring significant further work before it could be easily attached to a robot arm. It was therefore rated as having poor or Low integration ability in its current form.

It is noted that the incorporation of a more powerful fan within the system may have provided a viable and cheaper alternative to the use of an air compressor and air blow gun, though further considerations around design for such a fan would be necessary to prove this conjecture.

4.3.4 Summary and Analysis

From the data collected during Phases 1 and 3 of the project, the preliminary *Build Performance* for each of the prototypes, in terms of cost, complexity, build time and integration ability was observed to be as per Table 24. Note that, for purposes of comparison against having done nothing, results for this "Control" device, have been considered, and added to the data set, as evidenced in Table 24.

Table 24. Phase 1 Build Performance Summary

Prototype	Cost	Perceived Complexity	Build Time (Hrs)	Integration Ability
A: Gripper	$ 79.30	Medium-High	17	High
B: Zapper	$ 35.99	Medium	9.5	High
C: Sucker	$ 188.94	Medium-Low	9.25	Low
D: Control	$ 0.00	None	0	Non-existent

From these results, ignoring the control case, it is evident that Prototype B (the Zapper) was the cheapest to build with equal best integration ability. Prototype C (the Sucker) was the least complicated and takes the least time to build, though in its final iteration proved to be the most expensive of the prototypes (assuming air compressor and associated equipment required to produce the desired results) and ultimately required the most work before it could be integrated successfully with a robot arm. Prototype A (the Gripper) was seen to be the most complex of the prototypes, also taking the most time to build but has the equal best integration ability. Graphically, these relationships can be more clearly observed as seen in Figure 86, which shows Relative Cost, Relative Complexity, Relative Build Time, and Relative Integration Ability with respect to the control scenario for each of the examined prototypes

(Control being assigned 0% and other prototype scores shown as a percentage of the maximum values or possible scores, relative to this).

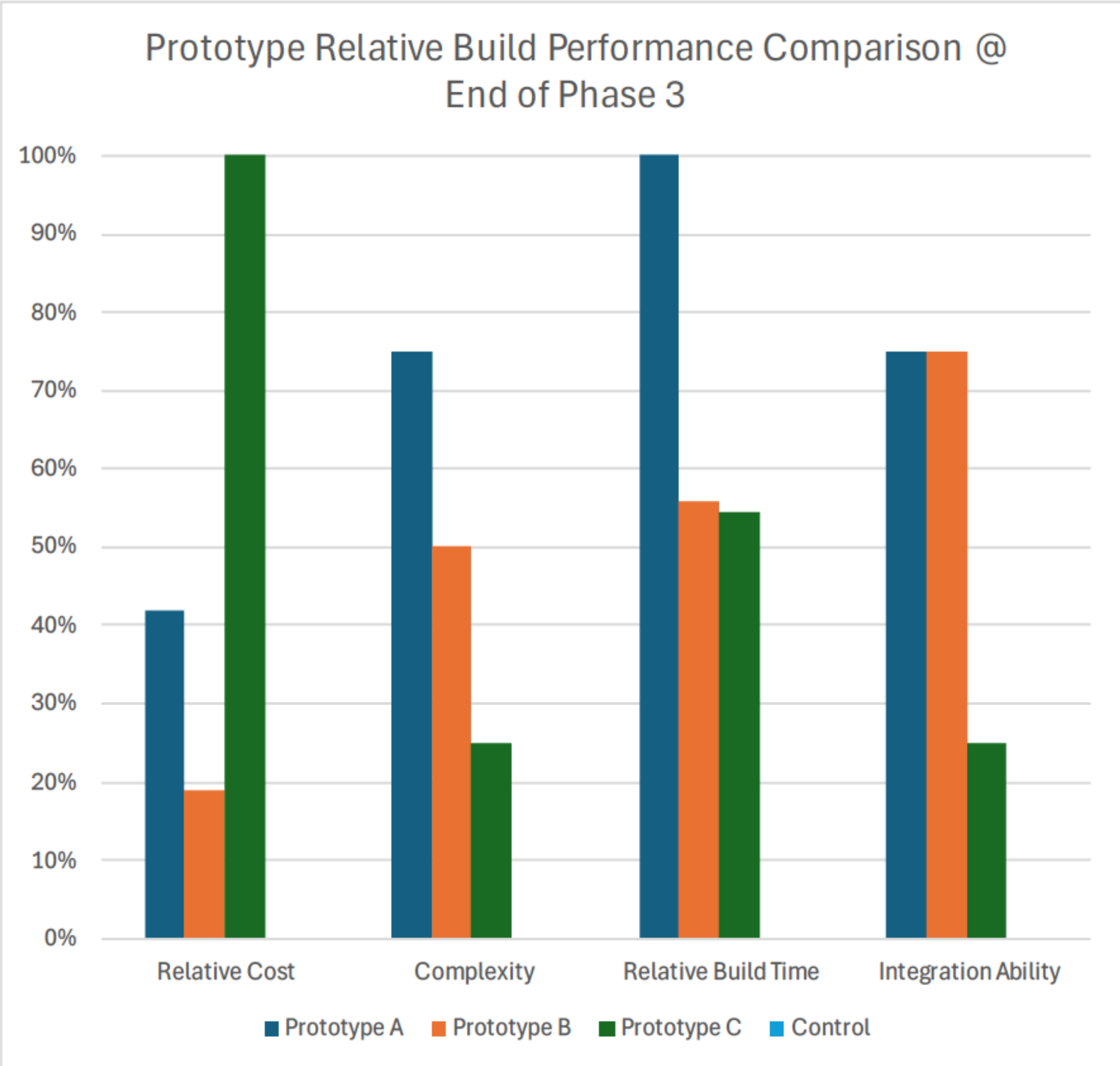


Figure 86. Relative Build Performance Comparison after Phase 3

With the best performance resulting from low scores in the first three parameters (Cost, Complexity and Build Time) and a high score for the final parameter (Integration Ability), visually, it is apparent that apart from doing nothing (which has zero integration ability), Prototype B appears to best device upon the completion of Phase 3, based purely on a build performance perspective.

4.4 Primary and Follow-up Testing: Phase 4

4.4.1 Host Damage

Application of the respective prototypes (treatments), to the host plants over the course of approximately 6 days (as described in Chapter 3.6.4.1), gave results as per the ensuing sections, at each of the noted time frames: $T_0 – T_4$.

4.1.1.1 Results Before (T_0) and Directly After (T_1) Treatment Application

Visual inspection of specimen 1 (control) prior to treatment application (T_0) and with no treatment application (T_1) was as per Figure 87 and Figure 88, respectively.

Minor damage was noted to already exist on the right-most leaf. No obvious cause of damage was observed. No changes nor signs of damage were noted between T_0 and T_1.

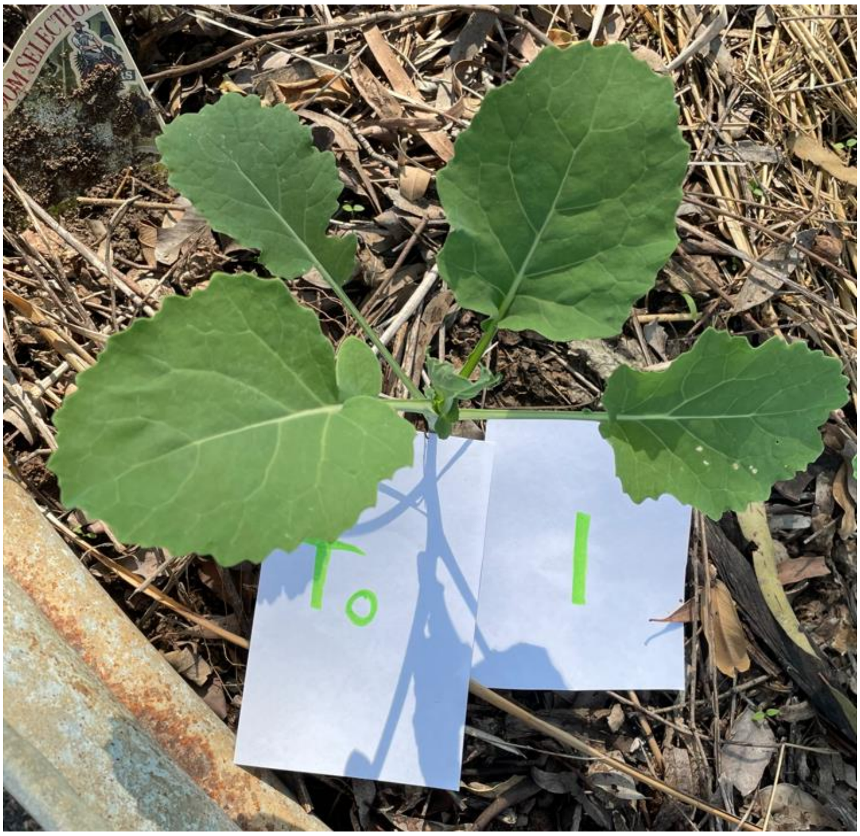


Figure 87. Plant 1 @ T_0 (Control)

Figure 88. Plant 1 @ T_1 (Control)

Visual inspection of specimen 2 prior to treatment application (T_0) and after treatment application (T_1) showed results as per Figure 89 and Figure 90, respectively.

Figure 89. Plant 2 @ T_0 (Single Application)

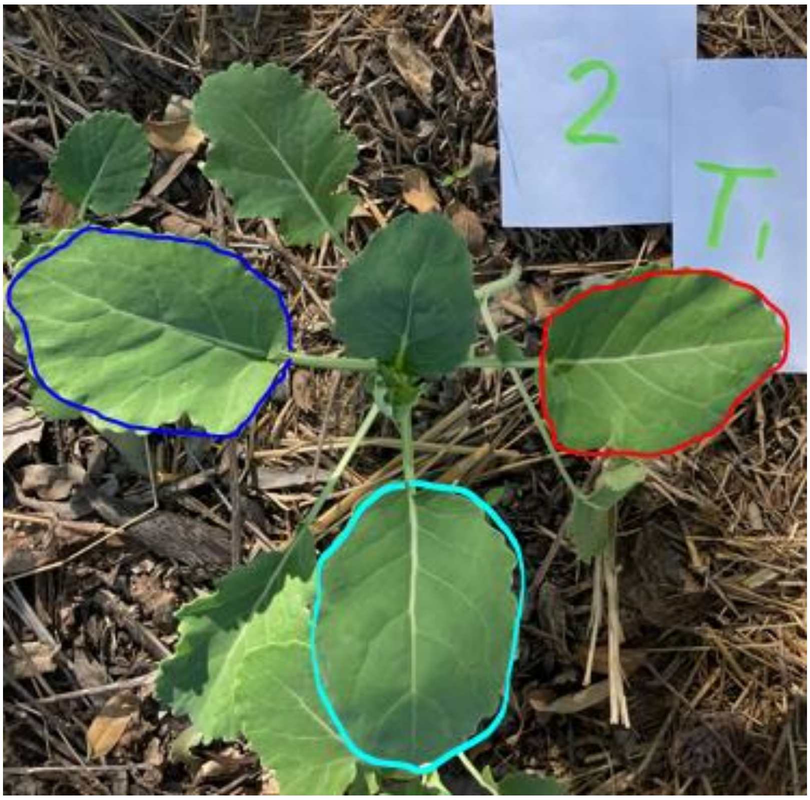


Figure 90. Plant 2 @ T_1 (Single Application)

Note Gripper application has been identified through dark blue outline, Zapper application identified through red outline and Sucker application identified through cyan outline.

Inspection of the leaves after all treatments revealed no changes nor signs of any obvious damage to the leaves directly after application. Closer inspection of the leaf where electrical discharge occurred showed no sign of damage from Prototype B as per Figure 91.

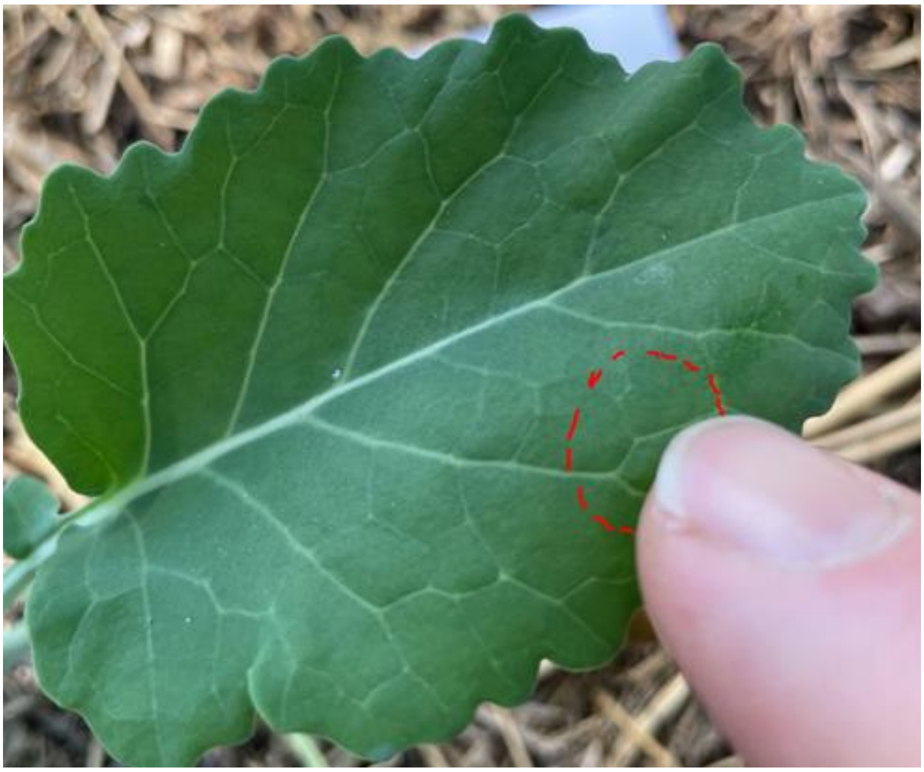


Figure 91. Plant 2 leaf damage from Prototype B @ T_1 (Single Application)

From the visual results, it can be assumed that a single treatment through the action of any of the three prototypes provides no clear indication of damage to the host plant. As such, recordings of damage to assess damage after application of the respective prototypes to the insect pests, in the case of removal from sprouting broccoli, are likely to serve little purpose, suggesting that potential damage should instead be based upon the number of times the respective prototypes may be applied directly to the host plant. It is thus suggested that continued observation of the respective plants occurs over time, and the number of times the prototypes are applied to a specific area be utilised as a means of assessing potential host plant damage.

Specimen 3 observation prior to treatment application (T_0) and after treatment application (T_1) was as per Figure 92 and Figure 93. As with Specimen 2, Gripper application has been identified through dark blue outline, Zapper application through red outline and Sucker application through cyan outline.

Figure 92. Plant 3 @ T_0 (Double Application)

Figure 93. Plant 3 @ T_1 (Double Application)

Similar results were observed after inspection of the leaves of Plant 3 after treatments, with no changes nor signs of damage on any of the leaves noted directly after application. Closer inspection of the leaf where electrical discharge occurred twice, once again showed no sign of damage from the interaction with the prototype, as per Figure 94.

Figure 94. Plant 3 leaf damage from Prototype B @ T_1 (Double Application)

From the visual results of this trial, it can also be assumed that a double treatment through the action of any of the three prototypes will provide no clear indication of damage to the host plant.

Specimen 4 observation prior to treatment application (T_0) and after treatment application (T_1) was as per Figure 95 and Figure 96, respectively. As with the previous specimens, Gripper (Prototype A) application has been identified through dark blue outline, Zapper (Prototype B) application through red outline and Sucker (Prototype B) application through cyan outline.

Figure 95. Plant 4 @ T_0 (4x Application)

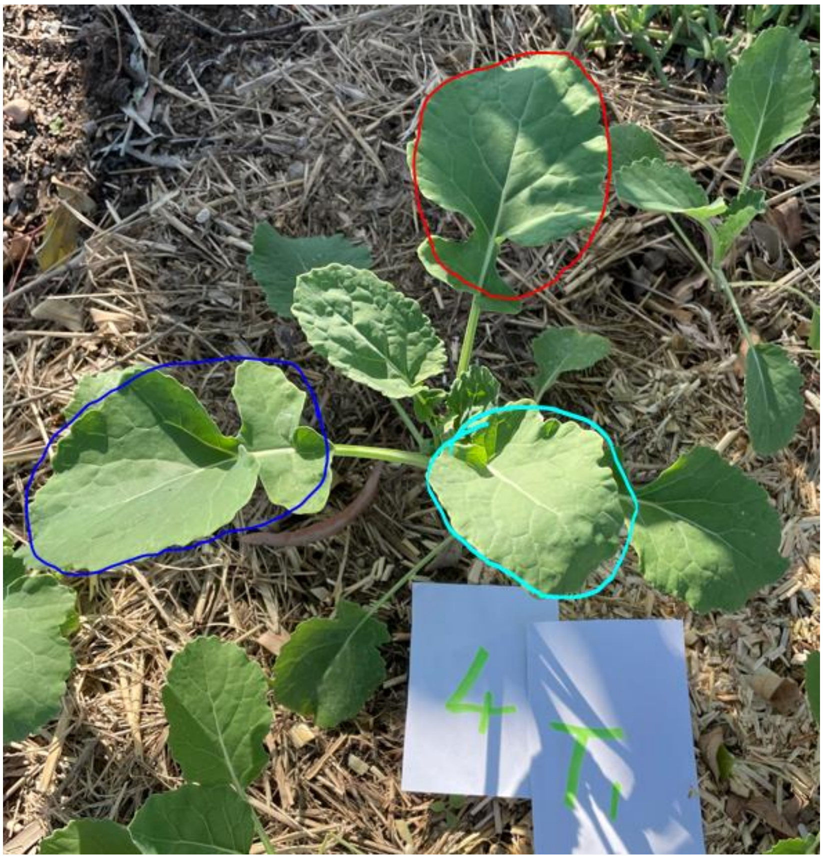


Figure 96. Plant 4 @ T_1 (4x Application)

Similar results as those noted against the other plant specimens were generally observed for the leaves of Plant 4 after treatments. Closer inspection of the leaf where electrical discharge occurred on four occasions, again showed no sign of damage from the interaction with the prototype, as per Figure 97.

Figure 97. Plant 4 leaf damage from Prototype B @ T_1 (4x Application)

A singular exception occurred where it was observed there to be potential bruising to the leaf that was exposed to four direct applications of the Sucker device in the same location. This repeated application also appeared to leave some signs of having slightly deformed the leaf, as noted in Figure 98.

Figure 98. Plant 4 leaf damage from Prototype C @ T_1 (4x Application)

4.1.1.2 Plant Damage Results 24 hours after Treatment (T_2)

Results of damage impacts on the treated plants approximately 24 hours after Treatment were as per Figure 99 to Figure 106.

Figure 99. Plant 1 @ T_2 (No Treatment)

From Figure 99, it is apparent that Plant 1, the control specimen showed no evidence of damage, consistent with it having no treatments applied.

With Plant 2 (Figure 100), it was observed there were no clear signs of damage to the leaves treated once with Prototypes A and C, however, the leaf treated with Prototype B, showed evidence of damage, as per Figure 101. The loss of colour in the area was suggestive of loss of chlorophyl in that area, potentially indicative of localised cell death. Evidence was thus supportive of a single discharge of the Zapper having the potential to cause tissue damage to the host plant, in the event of this prototype being directly discharged against the host plant tissue.

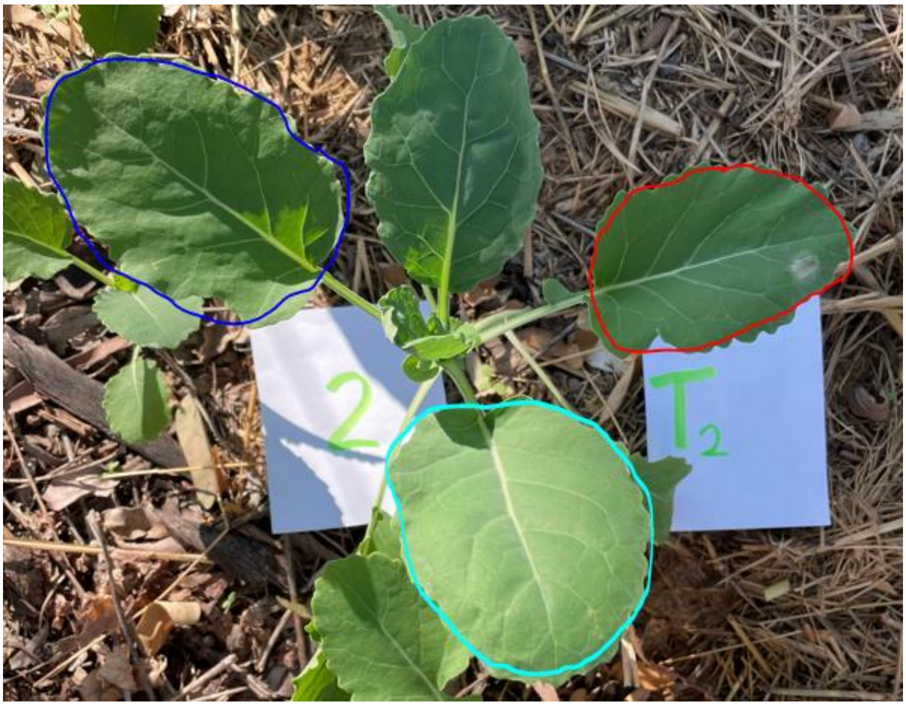


Figure 100. Plant 2 @ T_2 (Single Application)

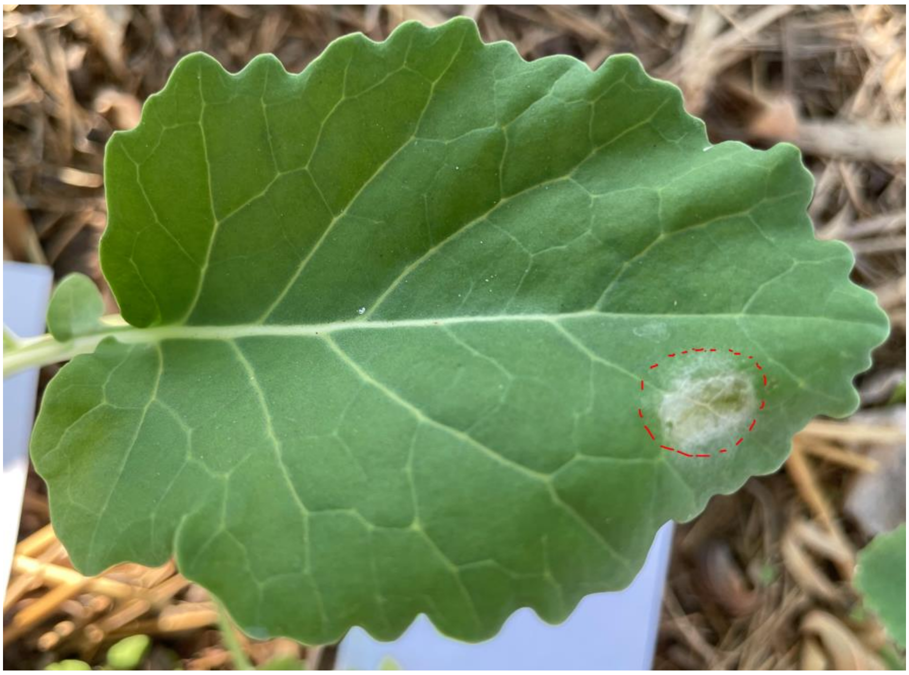


Figure 101. Plant 2 leaf damage from Prototype B @ T_2 (Single Application)

From Figure 102, it was observed that after 24 hours, there were still no clear signs of damage to the leaves treated by Prototypes A and C for Plant 3, despite being treated twice. The leaf treated with Prototype B, however, once again showed clear evidence of damage, as per Figure 103. Damage after two discharges was noted to appear of greater severity that that of the single application. It was also noted that with damage being applied near the leaf edge (a growing point), growth in the affected area appeared to have been negatively impacted.

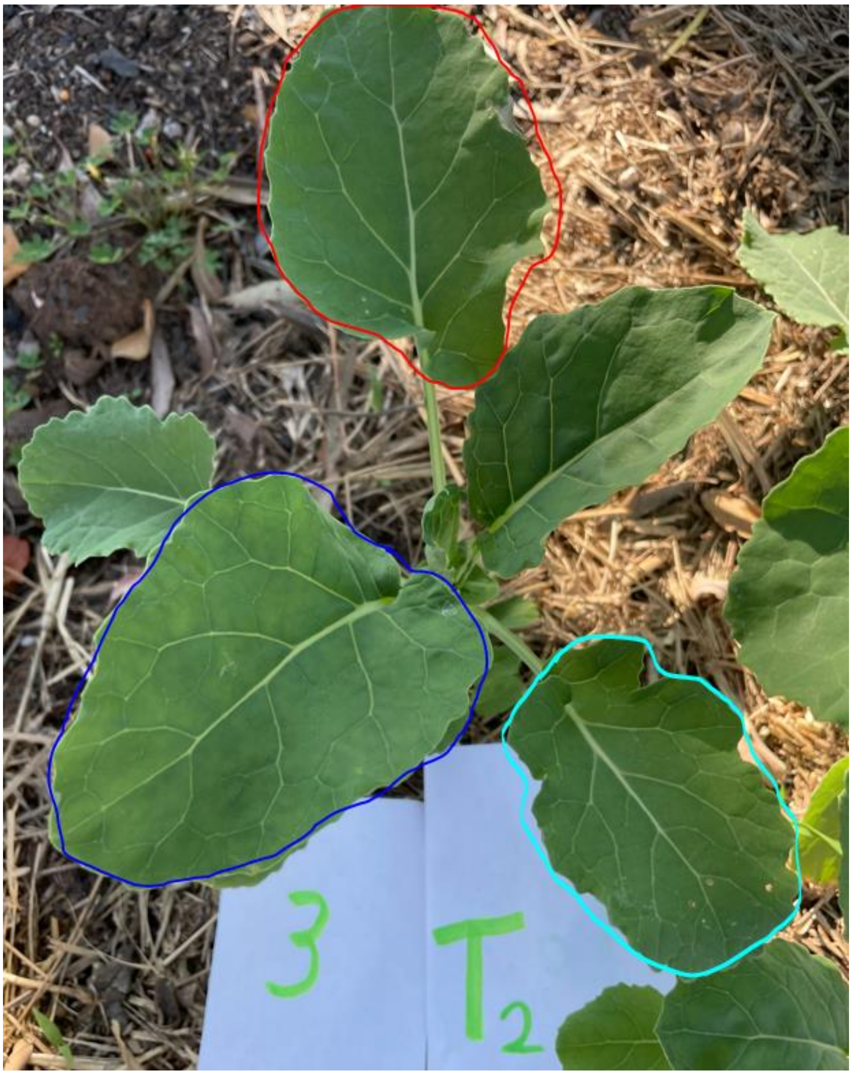


Figure 102. Plant 3 @ T_2 (Double Application)

Figure 103. Plant 3 leaf damage from Prototype B @ T_2 (Double Application)

Visual evidence at 24 hours, was thus supportive of a double discharge of the Zapper having the potential to cause significant tissue damage to the host plant, with the potential to negatively impact plant growth, in the event the Zapper was directly discharged against the plant tissue in the same location twice.

After 24 hours, Plant 4 also showed no clear signs of damage to the leaves treated on four occasions with Prototypes A and C (see Figure 104). As with previous trials, the leaf treated with Prototype B (Zapper) showed clear evidence of damage, as per Figure 105. Damage after four discharges appeared to be of similar severity to that that of the double application with the addition of a darkened edge profile consistent with tissue having been burnt. As with the double Zapper application, it was also noted that damage, being applied near the leaf edge, resulted in growth of the affected area being negatively impacted.

Closer inspection of the leaf to which Prototype C was applied on multiple occasions, while still showing faint marks around the edge of where the Sucker tube was applied (see Figure 106), no longer showed signs of deformation, indicative of recovery from the vacuum application having commenced.

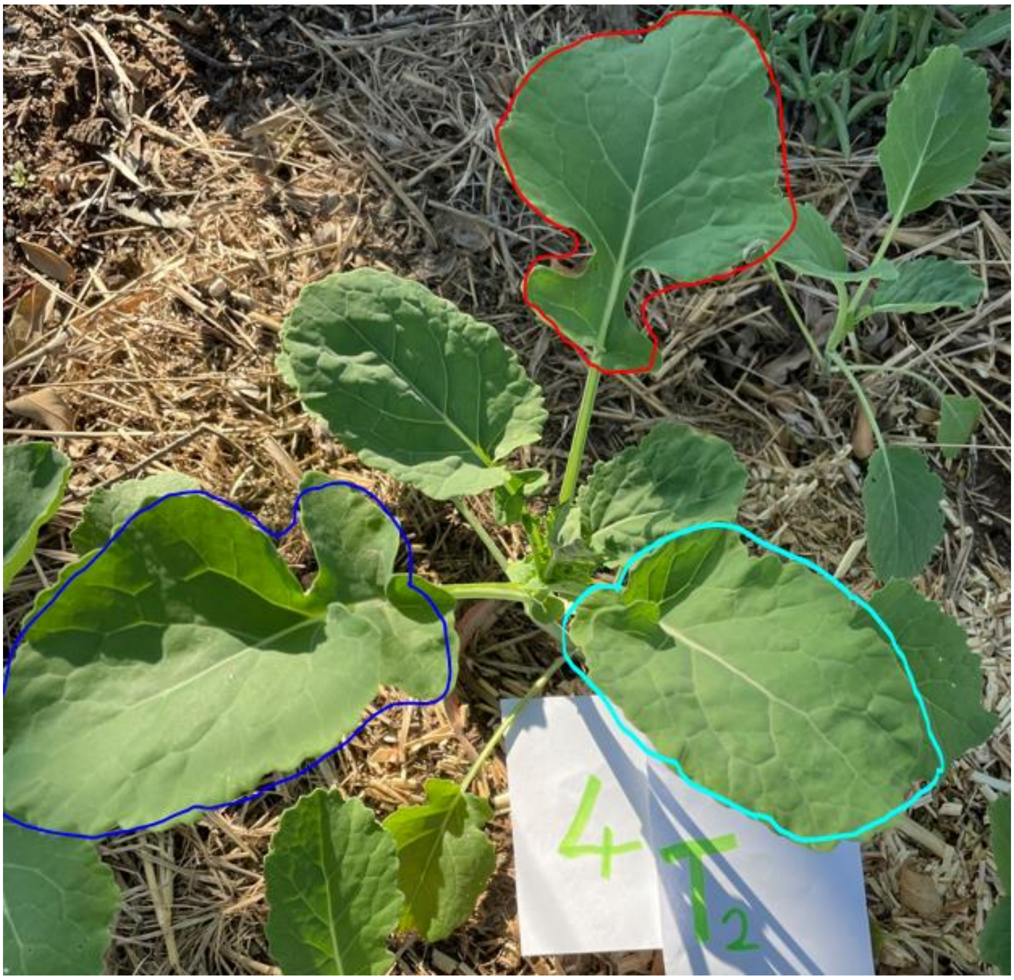


Figure 104. Plant 4 @ T_2 (4x Application)

Figure 105. Plant 4 leaf damage from Prototype B @ T_2 (4x Application)

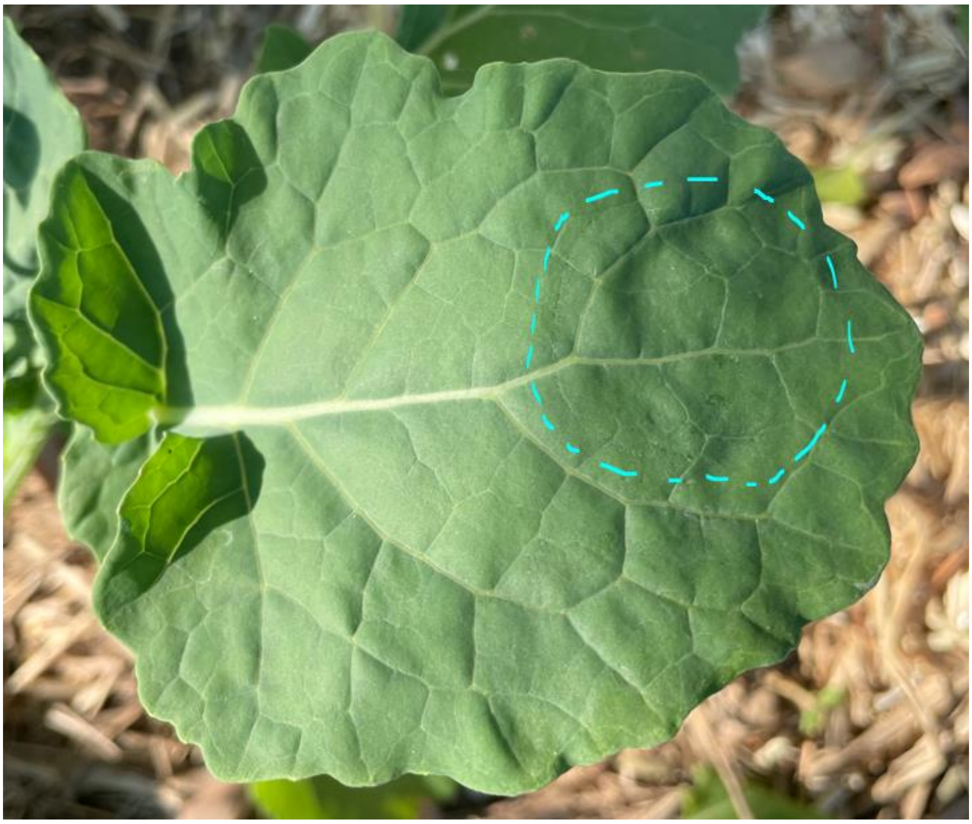


Figure 106. Plant 4 leaf damage from Prototype C @ T_2 (4x Application)

Evidence was thus supportive of multiple discharges of the Zapper having the potential to cause significant tissue damage to the host plant, when directly discharged against the plant tissue in the same location on multiple occasions. Evidence furthermore was indicative of the bruising caused by multiple applications of Prototype C (Sucker), having resulted in very little damage to the host plant. There was no evidence to suggest multiple applications of Prototype A (Gripper) having resulted in any significant damage at this point in time.

4.1.1.3 Plant Damage Results 3.5 days after Treatment (T_3)

Results of damage impacts on the treated plants approximately 3.5 days after treatment via application of the prototypes to the Sprouting Broccoli seedlings, were as per Figure 107 through to Figure 114.

Figure 107. Plant 1 @ T_3 (No Treatment)

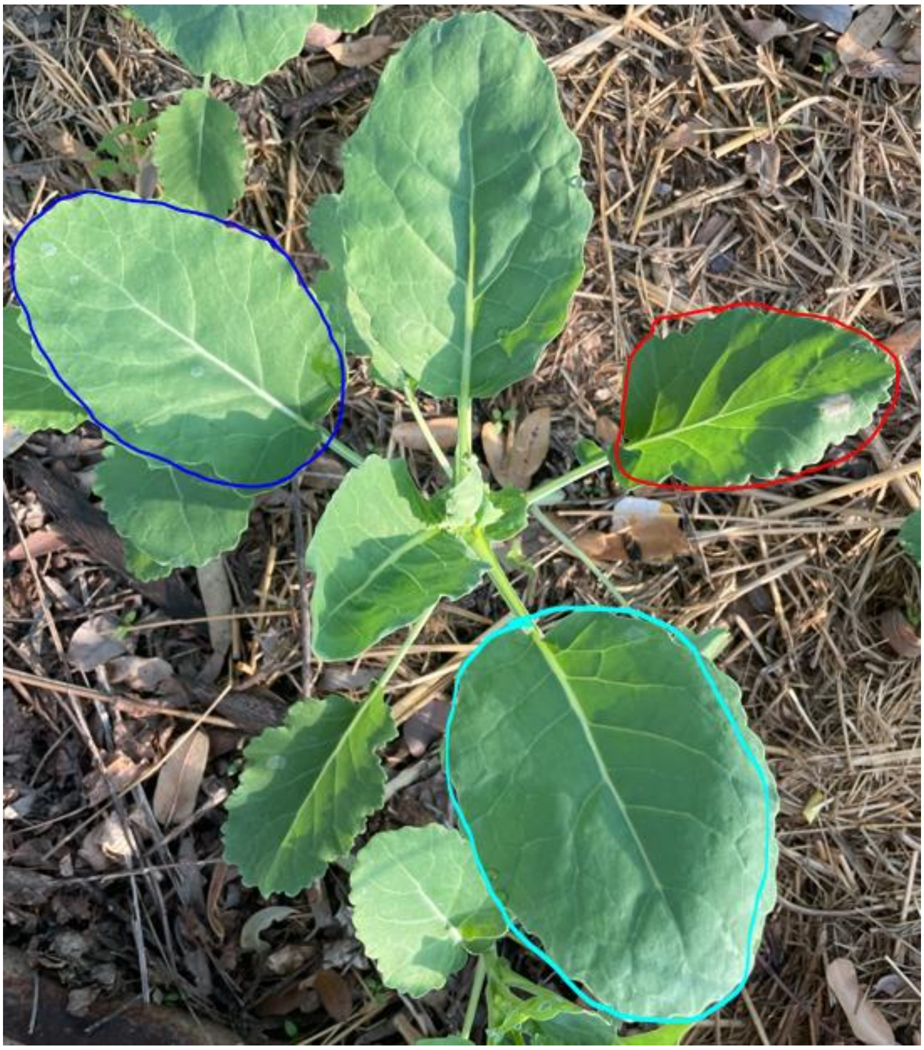


Figure 108. Plant 2 @ T_3 (Single Application)

Figure 109. Plant 2 leaf damage from Prototype B @ T_3 (Single Application)

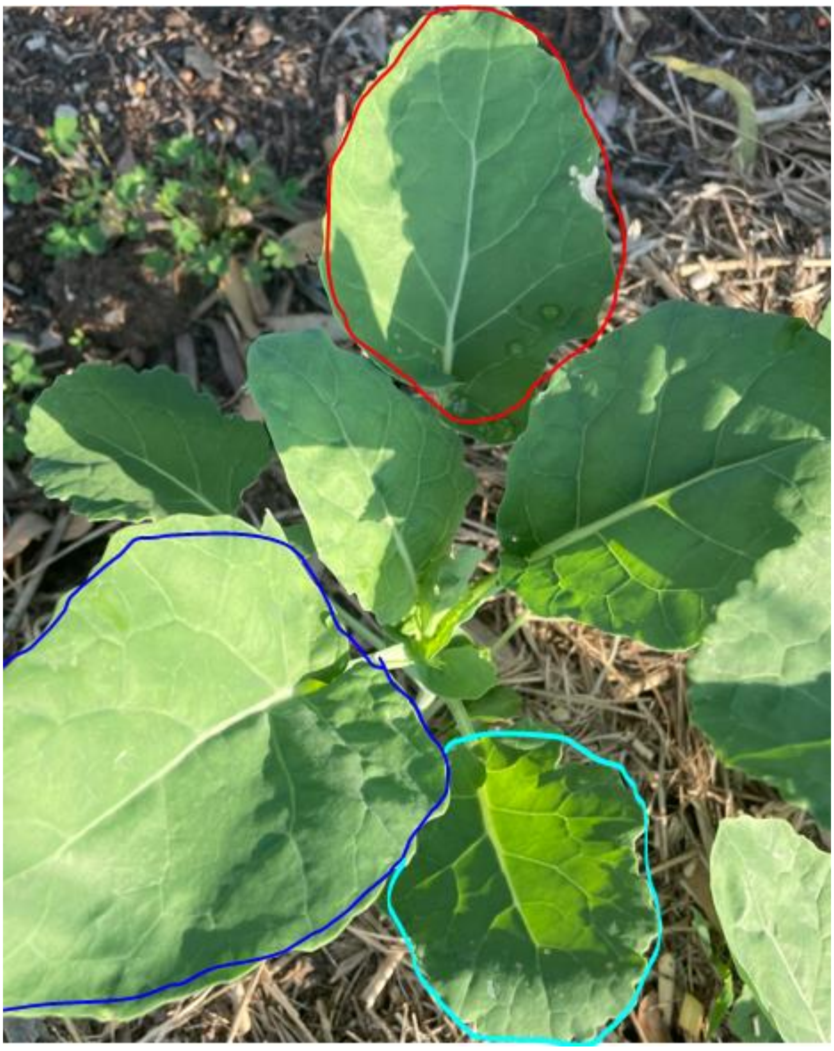


Figure 110. Plant 3 @ T_3 (Double Application)

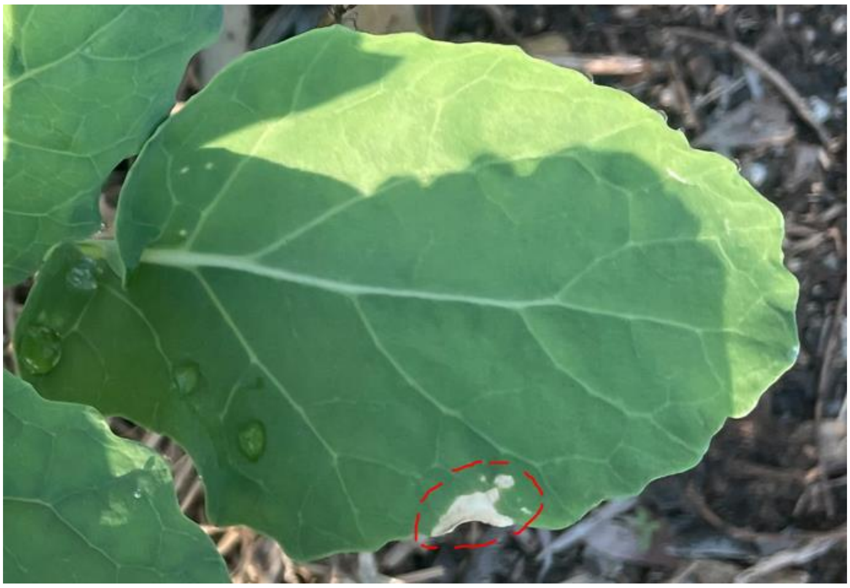


Figure 111. Plant 3 leaf damage from Prototype B @ T_3 (Double Application)

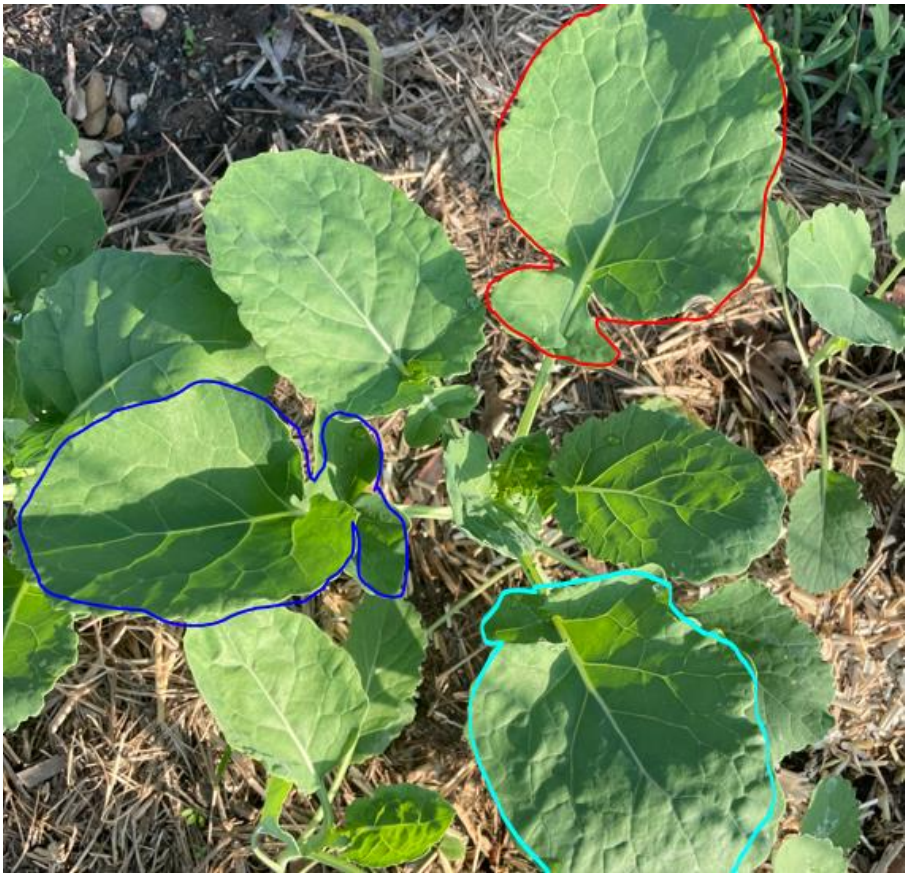


Figure 112. Plant 4 @ T_3 (4x Application)

Figure 113. Plant 4 leaf damage from Prototype B @ T_3 (4x Application)

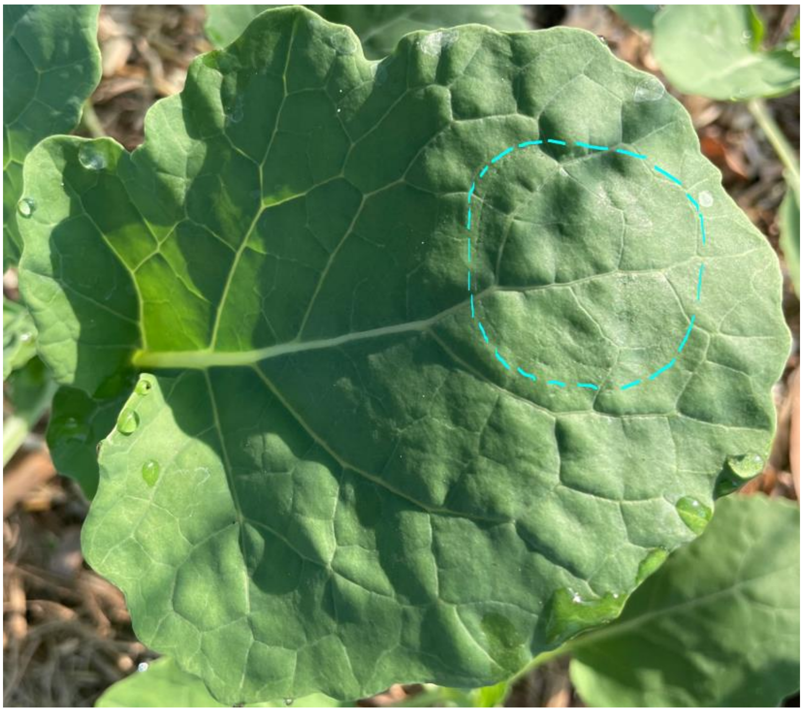


Figure 114. Plant 4 Damage from Prototype C @ T_3 (4x Application)

4.1.1.4 Plant Damage Results 5.5 days after Treatment (T_4)

Results of damage impacts on the treated plants approximately 5.5 days after treatment via application of the prototypes to the Sprouting Broccoli seedlings, were as per Figure 115 through to Figure 122.

Figure 115. Plant 1 @ T_4 (No Treatment)

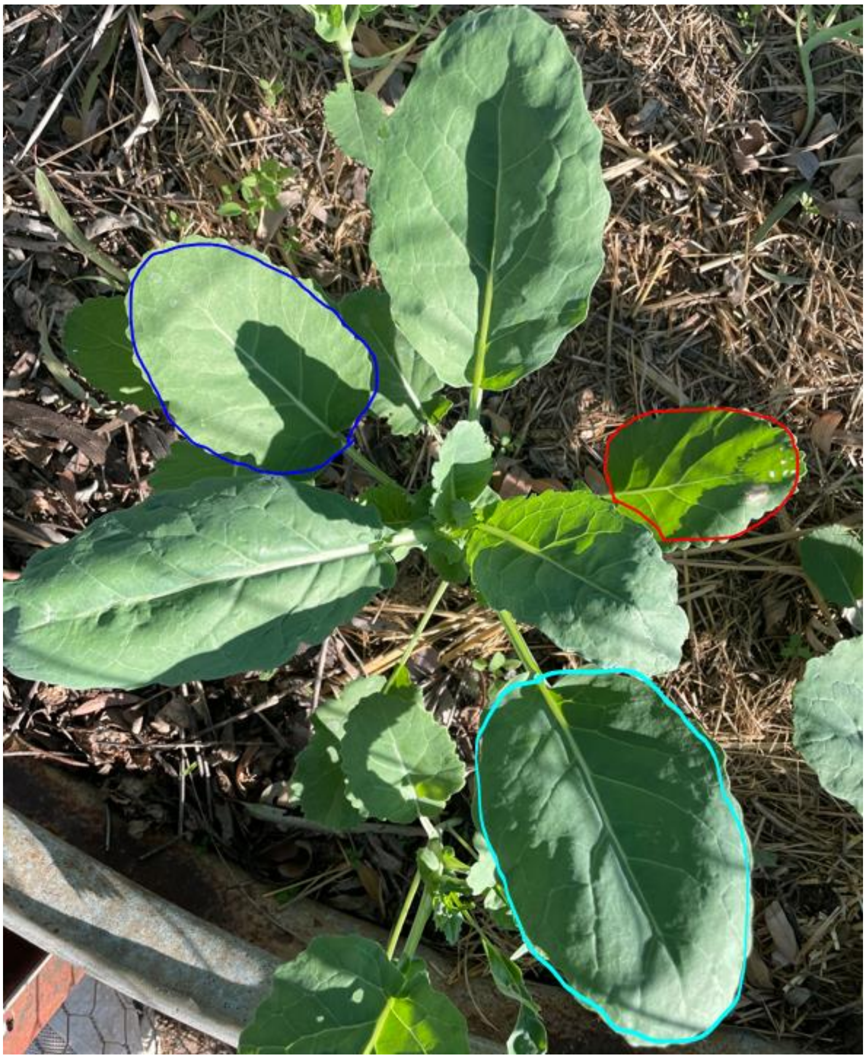


Figure 116. Plant 2 @ T_4 (Single Application)

Figure 117. Plant 2 leaf damage from Prototype B @ T_4 (Single Application)

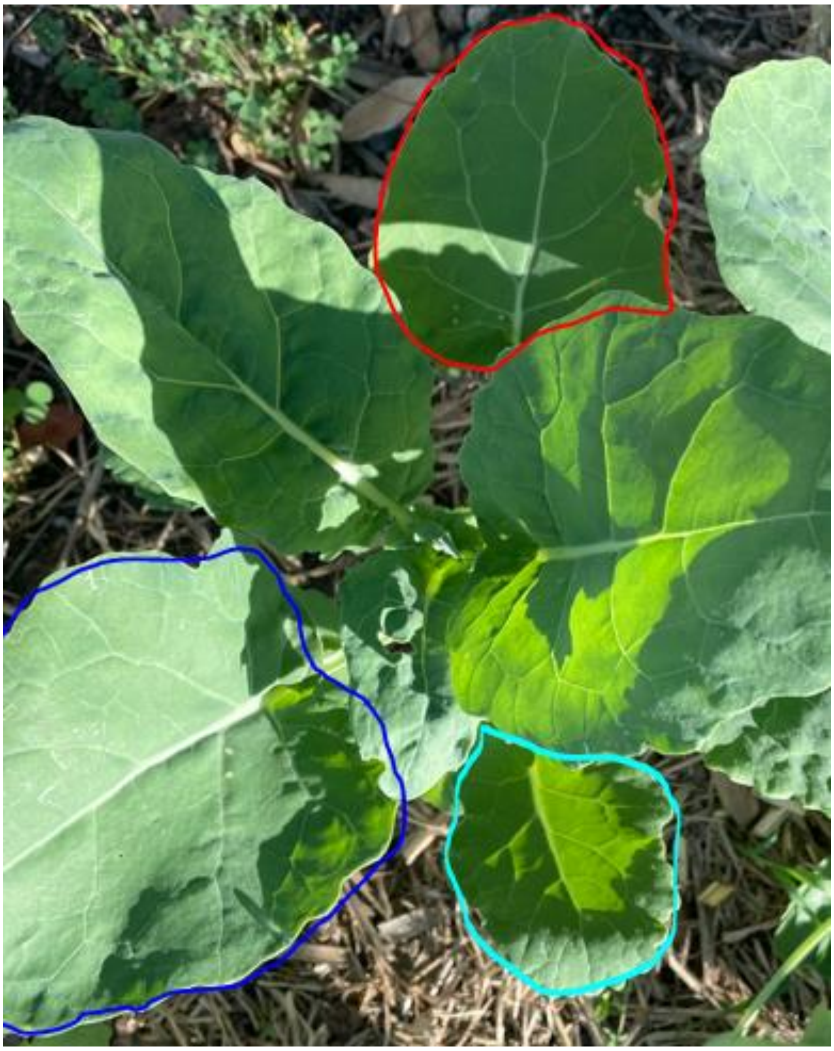


Figure 118. Plant 3 @ T_4 (Double Application)

Figure 119. Plant 3 leaf damage from Prototype B @ T_4 (Double Application)

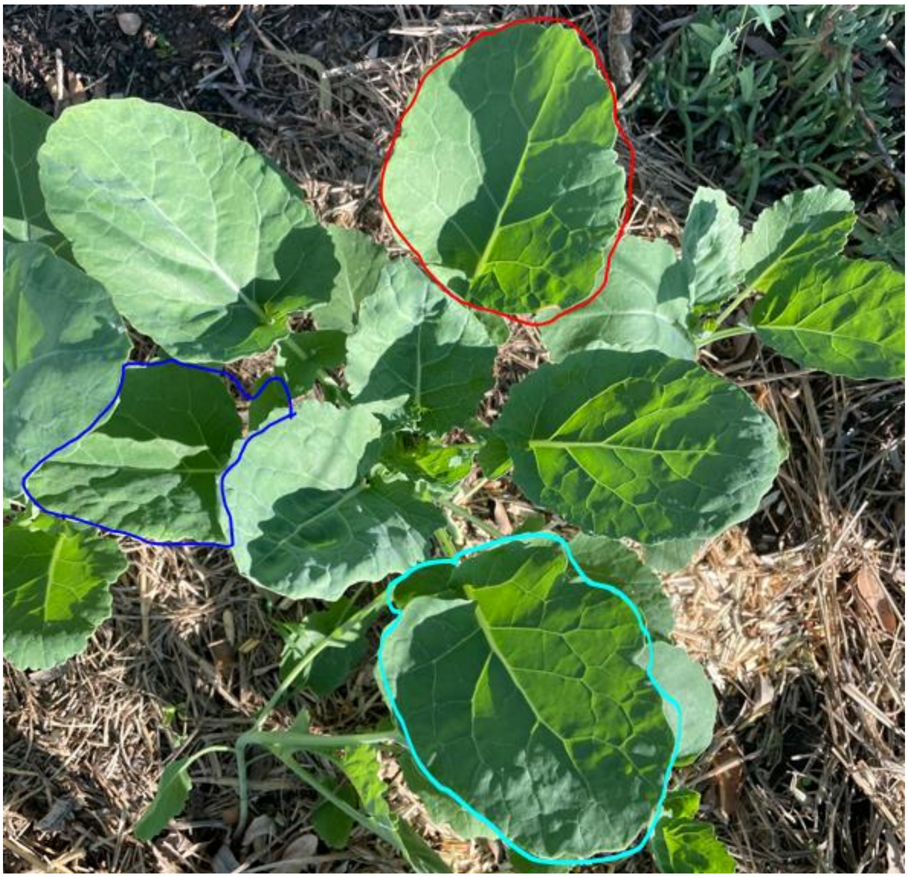


Figure 120. Plant 4 @ T_4 (4x Application)

Figure 121. Plant 4 leaf damage from Prototype B @ T_4 (4x Application)

Figure 122. Plant 4 leaf damage from Prototype C @ T_4 (4x Application)

After five and a half days, evidence was still consistent with that observed at T_2, confirming that multiple discharges of Prototype B (Zapper), had the potential to cause significant and permanent tissue damage to the host plant, when directly discharged against the plant tissue in the same location on multiple occasions. In contrast, the bruising caused by multiple applications of Prototype C (Sucker), while causing mild damage in the first instance, ultimately resulted in no sustained damage to the host plant. As previously observed, there was no evidence to suggest multiple applications of Prototype A (Gripper), as having resulted in any noticeable damage.

4.4.2 Gripper Primary Results

Averaged results achieved for pest removal testing of the Gripper, in terms of removal ability were noted to be extremely high, with the Gripper consistently proving highly effective at removing the test species. From these results, an average removal score of 2 was achieved of a possible 2 (for raw results, see Appendix F). With all Phase 4 testing being performed against larger less mobile specimens, the effectiveness results for the Gripper are acknowledged to be positively influenced by the nature of the specimen selection. That said, the Gripper was shown to be extremely effective at picking up both larval and pupal stages.

In terms of the averaged kill ability results for the Gripper, the score was 1.1 out of a possible 3. While proving quite effective against the Mealworm pupae, killing 5 of the 10 tested (see Figure 123), and incapacitating a further two, the larval stages seemed far more resilient to being grabbed, with only 2 larvae out of 20 dying/being permanently incapacitated within 24 hours. It is noted these results are much lower that what was observed when the device was tested against the Cabbage White Butterfly specimens, where mortality was close to 100% for both Pupae and Larvae. That said, the Gripper did negatively impact all the Mealworm larvae, with significantly reduced levels of activity being noted during the 24 hours after treatment. A further six specimens were also observed to no longer be showing any signs of activity unless directly stimulated 24 hours after treatment.

Figure 123. Crushed Mealworm Pupae

Further key observations during testing were as follows:

- In several cases the test specimens exploded upon being grasped, in these cases the gut contents were noted to remain on the Gripper jaws (see Figure 124).
- Where gut contents had not had sufficient time to dry, they glued following specimens temporarily to the jaws during removal, preventing them from being dropped off (see Figure 125), requiring user intervention to remove.
- On two occasions, when attempting to remove a specimen from a fold in the plant leaf, the Gripper was observed to grab the entire leaf (see Figure 126), requiring it to be released, thereby releasing the test specimen.
- Almost all larvae showed some level of side effect from being grabbed, with physical shortening of most specimens noted over 24 hours. As a result of size changes, it was not possible to specifically establish which specimens aligned to the original measurements.

Figure 124. Test Specimen Gut Contents on Gripper

Figure 125. Test Specimen Stuck to Gripper Jaws During Removal

Figure 126. Gripper Grabbing Entire Host Plant Leaf

With regards to effectiveness in killing the test specimens, it was observed that best success against the pupae occurred when grasping them by the upper head end. With the larvae forms, those most affected was one whose entire body ended up between the two jaws, thus flattening it, and another whose head end was grasped. The remaining specimens were for the most part grasped in the middle of the body, which appeared to have little impact upon their health. This was in significant contrast to earlier findings against the Cabbage White Butterfly specimens, where both the pupae and the larvae essentially exploded out through either or both ends when grasped in a similar manner.

The smallest specimen killed during Phase 4 testing was thought to be a 23 mm x 3.4 mm larval stage and the largest, a pupae, approximately 18 mm x 5.8 mm in size.

4.4.3 Zapper Primary Results

Averaged results achieved for pest removal testing of the Zapper, in terms of removal ability were noted to be quite low, with the Zapper having no ability in directly removing the test species, but rather having the potential to briefly cause them to stop holding on to the host plant (thus an assumption made they would drop off). From the results, an average removal score of 0.67 was achieved (for raw results, see appendix F). With one third of Phase 4 primary testing being performed against pupae, which would normally be attached directly to the host plant, and thus would not drop upon being stunned, the removal effectiveness results for the Zapper are acknowledged to be negatively influenced by the nature of the specimen selection.

In terms of the averaged kill ability results for the Zapper, the score was 0.93 out of a possible 3. While proving reasonably effective against the Mealworm pupae, killing 4 of the 10 tested, the larval stages seemed more resilient to electrical discharge, with only 3 larvae out of 20 dying within 24 hours. It is noted these results were significantly different to those observed when the device was tested against the Cabbage White Butterfly specimens during Phase 2, where mortality was closer to 30% for larvae and 0% for pupae (though acknowledging a very small sample size having been used during this testing). That said, the Zapper did negatively impact all the Mealworm larvae, with significantly reduced levels of activity being noted during the 24 hours after treatment. Similar to what was noted after Gripper application, a further six specimens were observed to no longer be showing any signs of activity unless directly stimulated 24 hours after treatment.

Further key observations during testing were as follows:

- In two cases the test specimens exploded upon being electrocuted. Both specimens had the terminals oriented lengthways beneath their thorax with the Zapper appearing to short across the specimen without obvious discharge, followed by body fluids exploding out from between the legs (see Figure 127).

Figure 127. Exploded Mealworm Pupae

- On one occasion, when attempting to remove a larval specimen from near a fold in the plant leaf, the Zapper was observed to short out (though not discharge), requiring removal from the area to allow recharge, and then applied once again. This happened multiple times until the terminals were oriented to avoid proximity to the leaf during attempts to apply to the test specimens.
- On two occasions, pupae were observed to be pushed away by the charge being developed on the end of the Zapper device as it was brought near them (noting this movement was possible due to the pupae being unattached to the host plant). On both occasions no discharge occurred, and the Zapper had to be moved away, recharged and the attempt remade.
- Almost all larvae showed some level of side effect from the electrical discharge, with darkening and shortening of most specimens noted over 24 hours (Figure 128). As a result of size changes, it was not possible to specifically establish which specimens aligned to the original measurements.

Figure 128. Electrocuted Mealworm Larvae

With regards to effectiveness in killing the test specimens, it was observed that best success against larvae forms occurred when the terminals were discharged across the pupae lower thorax area. No clear pattern was observed with respect to treatment of the larval forms. The remaining specimens for the most part had the terminals placed somewhere near the middle of their ventral body surface prior to discharge. For the most part, while causing clear discomfort, this appeared to have little impact upon the immediate health of the test specimens. It is unclear what the difference was with the specimen that died shortly after electrocution. While observations around larvae were not too dissimilar to earlier Phase 2 findings against the Cabbage White Butterfly specimens, explosion of pupal forms was not previously observed, with discharge against pupal stages of these specimens proving to have no impact upon their survival.

The smallest specimen killed during Phase 4 testing was thought to be a larval Mealworm approximately 24 mm x 3.6 mm and the largest, a pupae, approximately 20 mm x 6 mm in size.

4.4.4 Sucker Primary Results

Averaged results achieved for pest removal testing of the final Sucker protype iteration, in terms of removal ability were noted to be exceptional, with the Sucker proving 100% effective at removing the test species during Phase 4. From these results, an average removal score of 2 out of a maximum of 2 was therefore achieved (for raw results, see appendix F), thus a perfect score. With all Phase 4 testing being performed against larger, less mobile specimens, the effectiveness results for the Sucker are acknowledged to be heavily and positively influenced by the nature of the specimen selection. Apart from the size and mobility observations, of further significance was the inability of the Mealworm test specimens to effectively grip the host plant, in stark contrast to the original Cabbage White Butterfly specimens. Ultimately, it is believed this has resulted in significant positive bias for this measure, warranting further investigation.

In terms of the averaged kill ability results for the final Sucker iteration, the score was 3 out of a possible 3, again a perfect score. With pupae not being attached, the device proved equally effective against the Mealworm pupae and larvae (Figure 129), killing 100% of both almost immediately. It is noted these results are much higher that what was observed when the device was originally tested against the Cabbage White Butterfly specimens, with the earlier iteration of the device, where survival was 100% for both Pupae and Larvae. With the change in species, however, it was not possible to definitively establish the current iteration of the device would have achieved 100% mortality. That said, the final iteration of the Sucker with its much-improved ability, combined with observations around its ability to capture both larvae and adult Cabbage White Butterflies, is expected to have had similar success against these specimens. Without further testing, it is not possible to comment around likely effectiveness against pupal forms, however this discrepancy also warrants further investigation to help validate the observed results. As with removal success, kill success appears to have been significantly and positively biased as a result of the change in the test species used.

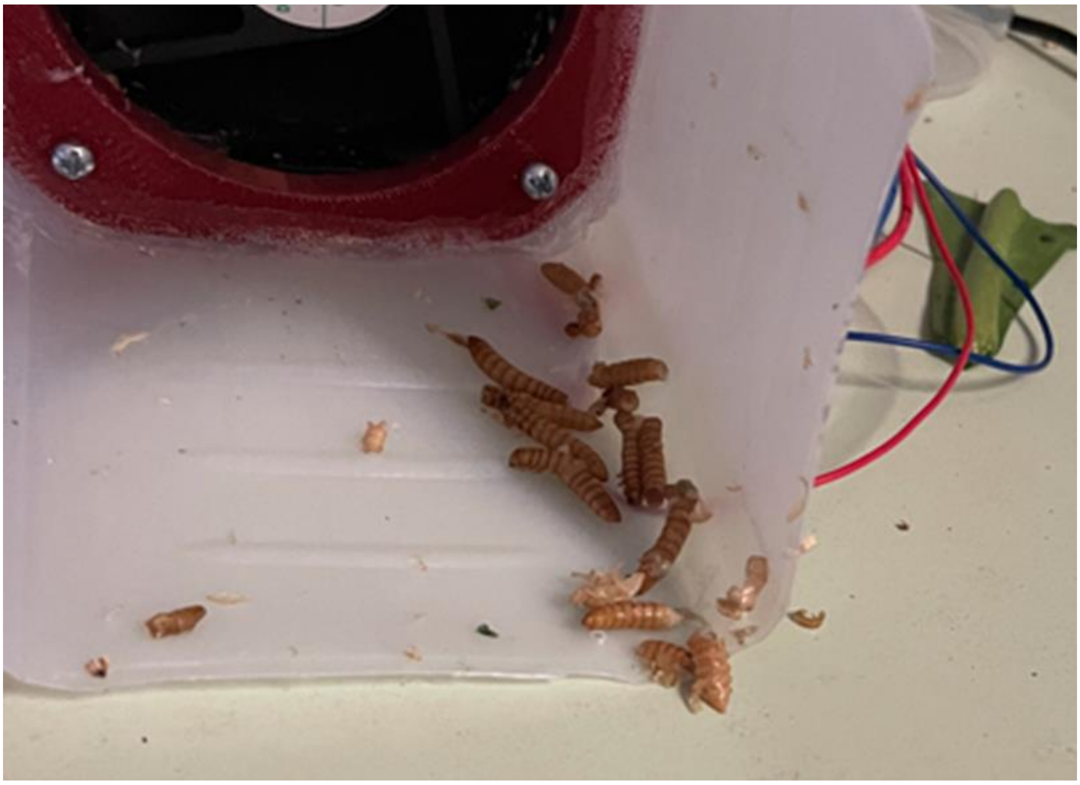


Figure 129. Smashed Mealworm Larvae and Pupae

Further key observations during testing were as follows:

- In two cases the larval test specimens did not pass through the fan, however when removed from the inlet area, the bodies were noted to be broken and leaking body fluids, with both specimens appearing dead. Examination of the inlet tube (see Figure 130), in a corner region, revealed similar residues of fluid, leading to the conjecture that the test specimen bodies had been smashed against the tube wall, this resulting in trauma and death. The volume of residue present was furthermore indicative of this having occurred to more than just these two specimens.
- As a result of passing through the fan blade along with exposure to high air flow, specimen bodies were mutilated or had shrunk (as observed in Figure 129), such that it was not possible to specifically establish which specimens aligned to the original measurements taken.
- Gut contents and body fluids from destroyed specimens were noted throughout the inlet area as well as upon the fan of the device. Though no impact on fan function was observed during testing, consideration of build-up and consequences of this, is likely warranted.

Figure 130. Residue Inside Inlet Tube Corner

With regards to effectiveness in killing the test specimens, there was no clear best application approach noted. With both larval and pupal forms unable to hold the host plant, all were quickly drawn into the device and smashed against its walls or against the fan blades. Those that did not pass through appeared to have been captured by the gut contents present on the baffle in the inlet tube, which had a glue-like consistency.

The smallest specimen killed during Phase 4 primary testing of the Sucker prototype was a 21 mm x 3.0 mm larval stage and the largest, a pupae approximately 18 mm x 5.6 mm in size.

4.4.5 Control Primary Results

While no physical measurements were made on these specimens, the following was noted:

- One of the larvae was no longer responsive 24 hours after transfer. It was assumed dead. Cause of death was unclear, though this larva appeared to be in the process of moulting.
- General activity of the remaining larvae was slightly depressed 24 hours after transfer to the rolled-oat medium. Activity was, however, notably higher than that observed in the Gripper and the Zapper test specimens. Only one of the larvae appeared to be adversely affected in terms of its activity after transfer.
- Visually, there was no noted change in the appearance or the size of the transferred specimens, nor any obvious deterioration in their state, apart from their slightly depressed activity.
- Mean Removal Ability was 0.
- Mean Kill Ability was 0.08, with a standard deviation of 0.37. From this it is apparent that the single death of unknown cause, had a significant impact upon data variability, as well as indicating that a difference in kill ability of 0.08 or less between the tested prototypes, is likely not significant, potentially attributable to natural attrition.

4.4.6 Summary and Analysis of Primary Results

From the Phase 4 primary testing, initial examination of the removal results is supportive of the Gripper and the Sucker prototypes being equally effective in removing both larval and pupal test specimens from the host plant, averaging 2 out of 2 in their removal ability scores. In consideration of how these results would likely have looked in a more accurate field-based testing situation, it is noted that pupae would generally be firmly attached to the host plant. It is expected that in such a situation, the greater force able to be applied by the Gripper device (via the embedded servo), would prove superior to that generated by the Sucker and would therefore be expected to continue to produce favourable removal results. The Sucker in comparison, might be expected struggle to generate sufficient force to break the connection between the pupae and the leaf, which would negatively impact its removal ability score, though this remains to be confirmed. While greater suction pressure might be applied, there would likely be a corresponding increased potential for host damage. In contrast to the other devices, as expected due to its nature, the Zapper prototype continued to show poor removal ability. While a score was achieved, this was based on points being allocated based on the assumption that shocked larvae would likely fall off the host plant after treatment, giving an averaged removal score of 0.67 (noting pupae would not be affected this way). The difference in the success with the different lifecycle stages is reflected by the Standard Deviation, observed to be 0.48. With all larvae and pupae of similar size during Phase 4 primary testing, there was no significant difference observed between the sizes of the pests able to be removed by the respective prototypes. Average Removal Ability scores (Mean and Standard Deviation), based on the removal of 20 Mealworm larvae and 10 unattached Mealworm pupae, are as per Table 25.

Table 25. Phase 4 Removal Ability Summary

Prototype	A - Gripper	B - Zapper	C - Sucker	Control
Removal Ability Mean	2.00	0.67	2.00	0.00
Removal Ability Std.Dev.	0.00	0.48	0.00	0.00

Examination of the Kill Ability scores clearly established the Sucker prototype as being the most successful of the devices, with an average score of 3. Testing was noted as having killed all larval and pupal forms treated by this prototype, with only very small numbers having survived initial exposure but succumbing to death shortly afterwards. Evidence was indicative of death likely occurring in both forms via being smashed against the inside of the tube, or through being struck by the fan blades during passage through the device. It is expected that this is similar to the process occurring within the Micothon greenhouse devices (as per Chapter 2.2.2.2), with the insects there also being thrown with significant force against the side walls during travel or striking the fan blade prior to exit. In comparison, Kill Ability score achieved against the test specimens for the Gripper and the Zapper was observed to be 1.1 and 0.93 respectively, a difference of 0.17. While this is suggestive of a degree of evidence supporting the Gripper as having proved more effective at killing the test specimens within a 24-hour time frame, with the control Kill Ability score being 0.08, the evidence is indicative of the difference being of only minor significance. Both devices were noted to be more effective at killing the pupal forms of the test specimens, with the Gripper resulting in 70% mortality and the Zapper achieving 40% mortality. This difference accounts for the observed Standard Deviations (SD) for both devices, these being 0.98 and 0.85 respectively, the slightly higher SD of the Gripper, resulting from its higher success with the pupal life stage. From this it is apparent that the lifecycle stage targeted has a significant impact upon end-effector kill ability. As with removal ability, given all larvae and pupae were of similar size during Phase 4 testing, there was no significant difference observed between the sizes of the pests able to be killed by the respective prototypes. Average Kill Ability scores, in terms of Mean and Standard Deviation, based on the removal of 20 Mealworm larvae and 10 unattached Mealworm pupae, were as per Table 26.

Table 26. Phase 4 Kill Ability Summary

Prototype	A - Gripper	B - Zapper	C - Sucker	Control
Kill Ability Mean	1.10	0.93	3.00	0.08
Kill Ability Std.Dev.	0.98	0.85	0.00	0.37

With regards to host plant damage, Prototype A, the Gripper, can be considered as having generated no observable damage, though from observations during prototype testing on the pest specimens, it was noted to have the potential to grab the host plant leaf during pest removal, meaning there exists the possibility of host plant damage during operation of the current Gripper prototype iteration. From this, a Host Damage score of 2 was assigned (as per descriptions in Chapter 3.1 - Limited damage noted within 24 hours of application and/or low likelihood of greater levels of damage occurring during pest removal). Prototype B, the Zapper, in comparison caused clear and persistent damage to the host plant, the nature of which was noted to increase with increased application. While most applications resulted in discharge to the test subject, several accidental discharges to the host plant leaf were noted. This would have the potential to increase in the event such a prototype was being manipulated around a plant. From these observations, a score of 1 was assigned for Host Damage (as per description in Chapter 3.1 - Moderate damage noted within 24 hours of application and/or moderate likelihood of equivalent levels of damage occurring during pest removal). With minor damage only observed after multiple applications of the Sucker prototype, it was ultimately established that this damage was negligible after the plant had been left for around 5 days. From this, it can safely be assumed that multiple applications of Prototype C have no long-term effects upon Broccoli plant leaves. While it was observed that the initial damage from the Sucker device effectively had no impact upon the test plant leaf, even after multiple applications, it was still recommended that the end of the tube on the final Prototype C iteration be slightly modified through addition of air gaps at the end of the tube, to prevent the leaf sealing off the tube end, thereby reducing the likelihood of damage occurring. Without this adjustment, the observed results during testing are indicative of the Sucker prototype (with its current level of suction when applied to broccoli leaves), should be allocated a Host Damage score of 2.5 (as per descriptions in Chapter 3.1 - Limited to no damage noted within 24 hours of application with little to no damage still observable after 5 days and/or very low likelihood of greater levels of damage occurring during pest removal). With the included change, however, it is proposed that the Host Damage score be re-evaluated to 3, based upon the significantly decreased likelihood of any damage occurring with the proposed modification in place (in combination with pest removal testing having shown there to be no need for more than a single application to remove the examined test specimens). In summary, Host Damage scores, based upon treatment of Broccoli host plants by the respective end-effector prototypes were as per Table 26 (noting a higher score is reflective of lower damage).

Table 27. Phase 4 Host Damage Summary

Prototype	A - Gripper	B - Zapper	C - Sucker	Control
Host Damage	2.00	1.00	3.00	3.00

Graphically, these relationships can be more clearly observed as per Figure 131, which shows Removal Ability, Kill Ability and Host Damage, relative to the best-case scenario for each of the examined prototypes. From this figure, it is apparent that from a *Removal Performance* perspective, Prototype C, the Sucker is the strongest performing end-effector, achieving maximum scores across all three parameters, with negative impacts equivalent to the control i.e. as in having not been treated at all. Prototype A, the Gripper, appears to be the next best performing end-effector, with a maximum score achieved in removal ability, along with a solid performance with respect to minimising likely host damage. Prototype B, the Zapper, is noted to have scored most poorly in comparison to the other prototypes. That said, it clearly outperforms the Control with respect to both removal ability and kill ability, thereby establishing at least some degree of effectiveness as an insect control approach, against the tested species and lifecycle stages.

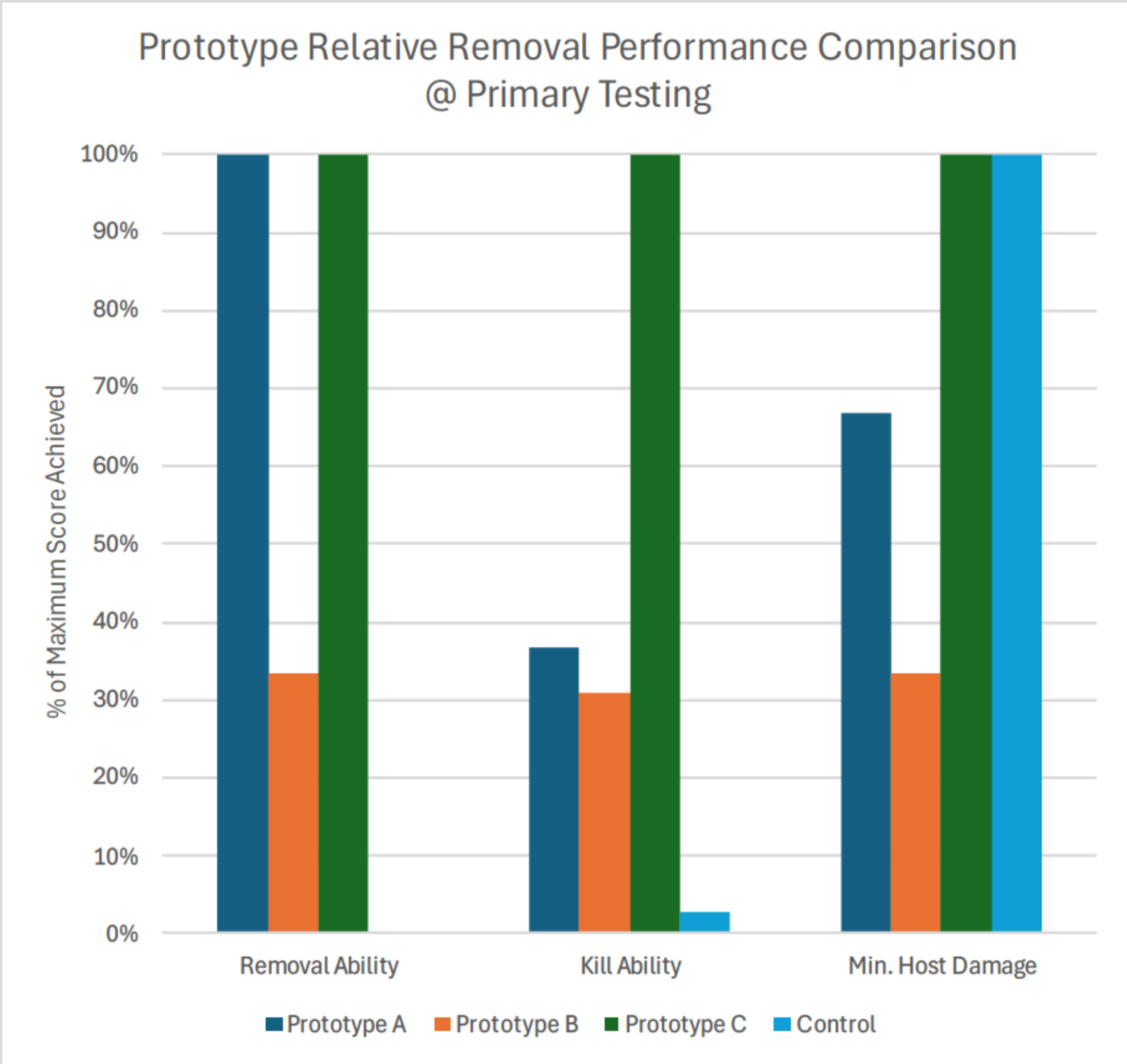


Figure 131. Removal Performance Comparison after Phase 4

4.5 Follow-up Testing: Phase 4

4.5.1 Gripper Follow-up Results

Averaged results achieved for pest removal testing of the Gripper, in terms of removal ability were noted to be high, the Gripper consistently proving its effectiveness at removing the Cabbage White Butterfly caterpillars and adult ladybeetles. From the follow-up testing results, an average removal score of 1.5 was achieved from a maximum possible score of 2 (for raw results, see appendix G.1). With half of the specimens being more mobile, and the other half able to avoid the gripper when positioned in leaf grooves (see Figure 132), the gripper approach had to be changed to improve its overall effectiveness. This required the gripper to be placed over both the leaf and specimen before being activated to close, approximately 50% of the time. While improving prototype engagement with the test specimens, it also resulted in a reduction in removal ability scores. Beetles rapidly moving over the host plant were also noted to be much easier to engage with when using the second approach, the former "grab from above" approach proving difficult to accomplish successfully under such circumstances.

Figure 132. Caterpillar in Leaf Groove

In terms of the average kill ability results for the Gripper, the score was also high, being 2.5 out of a possible 3. The device proved highly effective at killing caterpillars and beetles when used to squash them rather than remove them, though also proved to have good success when used to pick (see Figure 133) and drop caterpillars which were observed to be quickly attacked and eaten by ants (Figure 134). Of note was the "squashing specimen against the leaf" approach was observed to leave the gut contents on the host plant, though it was also observed that the gut remains washed away relatively easily (see Figure 135 and Figure 136). While not a significant concern for Broccoli crops, where leaves are not eaten, some concerns exist here as to the appropriateness of this approach where the leaves of the crop are the final product (e.g. lettuce and cabbage). It is also observed that such an approach would not work with some species of plants, with the device being unlike to be able to be placed either side of the leaf (e.g. cabbages once the heart starts to form).

Figure 133. Gripper Removing Small Caterpillar

Figure 134. Ants Attacking and Eating Dropped Caterpillars

With regards to effectiveness in killing the test specimens, it was observed that best success for this host plant occurred when placing the device over the host leaf with the specimen on it rather than trying to selectively remove the specimen. Field testing noted that the way in which the caterpillars were removed from the leaves only caused localised damage in the area of the body grabbed. Similar was noted with the ladybeetles, with the smallest specimen not killed when approached in this manner, and the medium sized specimen only slightly damaged.

The smallest specimen killed during Phase 4 follow-up testing was a 12 mm x 2.0 mm caterpillar and the largest, a caterpillar approximately 30 mm x 4 mm in size. The smallest specimen removed was a 2.8 mm x 2.2 mm ladybeetle. No evidence of host plant damage or situations likely to result in damage were noted to occur during follow-up field testing.

Figure 135. Squashed Caterpillar and Gut Contents on Leaf

Figure 136. Squashed Caterpillar on Leaf After Rain

4.5.2 Zapper Follow-up Results

Averaged results achieved for pest removal testing of the Zapper, in terms of removal ability, were noted to be very low, with the Zapper having no ability to directly remove the test species. While having the ability to briefly cause caterpillars to stop holding on to the host plant with their primary legs, due to the presence of four pairs of prolegs at the rear of their bodies, they were not dislodged. With respect to device application to ladybeetles, it was noted that one of the four beetles was essentially blasted from the leaf by the discharge, while another fell off soon after being stunned. From the results, an average removal score of 0.38 out of 2 was achieved (for raw results, see appendix G.2). With one half of the testing being performed against caterpillar larvae, which were able to remain attached via their prolegs while being shocked, and thus not dropping upon being stunned, the removal effectiveness results for the Zapper were noted to be heavily influenced by the nature of the specimen selection.

In terms of the average kill ability results for the Zapper, the score was observed to be 0.75 out of a possible 3. While proving reasonably effective against the adult lady beetles, killing 2 of the 4 tested, the Cabbage White Butterfly caterpillars seemed more resilient to electrical discharge, with none of the four caterpillars showing any short-term damage (see Figure 137), and none observed to have died within 24 hours. It is noted these results were significantly different to those observed when the device was previously tested against these specimens during Phase 2, where mortality was closer to 30% (acknowledging one of the caterpillars tested during follow-up testing disappeared during the 24 hour observation window, meaning its status at 24 hours remained unknown). In comparison to primary testing, overall kill ability was noted to be slightly lower. With regards to effectiveness in killing the test specimens, no clear pattern was observed with respect to application of the treatment. Specimens, for the most part had the terminals placed somewhere near the middle of their ventral body surface prior to discharge. While causing clear discomfort for the caterpillars, device discharge appeared to have little impact upon the immediate health of these test specimens. Conversely, application to ladybeetles, at a minimum, successful discharge resulted in temporary shock and cessation of activity, with 50% of test subjects ultimately dying. It is unclear what the application difference was with the specimen that was blown off the leaf and the specimen whose inner wings exploded out from under its elytra (see Figure 138), and that of the specimen that was only briefly stunned, with three of these subjects being of similar size and device application attempted in a similar manner. The fourth smaller ladybeetle (approximately 2 mm x 2 mm in size), did not affect a discharge, instead being pulled close to one of the terminals, without any obvious negative effects.

Figure 137. Caterpillar Half Hour After Zapper Treatment

The smallest specimen removed and killed during Phase 4 follow-up testing was a medium sized lady beetle, approximately 3.5 mm x 4.5 mm in size. This was also the size of largest test specimen removed and killed. One accidental discharge was noted to occur directly against the host plant.

Figure 138. Ladybeetle Directly After Zapper Treatment

4.5.3 Sucker Follow-up Results

Averaged results achieved for pest removal testing of the final Sucker protype iteration during follow-up testing were again noted to be exceptional, with the Sucker proving 100% effective at removing the test specimens. From these results, an average removal score of 2 out of a possible 2 was achieved (for raw results, see appendix G.3). While testing of the other prototypes indicated the presence of prolegs to have improved the ability of the caterpillars to remain attached to the leaf, contrary to expectations, the Sucker device proved able to develop sufficient force to overcome this, successfully removing these specimens without issue. With the more strongly attached pupal forms not available for testing, it was unable to be determined if this force was sufficient to also effect the removal of such specimens.

In terms of the averaged kill ability results for the final Sucker, the score was 2.63 out of a possible 3, thus rating very highly. The device proved particularly effective against the Cabbage White Butterfly caterpillars, killing 100% of them immediately (see Figure 139). While also quite successful against the ladybeetle adults (Figure 140), two managed to survive the initial treatment, though with damage noted, and one of these was furthermore observed to still be alive 24 hours later. It is noted these results are much higher that what was observed when the device was originally tested against these same types of specimens, where survival was 100% for both, due to the lack of air velocity resulting in the specimens having previously been pulled through the device. Without further testing, and establishing if removal would occur, it is not possible to comment around likely kill effectiveness against pupal forms of the Cabbage White Butterfly.

With regards to effectiveness in killing the test specimens, there was no clear best application approach, with all specimens quickly drawn into the device and smashed against its walls or against the fan blades. Of note was that the device in its 6th iteration was unable to utilised against the ladybeetles under field conditions, with the location of the specimens having no access to 240V AC power, which was necessary to drive the air compressor and fan. As such, treatment of ladybeetles is noted not to have occurred under field conditions, so results may not be reflective of field responses.

The smallest specimen removed and killed during follow-up testing was a medium sized, 3.5 mm x 4.5 mm ladybeetle. The largest both removed and killed, was a caterpillar approximately 30 mm x 4 mm in size. No damage was noted to have occurred to the host plants during specimen removal.

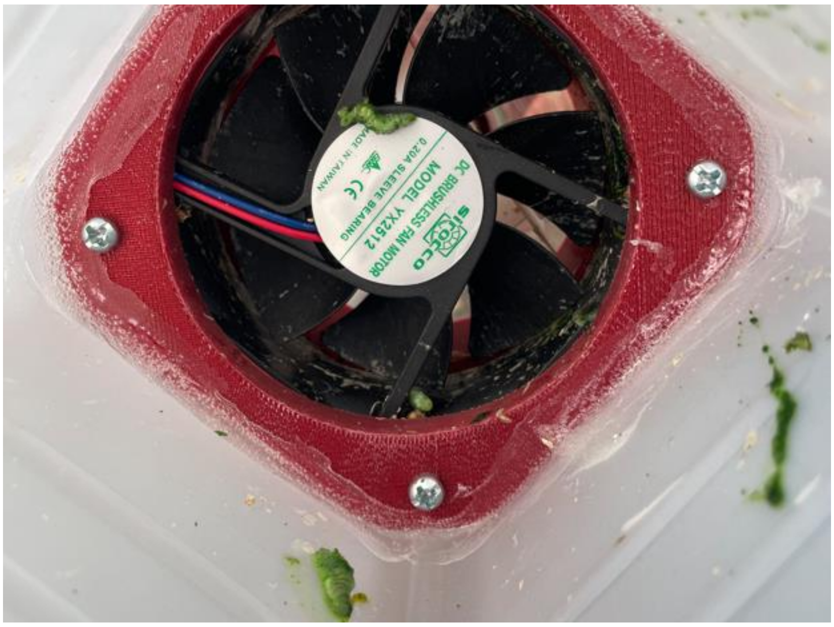


Figure 139. Remains of Caterpillars After Sucker Treatment

Figure 140. Remains of Ladybeetles After Sucker Treatment

4.5.4 Control Follow-up Results

While no physical measurements were made on these specimens, the following was observed:

- Visually, there was no apparent changes in any of the control subjects.
- Mean Removal Ability was 0.
- Mean Kill Ability was 0.

Note that raw results for the follow-up control experiment were as recorded in Appendix G.4.

4.5.5 Summary and Analysis of Follow-up Results

From the Phase 4 follow-up testing, examination of the removal results was supportive of the Zapper having limited removal ability, with a score of 0.38 out of 2. The Gripper prototype was noted to be far more successful with an average score of 1.5 out of 2, while the Sucker prototype proved to be the most effective end-effector for pest removal, averaging 2 out of 2 in its removal ability, proving equally effective against both caterpillars and ladybeetle adults and showing the most consistent results, with a Standard Deviation of zero. While a removal score was achieved for the Zapper device, its success was noted only to occur against ladybeetles. The difference in the success with the different target specimens is reflected by the relatively high (and largest observed) Standard Deviation, observed to be 0.74. With some size differences noted between test specimens, there was a size limitation difference observed between the respective devices regarding pest removal, with the Gripper at its removal limit with specimens of 1.5 mm x 2.5 mm and the Zapper unable to remove anything smaller than 3.5 mm x 4.5 mm.

In summary, average Removal Ability scores, based on the removal of four Cabbage White Butterfly caterpillars and four adult ladybeetles, were as per Table 28.

Table 28. Follow-up Testing Removal Ability Score Summary

Prototype	A - Gripper	B - Zapper	C - Sucker	Control
Removal Ability Mean	1.50	0.38	2.00	0.00
Removal Ability Std.Dev.	0.53	0.74	0.00	0.00

Examination of the Kill Ability scores once again established the Sucker prototype as being the most successful and most consistent of the devices, with an average score of 2.63 out of 3 and a standard deviation of 0.74. Testing was noted as having killed all caterpillars, however two ladybeetles survived the transit through the device, with one later dying and the other still alive, though damaged, 24 hours later. Evidence was indicative of caterpillar death occurring via being smashed against the inside of the tube, or through being struck by the fan blades during passage through the device. Cause of damage to the ladybeetles was less clear. As with the primary testing, it is expected that the action responsible for death or damage to specimens is similar to that occurring within the Micothon greenhouse devices (as per Chapter 2.2.2.2). Kill Ability score achieved against the test specimens for the Gripper and the Zapper for follow-up testing, was observed to be 2.5 and 0.75 respectively, the Gripper proving to have similar kill ability to the Sucker device and both clearly outperforming the Zapper for this measure. That said, consistency in device effectiveness was observed to be similar for both devices, both higher than that of the Sucker, with standard deviations of 1.07 and 1.04 respectively. The Control Kill Ability score was observed to be 0, with none of the specimens having died with the 24 hour observation window. Evidence was indicative of the Sucker being more effective in killing caterpillars than ladybeetles, while the kill ability of the Gripper, appeared to be related to the way in which it was applied, more so than the nature of the test specimens. While limitations in specimen size heavily impacted Gripper kill ability where the device was used to grab and remove specimens from the host leaf, re-orienting the device, such that specimens were crushed between the jaws and the leaf, with no attempt to remove the specimen, proved 100% effective, even against the smallest tested specimen. The Zapper device, conversely, showed no ability to kill the caterpillars within the 24 hour observation window, though appeared to cause them some distress. It also managed to immediately kill one of the ladybeetles, and damage another such that it was dead within 24 hours.

From the follow-up testing results, it is evident that the nature of the species targeted had a clear impact on both the Zapper and Sucker end-effector's kill ability. As with removal ability, there was also a noted difference observed between the sizes of the pests able to be killed by the Gripper and the Zapper prototypes, though acknowledging the application method for the Gripper played an important role in the nature of the results for this device.

In summary, average Kill Ability scores, based on the removal of four Cabbage White Butterfly and four ladybeetles, were as per Table 29.

Table 29. Follow-up Testing Kill Ability Score Summary

Prototype	A - Gripper	B - Zapper	C - Sucker	Control
Kill Ability Mean	2.50	0.75	2.63	0.00
Kill Ability Std.Dev.	1.07	1.04	0.74	0.00

With regards to host plant damage, there was no evidence during field testing of the Gripper causing, nor likely being responsible for causing, any damage. That said, the possibility of the device accidentally not releasing the leaf after crushing the pest specimen against was still noted to exist. In consideration of these observations, the Host Damage score for the Gripper was increased slightly from 2.0 to 2.5. With Prototype B, the Zapper, field testing against pest specimens only resulted in accidental discharge against the leaf on one occasion, with remaining failures to discharge against the pest specimens, failing completely to discharge against either the leaf or the specimen. Based on these observations, the Host Damage score for the Zapper was also increased slightly, from 1.0 to 1.5. Host Damage scores for the Sucker and Control were unchanged at 3.0, as noted below in Table 30.

Table 30. Follow-up Testing Host Damage Score Summary

Prototype	A - Gripper	B - Zapper	C - Sucker	Control
Host Damage	2.50	1.50	3.00	3.00

Graphically, the device comparisons, with respect to *Removal Performance*, can be more clearly observed as seen in Figure 131, which shows Removal Ability, Kill Ability and Host Damage, relative to the best-case scenario for each of the examined prototypes (including that of the Control). From this figure, it is apparent from a *Removal Performance* perspective, Prototype C, the Sucker was the strongest performing end-effector during follow-up testing, achieving maximum scores across all three parameters, with negative impacts on the host plant being equivalent to the control (i.e. equivalent to having not been treated at all). Prototype A, the Gripper, appears to be the next best performing end-effector, with excellent scores achieved in both removal ability and kill ability, along with a very solid performance in minimising likely host damage. Prototype B, the Zapper, was observed to have scored most poorly in comparison to the other prototypes during this testing. That said, this device still clearly outperformed the Control with respect to both removal ability and kill ability, thereby establishing it to have a some degree of effectiveness as an insect control approach (noting that this was, however, only for control of ladybeetles during this round of testing).

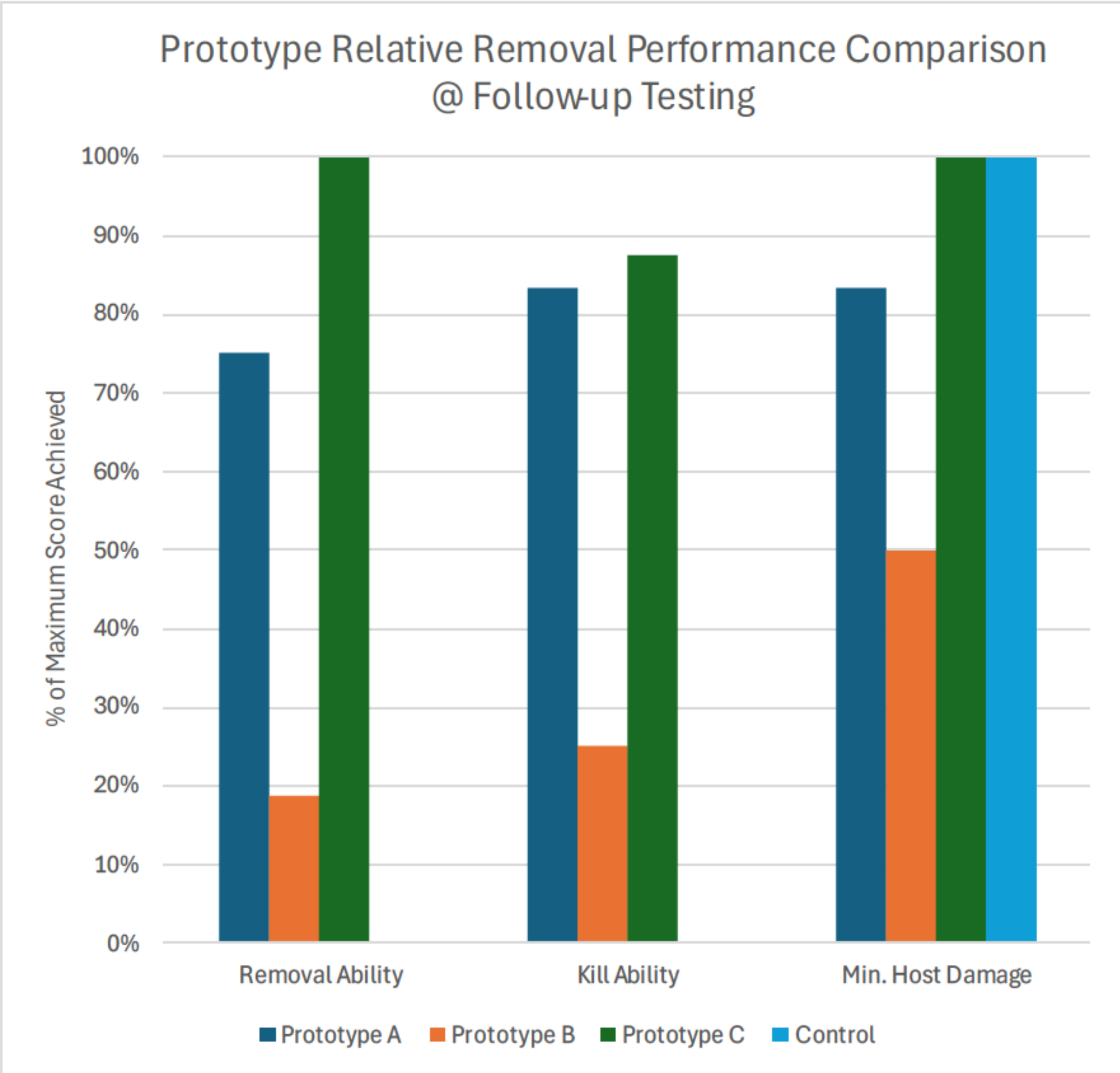


Figure 141. Removal Performance Comparison During Follow-up Testing

4.6 Prototype Analysis and Comparison: Phase 5

4.6.1 End-effector Performance by Device

In terms of Gripper *Removal Performance*, the removal ability during primary testing and follow-up testing was observed to be generally in alignment with expectations from preliminary testing in Phase Two, with scores being 2.0 and 1.5 respectively (where maximum score was 2). The difference, while notable, was the result of adjusting the Gripper application to ensure greater kill ability, which in turn negatively impacted removal ability. Kill results for primary testing were, however, inconsistent with expectations, a notably lower level of success in killing the Mealworm larvae in comparison to that observed when using the same approach against Cabbage White Butterfly larvae during preliminary testing. Follow-up testing confirmed this observation, with kill ability scores increasing from 1.1 to 2.5 (out of maximum score of 3), upon changing the test species from Mealworm larvae and pupae to Cabbage White Butterfly caterpillars and adult ladybeetles.

Zapper *Removal Performance* during Phase 4 primary testing, in terms of removal ability, also appeared to be largely in alignment with initial observations of results made during preliminary testing. However, follow-up testing indicated removal ability as likely over-rated, potentially as a result of earlier removal testing ability having been partially based on assumptions later established as likely being incorrect. Supporting this conjecture was the follow-up testing removal ability score of 0.38, noted as being close to only 50% of the primary testing result of 0.67. Kill results for primary testing of the Zapper also proved to largely consistent with expectations, which was supported by follow-up testing, with kill ability scores being 0.67 and 0.75 respectively. While overall results for kill ability did not appear to show much inconsistency across the different testing, the observational results did, however, indicate differences in effectiveness of the device against the different species and/or life stage.

The removal ability of the Sucker device (final iteration) during all Phase four testing was consistent with expectations garnered from preliminary testing observations, with a perfect score of 2 achieved. The kill ability of the device, while scoring highly in both Phase 4 testing runs, did show some variation from expectations, with a score of only 2.63 observed against adult ladybeetles and Cabbage White Butterly caterpillars, in comparison to the perfect score of 3 noted when applied to mealworm larvae and pupae. Of significance in the observational notes was that all caterpillars were killed during follow-up testing, whilst some of the ladybeetles managed to survive. This was suggestive of differences in removal performance existing between different species and/or life stages, similar to what was noted for the Zapper device.

After primary testing, overall unweighted performance results were as per Table 31, seeming to indicate that only the application of the Sucker end-effector proved to have any benefit, with overall performance of the Control scoring more highly than both Prototypes A and B, despite not providing any mechanism to remove or kill pests (apart from allowing natural attrition to occur). With both these prototype end-effectors showing some pest removal and/or pest killing ability, and thus likely to result in decreased damage to the host plant in the long-term (in comparison to doing nothing), a clear need to adjust the relative weighting of the examined parameters, so to better align performance results with observed result, was identified.

Table 31. Averaged Prototype Performance Scores for Phase 4: Primary Testing

	Build Performance				Removal Performance			Overall Performance (/16)
Parameter	Cost (0-2)	Complexity (0-2)	Build Time (0-2)	Integration Ability (0-2)	Removal Ability (0-2)	Kill Ability (0-3)	Host Damage (0-3)	
Prototype A	1	0.5	0.5	1.5	2.00	1.10	2	**8.60**
Prototype B	2	1	1.5	1.5	0.67	0.93	1	**8.60**
Prototype C	0	1.5	1.5	0.5	2	3	3	**11.50**
Control	2	2	2	0	0	0.08	3	**9.08**

Via application of the weightings (as previously described in Chapter 3.1), thereby scaling up the importance of integration ability, removal ability and kill ability, weighted performance results were noted to be as per Table 32. Examination of these weighted results shows all devices as performing better than the control, this being consistent with observations of a least some degree of success with Prototypes A and B, along with a high degree of success of Prototype C, thereby giving a degree of confidence in the suitability of the weightings used, and the results obtained.

Table 32. Weighted Prototype Performance Scores for Phase 4: Primary Testing

	Build Performance				Removal Performance			Overall Performance (/24)
Parameter	Cost (0-2)	Complexity (0-2)	Build Time (0-2)	Integration Ability (0-4)	Removal Ability (0-4)	Kill Ability (0-6)	Host Damage (0-4)	
Weighting	1	1	1	2	2	2	1.33	
Prototype A	1	0.5	0.5	3	4	2.20	2.67	**13.87**
Prototype B	2	1	1.5	3	1.33	1.87	1.33	**12.03**
Prototype C	0	1.5	1.5	1	4	6	4	**18.00**
Control	2	2	2	0	0	0.16	4	**10.16**

In a similar comparison, after follow-up testing, unscaled averaged prototype performance results were as per Table 32, indicative of Prototype B having no benefit with respect to the control, with Prototype A and Prototype C only showing a marginal success in the control of insect pests when compared against having applied no treatment.

Table 33. Averaged Prototype Performance Scores for Phase 4: Follow-up Testing

	Build Performance				Removal Performance			Overall Performance (/16)
Parameter	Cost (0-2)	Complexity (0-2)	Build Time (0-2)	Integration Ability (0-2)	Removal Ability (0-2)	Kill Ability (0-3)	Host Damage (0-3)	
Prototype A	1	0.5	0.5	1.5	2	2.50	2.50	**10**
Prototype B	2	1	1.5	1.5	0.38	0.75	1.50	**8.63**
Prototype C	0	1.5	1.5	0.5	2	2.63	3	**11.13**
Control	2	2	2	0	0	0	3	**9**

After scaling through application of the suggested weightings (as described in Chapter 3.1), performance results were noted to be as per Table 34. Examination of these weighted results is clearly indicative of all devices performing better than the control, being consistent with observations of a moderate degree of success with Prototype A (the Gripper), limited success with Prototype B (the Zapper), and a high degree of success with Prototype C (the Sucker), thereby giving confidence in the suitability of the weightings used, and the results obtained.

Table 34. Weighted Prototype Performance Scores for Phase 4: Follow-up Testing

	Build Performance				Removal Performance			Overall Performance (/24)
Parameter	Cost (0-2)	Complexity (0-2)	Build Time (0-2)	Integration Ability (0-4)	Removal Ability (0-4)	Kill Ability (0-6)	Host Damage (0-4)	
Weighting	1	1	1	2	2	2	1.33	
Prototype A	1	0.5	0.5	3	3	5.00	3.33	**16.33**
Prototype B	2	1	1.5	3	1	1.50	2.00	**11.75**
Prototype C	0	1.5	1.5	1	4	5.25	4	**17.25**
Control	2	2	2	0	0	0	4	**10.00**

From Figure 142, visual comparison of the two sets of weighted results can be seen as being supportive of the Sucker device having been the most successful end-effector developed, with the Gripper being the next most successful, and the Zapper being the least successful device. This noted, the electric charge based end-effector still proved to have some benefit in the control of pest insects, which is apparent when compared to not having applied any pest control approach (i.e. against the Control). In this respect, whilst showing differences for each device in terms of individual performance scores for primary and follow-up testing, the general trend of the data observed during primary testing, appears to have been largely validated by the follow-up testing results.

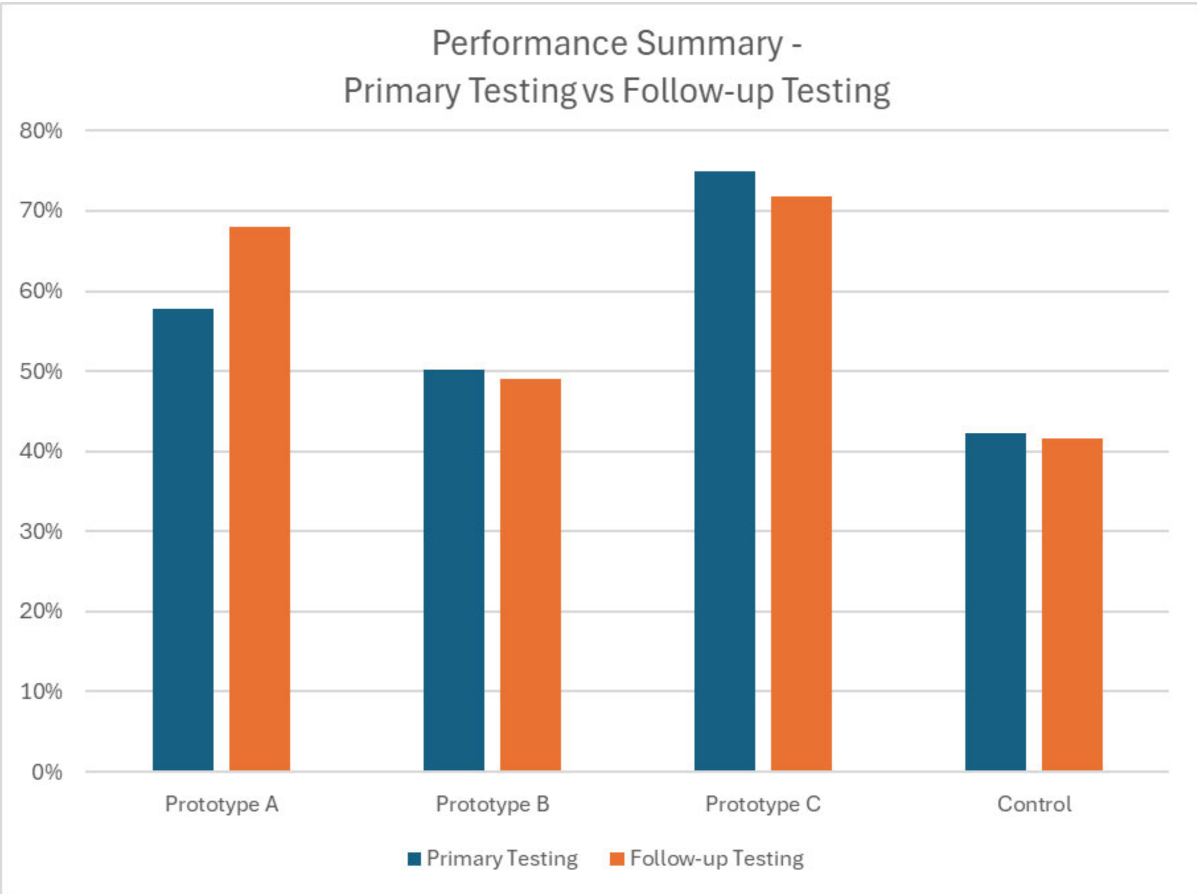


Figure 142. Performance Summary - Prototype Against Testing Approach

4.6.2 End-effector Performance by Specimen Type

Reviewing the data across all testing in Phase Four, and separating performance results based upon the "type" of specimen tested, provides a comparative performance of each device against each of the different specimens tested (reported as a percentage of the maximum possible score of 24 points). The results of this analysis were as per Table 35, and as graphically displayed in Figure 143.

Table 35. Performance Summary Against Specimen Type (As a % of Maximum Possible Score)

	Prototype A	Prototype B	Prototype C	Control
Cabbage White - Larvae	72%	44%	75%	42%
Ladybeetle - Adult	64%	54%	69%	42%
Mealworm - Larvae	58%	55%	75%	43%
Mealworm - Pupae	66%	49%	75%	42%

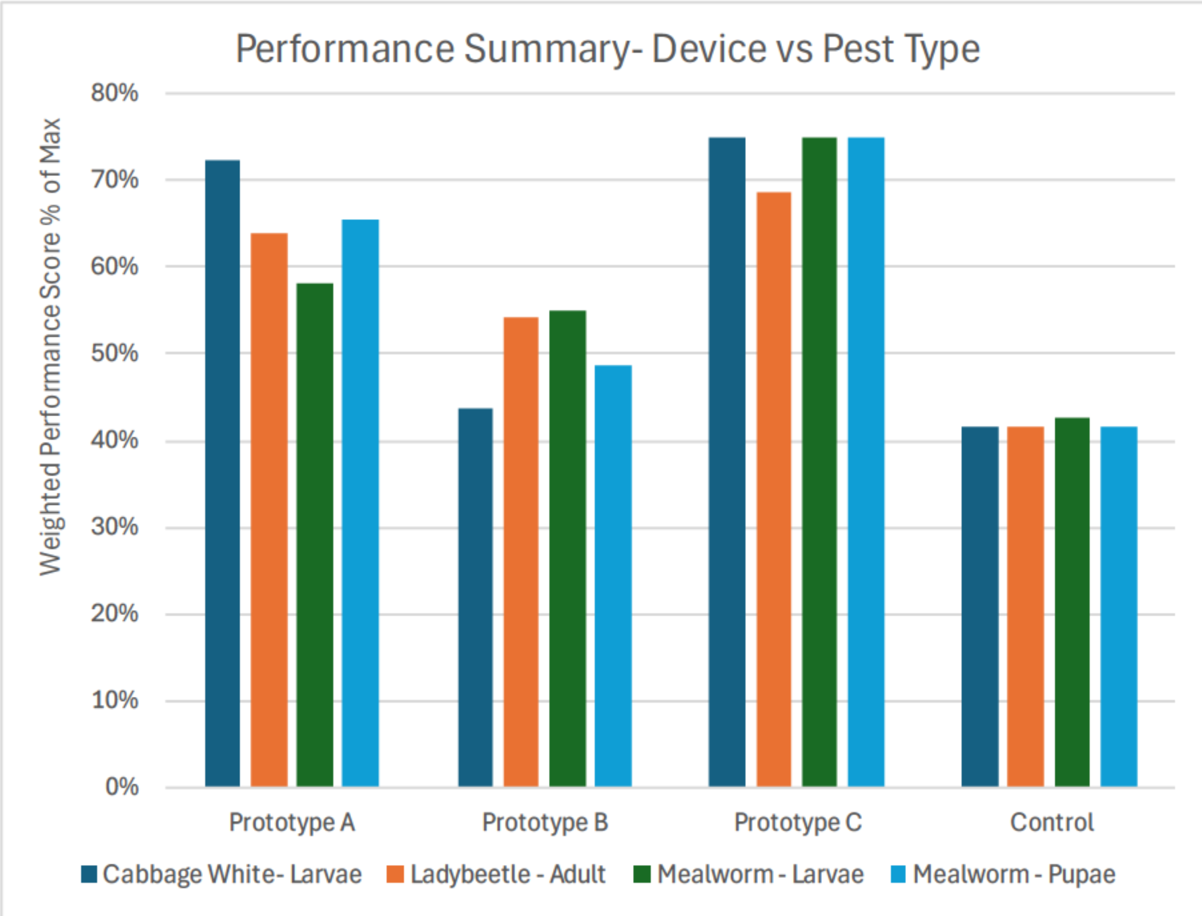


Figure 143. Performance Summary - Prototype Against Pest Type Tested

From Figure 143 some clear trends were apparent. Firstly, it was evident that Prototype C, the Sucker, consistently had the best performance of all the three end-effector prototypes, irrespective of the species or life cycle stage it was applied to. Prototype A, the Gripper, with the second-best overall performance scores, showed much stronger performance against the larval stage of the Cabbage White Butterfly (i.e. the caterpillars), than against Mealworm larvae. Prototype B, the Zapper, was consistently the worst performing device, showing best, though limited, success with the adult ladybeetles and the larval mealworms. While the Zapper proved slightly better than the Control with respect to control of Mealworm pupae, its effectiveness against Cabbage White Butterfly larvae was similar to that observed by the control, indicating it having no significant benefit when applied against these types of specimens.

CHAPTER 5: DISCUSSION AND CONCLUSIONS

5.1 Project Performance Analysis & Key Findings

From the results and data analysis, as presented in Chapter Four, it is evident that the first objective "to design and build three basic prototype end-effectors, each using a different approach to remove and potentially kill insect pests" was largely achieved during Phase One and Phase Two of the project. The second objective "to test each of these prototypes against a range of pest species, including adult and larval forms" was also partially completed. By the end of Phase Two, three prototype devices, each with at least some capacity to be modified further in the form of a pest removing/killing end-effector, had been designed, built and tested (though-be-it in a very rudimentary fashion). With the build process having been considered from a safety, budgetary and build complexity perspective, the fifth objective "to ensure that any end-effector developed is safe, affordable, and easy to construct" was noted to have also been at least partially met by the end of Phase Two.

Key findings from the first two phases of the project were:

- Design and build of end-effector prototypes was far more time consuming than expected.
- Build of end-effector prototypes was more expensive than expected.
- The Gripper prototype while being the most expensive, most time consuming and most expensive to build, appeared to show the most promise in terms of its likely insect control ability.
- The Zapper prototype, while having what was classified as a "medium" level of complexity, proved relatively simple and cheap to build. Insect control ability of the device was unclear at this stage, but preliminary examination demonstrated no removal ability and kill ability, while existing, appeared variable and limited in its nature.
- The Sucker prototype, was similar in some ways to the Zapper device, demonstrating a medium level of complexity, and proving relatively cheap and simple to build. While succeeding at picking up Styrofoam balls, the device, however, appeared likely to have very limited ability to remove or kill insect pests.
- The Sucker prototype was observed to require significant further development at this stage in order to fully meet Objective One, with preliminary results indicating it unlikely to be viable in its current state.
- Further testing of all devices was required to better satisfy the completion of Objective Two.
- Further work was required to better meet the requirements of the second and third objectives (noting in particular, the lack of data to support Objective Three having yet been achieved).
- *Build Performance* alone, after these first two phases, was unable to provide sufficient evidence to clearly establish whether the devices were capable of meeting the primary project objective, and the limited preliminary data collected, insufficient to establish *Removal Performance* of the respective devices.

- At this point, Objective Four had not yet been achieved.
- Further work would continue to require Objective Five being met to ensure the project remained safe and achievable within the identified constraints.

While Phase Three originally was aimed at accomplishing Objective Four “to improve on and optimise the design of the most favourable protype”, as previously identified, it was believed that the completion and basic testing of the original devices during the earlier two phases, provided insufficient supporting data to clearly establish which prototype was the “most favourable”. Though preliminary intentions were to undertake significant testing of all devices at this point, with the above realisation, along with a lack of specimen availability at testing time, a decision was made to instead apply the key feature of the fourth objective, to <u>improve and optimise</u> prototype design (with fair consideration of both safety and resource availability).

Development of the Gripper prototype proved relatively straightforward, with preliminary testing indicating many key performance features already present. While costs and build time were higher than desired, there was no clear nor easy solution for this aspect. Review of the available literature offered little information around potential solutions to these particular problems. Though build time was identified as having potential to be decreased, through purchase of an off-the-shelf gripper solution, this solution required increased capital expenditure (noting robotic Grippers suitable for the Arduino as costing in the vicinity of $80, as per ebay.com 2024), exceeding budgetary constraints. What was apparent, however, was the difficultly in handling the device, with multiple parts and wiring creating issues with device utilisation. A new 3D printed component was therefore designed and constructed and then incorporated in the build, resulting in a slight increase in build time and cost, but improving the design overall. Examination of the build at this point indicated it to be well suited for further adaptation so as to allow attachment of the device to a robotic arm.

With regards to the Zapper prototype, there also appeared limited pathways to significant improvement that did not involve replacing or modifying the existing circuitry, to enhance the effect of the produced charge. With the literature indicating a current lack of understanding around electric fields and insects (Joeb et al. 2024), and such changes likely significantly increasing time and cost, to unknown effect, changes made were instead restricted to stabilising the end terminals, to allow better application of the device to test subjects. From a build perspective, the prototype at this point appeared reasonably straight-forward to modify for connection to a robotic arm.

The Sucker prototype with its poor performance, yet according to the literature, clear potential for the successful removal of insect pests (Micothon n.d; Koger 2023), appeared to offer significant opportunity for development and improvement. The second iteration of this device involved improving the electrical harness to make the system more robust as well as decreasing the cross-sectional area of the end nozzle (see Figure 47). By the relationship previously described in Equation 1, the nozzle change should have, in theory, increased the velocity of the air moving through it proportionally to the inlet area reduction. This, by Bernoulli's principle, was expected to reduce the pressure at the nozzle, and thus enhance the suction effect experienced. Whilst appearing to improve the device's suction ability marginally, and as a result slightly improving removal ability, it was observed that the sound coming from the fan changed slightly upon addition of the smaller nozzle, indicative of it slowing down, decreasing flow rate, and thus unlikely to have been delivering the expected performance gain, consistent with actual observations. A further point of note was that the single specimen previously successfully killed by the device, was now too big for the nozzle, blocking it, negatively impacting the kill ability of the 2^{nd} iteration. As a result, the net effect of the change was ultimately slightly negative (though a decision was made to keep the nozzle, with its ability to improve suction having been established).

Upon realising greater air flow was still required, and in consideration of Equation 2, along with limited availability of resources, system outlet was attempted to be doubled through addition of a second device with similar air flow capabilities. As a result of running out of living test specimens, the methodology at this point required adjusting to instead test a range of small items essentially as "proof of concept". To allow comparison against the earlier iteration, so as to be able to make performance assessments, the iteration 2 version of the device was tested against these same items (as per the results previously presented in Chapter 4.3.3.2). While the modification was successfully accomplished, with minimal capital outlay (due to existing availability of key components and thus only needing some further 3D printed parts), results again proved disappointing. It was observed that two flaws existed in the new iteration 3 design. Firstly, upon connecting the two units to a single nozzle (as per Figure 50), the pitch in both fans changed, indicative of fan speeds slowing upon connection (noting this was additional to that also observed when each nozzle was connected to their respective device). Secondly, slightly larger, heavier objects, despite being able to be picked up, became stuck in the junction, with the air speed dropping at that point, such that pressure was no longer sufficient to overcome gravitational influences on the objects, preventing further movement through the system. Furthermore, apart from significantly increasing cost, the device became extremely bulky and unwieldy, decreasing its likelihood of working around plants with ease, and reducing its ability to connect to a robotic arm. Overall performance was therefore established as having been negatively impacted.

Abandoning the iteration 3 approach, iteration 4 instead attempted to increase the air speed coming in behind the fan, to help reduce the power needed by the fan in moving the air, with the theory this would help in maintaining the fan speed upon addition of the smaller nozzle (through addition of extra energy into the front of the system to help overcome the system losses being experienced by the entrance narrowing). This was hoped to be achieved by adding an element of compressed air into the system, delivered by a purpose designed nozzle and tube delivery system. As a result of the desire to get the air flow behind the fan without further impeding the inlet area, the second Sucker device (created using a 80 mm CPU fan, rather than an 80 mm case fan), constructed during the previous iteration was utilised due to its different fan configuration being more conducive to the particular type of modification intended (see Figure 55). While performance was no better than iteration 2 of the device, the observation that the addition of the compressed air stream was able to improve the performance of this particular device was supportive of the theory having some merit, despite results proving the device itself as offering no performance advantage over iteration 2.

Returning to the iteration 2 device, with a focus on alternative ways to reduce power loss, baffles were added to the inlet in front of the fan for the 5th iteration, to help direct the air flow, and thus reduce losses being caused by vortex creation and associated turbulence. With only minimal time and capital invested in this change, and a noted improvement in suction, likely *Removal Performance* was deemed as to have increased, however, given the dead caterpillar (now slightly desiccated), was still unable to be drawn through the device, it was apparent that kill ability remained negligible, and further design changes were required.

Reflecting on the relative performance improvement from the application of the compressed air stream during testing of iteration 4, iteration 6 sought to incorporate a similar approach within the device with the hope of adding sufficient energy, in the form of increased particle velocity delivered via an air blow gun (see Figure 60), to the air stream so as to be able to pull objects completely through the system. As noted in Chapter 4.3.3.5, this change had a profound impact upon device ability, easily drawing all test items through the system, thereby providing the required potential for the killing of pests pulled through it, and indicative of a significant positive performance increase.

Apart from clearly demonstrating the successful completion of Objective Four (despite this device not originally appearing to be the most favourable of those examined), completion of Phase Three also established:

- Reducing inlet cross-sectional area improved device suction ability, though at the cost of reduced ability to draw in larger specimens due to the narrowed system entrance.
- The chosen fans lacked sufficient power to overcome the system resistance, indicating an alternative fan choice or mechanism to induce suction at the end of the device was warranted.
- The closed case fan configuration proved to have better ability to pull air through the system than the more open CPU fan configuration.
- Doubling the number of fans, offered no clear performance improvement, with system losses appearing to increase, thus countering any extra air flow provided. Furthermore, the splitting of the air stream then negatively impacted air pressure at the junction, thereby preventing progression of captured objects through the system.
- Addition of a compressed air flow to the front end of a single fan-based system helped improve air speed and suction ability, provided applied in an appropriate manner and location.
- Addition of baffles to the system improved air flow through the system, likely through creation of a more laminar flow.

- The relatively large size and general configuration of the final Sucker iteration was suggestive of this prototype requiring significant further modifications in order to convert it into an attachable end-effector.

While it is acknowledged that the costs of incorporation of an air compressor into a robotic system would be somewhat higher than desired, and would thus negatively impact the affordability aspect of Objective Five for the Sucker device, it was noted that such compressors are readily available and not prohibitively expensive (12V compressors with a 6L tank being available online for less than $120 as per Vevor 2024). Therefore, a decision was made to continue with the device, so to achieve the desired level of performance improvement (this adding to the expected capital expenditure for the device, resulting in it scoring zero for its budgetary performance). Whilst seemingly supportive of Keupper's 2003 claim that use of vacuum based systems for pest control was too expensive and lacking in efficiency, in consideration of the relatively small cost of the prototype compared to typical agricultural outlays for machinery and equipment, it could be argued that from a systems cost perspective, Keupper's 2003 premise regarding vacuum based devices may no longer be valid, and should not be used as justification for not continuing further studies of this nature.

With significant end-effector progress having been made by the end of Phase Three, and potential for device success clearly existing, data supportive of this success was, however, still lacking, with Objective Three not yet completed. With this in mind, Phases Four and Five aimed to better support the achievement of this objective, along with providing extra support for Objective Two. This was achieved by testing all three devices more thoroughly, analysing the acquired data and establishing which of the end-effector prototypes developed offered the most potential with respect to non-pesticide based insect pest control.

Phase Four was initiated through testing of the completed prototypes for their likelihood to cause damage to host plants. This was important in addressing a specific point raised by Lacotte et al. (2022), who identified that a key parameter in an automated insect control system was to ensure that plants were not damaged as a result of a false detection. A similar argument can be made that the host plant should furthermore not be damaged during pest control attempts. Results from the testing of the devices on the host plants were collected, scores allocated (based upon the pre-established criteria) and applied per device as the primary testing result for the measure of "Host Damage". As a result of primary testing not occurring on an insect species typically associated with the host plants used for damage testing, follow-up testing, where devices were applied to more appropriate specimens in a field situation, was then utilised in an attempt to help establish the validity of the primary testing data. Due to observations made during follow-up testing, slight modifications were made to the respective plant host damage scores, to better reflect actual performance, this resulting in a minor change to overall performance results for the Gripper and the Zapper. Specifically, it was noted that device use aimed at controlling pests, as opposed to attempts to observe damage caused by direct application of the devices to the plant hosts, had a slight positive performance impact, as a result of decreased likelihood of damage.

During primary testing in Phase Four, whilst the survival rate of the larvae treated by the Gripper was observed to be similar to that of the control, the noted trauma to the bodies of the two larval specimens observed non-responsive after Gripper treatment, seemed clear indication of Gripper application being a causal factor in their deaths. This was in contrast to the one Control specimen, which appeared to have randomly died while moulting, thus helping establish causality of Gripper application in larval death. The significantly reduced activity levels observed after Gripper treatment, were, furthermore, consistent with what might be expected had the specimens been exposed to significant trauma or stress. While lack of specific knowledge of the species in question makes this largely conjecture, the fact that the control specimens were more active after transfer (having not been treated), lends this theory some credibility.

Differences in the effectiveness of the Gripper device against the Mealworms, in comparison to more limited testing on other pest species (as occurred during both preliminary testing and follow-up testing), was supportive of the likelihood that different end-effectors were better suited to specific insect types. While appearing highly effective against Cabbage White Butterfly larvae and pupae, as well as dealing well with ladybeetle adults, the Gripper proved much less effective against Mealworm larvae. In a similar vein, there were several other occasions where this same point of performance difference between treatment of different pest types was observed. One such point was the apparent removal success of the Zapper prototype during primary testing where Mealworm larvae were used. During performance assessment it was assumed that if these test specimens were holding onto a plant, their recoil reaction would cause them to drop. However, the morphology of these beetle larvae was noted as better suited to burrowing and moving through physical media such as bran or oats, meaning they had a relatively firm and slippery outer body casing and only three pairs of legs, so were not well suited for grasping onto the leaf. The Cabbage White Butterfly caterpillars, in comparison, were noted as far better adapted to holding onto their host plant, having pairs of prolegs on four of their body segments, as well as their three pairs of true legs. Application of the Zapper to these specimens, whilst still resulting in a similar recoil reaction, did not cause the specimens to release their grip with their prolegs, allowing them to remain attached after Zapper treatment. Observations around Sucker performance also showed differences in effectiveness against different insect types, with some ladybeetles surviving passage through the device, whilst all the soft-bodied caterpillars were completely destroyed. From these observations, it was apparent removal performance of all prototype devices was at least partially related to the nature of the pest species being controlled (evidenced further by the data analysis as presented in Chapter 4.6.2).

A similar argument can be made around the nature of the device application, with different responses occasionally observed despite treatment of the same type of insect with the same device. Whilst some level of performance variation was expected due to biological variation, on occasion the degree of response variation was observed to far exceed what might be expected between individuals of the same species, lifecycle stage, and size. Based on these observations, it was postulated that removal and/or kill performance potentially had some level of relationship with the manner in which the devices were applied. During testing, the degree to which this relationship occurred was complex and at times poorly understood. For example, while application approach impact on removal and kill ability was clearly visible during Gripper operation, the relationship was far less clear during use of the Zapper device. This was evidenced by the typically higher standard deviations observed in the Zapper data sets, especially in consideration of the relatively low means also observed during use of this device (see Table 25, Table 27, Table 28 and Table 29). While examination of Table 29 notes the Gripper also having a high standard deviation for its kill ability, what is not obvious, is this being a result of adjusting device usage to get better kill effect part way through the testing (in combination with having only used a small sample population for testing). Specifically, it was observed that Gripper action required adjusting depending upon the size and exact location of the test specimen, in order to achieve better success at killing test subjects, but in doing so, removal ability was typically sacrificed. Of further support regarding the complexity of the relationship between specimen type and device type, and nature of device application were several occasions where the Zapper quickly killed one specimen, without having any impact on the next specimen, despite being of the same species, life-cycle stage and size.

Whilst such differences were noted, general trends were still clearly present within the data, allowing conclusions around relative success to be established, through use of a weighted decision matrix (as previously described in Chapter 3.1). With the data analysis performed during Phase Five indicative of the Sucker (Prototype C) device having achieved the highest removal ability, highest kill ability and equal least amount of host damage (both during primary and follow-up testing), this device was clearly established as having the best *Removal Performance*. Despite being the most expensive device and needing the most work to finalise its transition into an attachable end-effector (thus having a relatively poor *Build Performance)*, its strong *Removal Performance* ultimately resulted in it being the best performing device overall, thereby completing principal Objective Three: “to use collected data to identify which of the prototypes offered the most insect control potential, through examination of their: relative success in removing and/or killing insect pests; ease of operation; ease of construction; cost; potential for robot connectivity; and potential for negative impacts”. With Phase Four having tested at least three different species, along with a range of lifecycle stages (adults, larvae and pupae), completion of Phases Four and Five were observed to have successfully met Objective Two.

Observing that all devices were constructed without harm or significant risk, and this having been achieved within a typical home environment and workshop (along with access to a 3D printer), two of the three requirements for Objective Five were also demonstrated as having been clearly and consistently achieved. Though noting costs did exceed expectations, particularly with respect to the Sucker device, the actual outlay to develop the prototypes was not believed to be excessive for most people/organisations likely to be using RAS, especially when considering costs of other RAS components, so is argued as having met the budgetary principle specified by Objective Five. In summary, upon the completion of Phase Five, the primary aim, along with all five principal objectives were considered as having been achieved.

Apart from the points mentioned above, further key findings established during Phases Four and Five were as follows:

- While host damage from the Zapper (Prototype B) device was notable, and initially considered as being highly problematic, damage done from a single large caterpillar was observed to be significantly worse than the discharge damage from this device, as evidenced by Figure 144 in comparison to the damage caused by multiple discharges at a single point as shown in Figure 121.

Figure 144. Damage from Single Large Caterpillar

- Use of the Gripper (Prototype A) on highly mobile specimens proved very difficult, suggesting limitations in its application under field conditions.
- Adjusting Gripper action to improve kill ability potentially resulted in decreased removal ability.
- The Zapper device had very limited removal ability and as with the Gripper, was difficult to use on highly mobile species, indicative of likely limitations regarding its field application.
- Zapper kill results were inconclusive, with variations in test outcomes difficult to explain, suggesting further study may be necessary to establish if application approaches play a significant role in device kill success, and if so, how application might be adjusted to maximise device effectiveness.
- The Zapper prototype had a clear lower test size limit, of approximately 2 mm x 2 mm, below which discharge would not occur. Insects of this size were noted to be pulled to one of the terminals, consistent with finding mentioned by Jobe et al. (2024), indicating electric fields had been known to be able to capture or repel insect specimens. It was identified that an opportunity for further investigation existed in this area.

- Whilst the Sucker (Prototype C) ultimately proved to be the most successful device, all developed prototypes showed some degree of success with respect to their overall *Removal Performance*.
- The Sucker device in its final prototype form was poorly suited to field testing in more remote locations. Further development to make the device more mobile is necessary to allow further and more robust testing of this device.
- Upper and lower limits of removal and kill ability were not fully established for either Prototype A or Prototype C, nor was an upper limit established for Prototype B, indicating a further area requiring greater investigation.
- The presence of parasitic wasps in the test plant plot during the project (see Figure 145 and Figure 146), was supportive of the selective nature of the device application having had no obvious negative impacts on beneficial insects, supporting the earlier conjecture (as stated in Chapter 2.3) that such devices could prove useful if utilised within an IPM system.

Figure 145. Parasitic Wasps in Broccoli Plot

Figure 146. Diseased/Parasitized Caterpillar

As a final note regarding the experiment performance, it is observed that despite good success with achieving the experimental aim and key project objectives, not all expected project outcomes were achieved. Specifically, the original outcomes aimed to achieve a final modified design proposal (based on learnings gained during the course of the project), able to be attached to an existing robotic arm. Whilst acknowledging this failure, which ultimately resulted from insufficient resource availability, the main impact of this deficiency is expected to have only slightly diminished the degree of success experienced for the primary aim, with proof of connectivity, and thus successful transition into a fully operational end-effector, yet to be established.

5.2 Limitations

A number of potential limitations were noted in the course of this project. Firstly, the nature of the experimental design was such that it clearly introduced bias due to the species of insects and life cycle stages chosen during the testing phase. While the original design proposal intended on testing a specific pest species and over a range of sizes (for example, Cabbage White Butterfly or Armyworm larvae or Heliothis), difficulties in locating and breeding such species, along with general issues around availability of large numbers of any single pest species, indicated a need for the experimental approach to be changed. Instead of testing a single species and life cycle stage, a variety of pest insect types were acquired during the preliminary testing phase to ensure sufficient test subjects were available. As a result of this, Objective Two was slightly modified to focus on a range of pest species, as opposed to single pest species. With timing of insect sourcing for preliminary testing being in winter, and a "trap crop" of broccoli being used to source these insects (along with other vegetation present in the author's yard including a White Cedar tree and numerous citrus trees), experimental results are noted as likely being initially being biased towards the successful elimination of the originally tested species and lifecycle stages, in particular Cabbage White Butterfly *(Pieris rapae)* adults, larvae and pupae, as well as Large Spotted Ladybeetle *(Harmonia conformis)* adults. During primary testing this bias changed towards successful elimination of the species used for this testing, Mealworm (*Tenebrio molitor*), larval and pupal stages, before changing back during follow-up testing, to being bias in the successful removal and/or elimination of Cabbage White Butterfly larvae, and adult ladybeetles (various species).

Though further testing of other pest species over spring and summer would have been ideal, and likely have provided a better assessment of general pest destruction effectiveness, limitations in project timing prevented this from occurring. It was furthermore noted that project time frames were such that species and lifecycle stage representation for the testing of the final end-effector prototypes varied from those utilised during prototype testing. As a result of a particularly cold period of weather just prior to primary testing (along with growth of the original host plants having proceeded past the optimal point for infestation by Cabbage White Butterfly, combined with the leaves of the White Cedar tree from which the Large Spotted Ladybeetles were sourced having fallen), there was no availability of the preliminary tested species. Due to lack of time, and inability to source significant numbers of equivalent species, the decision was made to instead perform the primary testing of the final prototypes upon Mealworms (*Tenebrio molitor*), an insect species readily available in bulk through most pet stores (see Figure 147). It is observed this species is from the beetle family (Family Coleoptera), whilst the Cabbage White Butterfly is of the Family Lepidoptera. Though noting the tested specimens to be of similar size and shape, as per Figure 148, it is recognised that due to morphological and physiological differences in their respective insect Families, some differences in the impacts of the prototypes would be expected.

With follow-up testing performed largely against the same types of insects as the preliminary testing, and observing that the general nature of the results of this testing was trending similarly to the results observed during the primary testing, it is assumed there was some level of similarity between the tested insect species with regards to end-effector impacts. From this, it is assumed that collectively the test results from Phase Four provided sufficient data to establish some level of design effectiveness for the respective prototypes (with regards to their likely ability in removing insect pests). As a result of this limitation, it is acknowledged that care will need to be taken around data extrapolation and any broader generalisations drawn from the experimental findings.

Project time availability was observed to play a significant role in project development and execution. With time restricted to between 1 and 2 days per week (approx. 10 to 15 hours on average), and significant amounts of this being required for test specimen collection, travel and attendance at external venues (in order to print the 3D printed components), during prototype development, there were limits around what was achievable in the available time. This, combined with seasonal issues, as previously described, resulted in the project direction not always following its intended trajectory, with greater time spent on early prototype development than originally intended, and less time spent on testing and analysis than originally hoped, with no time for further development and refinement of a final single device as originally desired. As such, project findings, while still deemed valid, are noted to be limited to the species and lifecycle stages tested, with significantly more work being yet required to complete end-effector development, before more definitive conclusions around end-effector success can be drawn.

Figure 147. Mealworm Adult

Figure 148. Mealworm Larvae (Orange) and Cabbage White Butterfly Larvae (Green)

Finally, a target budget of approximately $120 per device was set as the upper limit for the preliminary prototype development (reflected by a budgetary score of 0 where this was exceeded by more than $5, as per Chapter 3.1 – Phase 3), after noting the preliminary budget of approximately $40 per end-effector was insufficient to allow the meeting of project objectives. With one of these objectives being establishing the viability of a range of possible designs, a decision was made to instead set the total project budgetary constraints to be approximately $120 per device, to give a maximum theoretical outlay of $360. This limit was considered as allowing the meeting of the objective to develop and assess a range of end manipulators, without placing excessive limitations upon the project, whilst still allowing the project to meet the requirement of Objective 5 with respect to affordability. Despite this increase, budgetary constraints were still noted to be a significant consideration with respect to decisions around potential modifications, with available funding limiting the scope of changes.

In summary, it is acknowledged significant limitations existed with respect to the scope of this research project, largely as a result of constraints around resource availability, project duration and project timing. As a result of these limitation, care needs to be taken with regards to the nature and the scope of all generalisations and conclusions made, with fair consideration of: the impacts of limited funding (restricting the nature of the prototype development), the time of year and length of time over which testing occurred (restricting the length of time over which testing was able to be performed and the species available to be tested), and the limited access to numbers and species of insects able to be tested (limiting the reliability of the data and the applicability of the conclusions to just the species of insects tested, on the host plants described).

5.3 Challenges

During Phase One, *Build Performance* was established to involve significant interpretive requirements, with much of the data, and its relative importance (and thus classification), being highly subjective. In the process of completing this phase, concerns around the meeting of budgetary and other resource limitations quickly became apparent, with some modifications to preliminary assessment criteria required, so as to ensure the proposed project goals could still be met. This was primarily with respect to the initially prescribed budget for the project, of which over half was used just developing the first iteration of the first prototype. With concerns around the project being unable to meet key outcomes due to this, and after discussions with the project supervisor, total project budget was increased, and budgetary weightings adjusted accordingly (as previously described in Chapter 5.2). A similar issue occurred with respect to the preliminary build hours classification, which was initially based on what was assumed to be reasonable time allocations for the purpose of device construction. This assumption, however, failed to account for issues encountered during the 3D printing process, resulting in both increases in time frames being made for each category, as well as a decision made to ignore any time involved in preliminary problem solving, troubleshooting, and printing wait time, during the build process.

While some preliminary technical challenges were encountered during the design phase, with some difficulty in the initial sourcing of appropriate design software, and later with use of the 3D modelling software obtained (due to unfamiliarity with the particular package used), a free student copy of AutoCAD Inventor was eventually acquired, and relevant videos and tutorials around its use located and utilised. As per most challenges encountered, this issue was resolved through commitment of effort over time including online research, the asking of questions, along with the application of trial and error. Other challenges noted during the build concerned small errors in initial measurements, which were overcome through the use of a more accurate measuring device (digital callipers), as well as issues with insufficient allowance for size variations within the 3D printed models, which required changes to tolerance considerations within the 3D designs. Later issues arose when dimensioning of materials purchased did not quite match that of online descriptions of similar products, upon which the preliminary designs were based, requiring re-dimensioning designs to cater for these differences. There was also initially some overestimation of the strength and general performance of the 3D printing material used, which required further design changes, to help minimise deformation and maximise strength. As a final point regarding technical challenges, the 3D printing process turned out to be more temperamental than expected with numerous issues encountered, including breakages in the filament during printing (which the printer did not detect), difficulties in getting some parts to start printing (as a result of their shape), the print head clogging up on several occasions, difficulties in removing the required scaffolding on some parts after printing, and difficulties in accessing a sufficiently large 3D printer at one point, requiring assistance from the UniSQ Engineering department.

One of the most significant challenges experienced was obtaining sufficient numbers of an appropriate test species. Despite starting early, and attempting to establish a breeding caterpillar colony, such a colony was unable to be established within a fish tank as originally envisaged. The idea was disbanded after a month, having experienced virtually no success. After discussions with the project supervisor, a decision was made collect any type of insect available at testing time, as well as through use of a newly established broccoli plot as a future potential source of test pest specimens. Contact was also made with a local agronomist as to when pest insects might once again be available within the area and enquires made as to where these might be found. Ultimately, the decision was made to harvest/collect test specimens as required and to apply a randomised stratified grouping approach to these specimens, to help ensure results were comparable across devices and thus allow meaningful device comparison. At the time of testing, however, the weather was such that there were very few insects available, with attempts to collect specimens from lights at night failing due to a complete lack of insects and the broccoli plot only able to provide limited specimens. Those located in the broccoli plot were collected over a number of occasions, providing enough specimens to produce three small replicate test sets, which allowed for some preliminary testing. At this point another broccoli plot was established to help with host plant damage testing, and secondly in an attempt to attract more test specimens as the weather warmed. However, with the Sucker device incomplete, and a particularly cold spell of weather appearing to wipe out the remaining insects in the local area, a decision was made to resort to the utilisation of non-living test items of similar size and weight to the original test specimens. This allowed progression of the build until reaching a point where the device was showing significant potential, at which time the local insect populations were starting to recover. With time running short, and insufficient test subjects able to found, it was decided to do the primary testing on Mealworms. While not exactly a plant pest, these insect larvae still offered a means of testing and comparing all prototypes, so were deemed an acceptable substitute for the preferred Cabbage White Butterfly larvae (caterpillars). Allowing these to feed and grow, to allow testing to also occur against Mealworm pupae (thus aiding in the completion of objective two), sufficient specimens were acquired so as to allow testing of 20 mealworm larvae and 10 mealworm pupae per device. Upon completion of primary testing, a small number of Cabbage White Butterfly larvae had managed to establish within the test broccoli plot, allowing collection of sufficient specimens to do some follow-up testing (12 in total). This was combined with testing of the same number of ladybeetles, which though not the same species as the more harmful 28-spotted ladybeetle, were deemed similar enough to allow comparison as to likely effectiveness against this type of pest. Results of the follow-up testing, in combination with observations made during preliminary testing, were then used to help validate the results of the primary testing.

Despite the challenges, many of which resulting from the project's limitations, by the end of the project, three prototypes were successfully built, and sufficient test data was able to be obtained to establish clear trends. The methodology was such that all objectives were ultimately met, and the primary aim accomplished, with the project thus considered a success.

5.4 Error and Experimental Validation

While systemic error, in the form of measurement inaccuracies combined with limitations in 3D printing accuracy, has already been established as having occurred early on in the project, the primary effect of this particular error was to adversely affect the construction process. This was addressed through use of a measuring device with greater accuracy, and through relaxing the fitting tolerances, which ultimately negated all significant impacts of this error. Further systemic error was attempted to be avoided through the development of prescriptive descriptions for use with qualitative, judgement-based assessment of a variety of performance criteria. Through this approach, inconsistencies in performance score assignments between devices are expected to have been minimised. The other primary approach used to keep systemic error low during the project was through attempting to utilise equivalent samples (with equivalent numbers, sizes and distribution of subjects), during testing of the prototypes. Though it is believed the sample composition was such that it allowed fair comparison of the three devices, thereby minimising this aspect of systemic error, it is acknowledged that the test specimens used could not be considered as fully representative of typical agricultural "insect pests", and that conclusions drawn from the obtained results are thus unable to be more broadly applied to "insect pests" in agricultural systems.

Having utilised living specimens during most testing, there is an expectation that random errors will have occurred during this process. The variation existing in biological based specimens is essentially an unknown, and thus largely uncontrollable variable, having the potential to result in similarly variable results. Whilst typically this error is minimised through use of large and representative data sets, followed by application of rigorous statistical analysis, specimen numbers used during testing phases in this project are noted to have been relatively low, potentially allowing random error to have had a significant impact upon the data and its interpretation. The most significant impact of this random error is that reproduction of results of a similar nature when repeating the described experimental procedure may prove challenging and thus has the potential to undermine the validity of the experimental results.

A further consequence of using living specimens relates to the timing and the location of the experiment, with many biological species noted as experiencing seasonal and regional variation. As such, it would be important to consider these factors during any follow-up experimentation, recognising these factors as having the potential to significantly impact the nature of specimen acquisition.

5.5 Methodology Considerations

Examination and reflection of the methodology to improve experimental outcomes (with consideration of the available resources and limitations as previously described), identified two primary areas where it is believed changes could have been made. These being:

- Clarifying supervisor availability earlier, thus allowing confirmation and commencement of the project earlier. *Doing so would have provided more time for the execution of the project, potentially having resulted in better test specimen availability, thus improving the quality of the data able to be collected*; &
- Focussing on the development of a single device to improve resource availability for that one device (i.e. time, capital, and specimen availability). *Through dedicating all available resources to a single device this would have allowed greater progression of the project aim, significantly aiding in the ability to meet the project outcome of designing and building an end-effector able to attach to an existing robotic arm*.

Ultimately, these changes would have improved resources availability for device development in terms of both budget and time. Through a more focussed approach, greater success in successfully completing the design of an end-effector able to be attached to an existing robot arm could have been realised. It is important to note that this would have required revision of the project objectives and remaining project outcomes to be more focussed around single device development. Consequently, the ability to design and test a range of devices, as achieved by the existing methodology, would have been sacrificed.

Had greater capital, more time, and better access to the University (or potentially Agricultural Research Facilities), been available, some further changes that would likely have proved of benefit to the project outcomes would have been:

- Personal, 24-hour access to a 3D printer, so as to improve design change and iteration turn-around time, thus helping overcome some of the experienced limitations regarding time availability;
- Obtaining a greater number of more relevant species for testing. Potential mechanisms to do this including:
  - Purchase/Access to, and use of a small greenhouse to help reduce the impacts of the weather on the test plot, thereby improving availability of the preferred test species; &
  - Seeking assistance from an entomologist (or agricultural research organisation), regarding the best way to establish or to access the types and numbers of test specimens required (acknowledging that this would have required seeking assistance from outside of the UniSQ Engineering department and potentially even from outside of UniSQ). Furthermore, through gaining greater understanding around appropriate testing methodologies for use with insect specimens.
- Completion of testing for a period of 12 months or more, so as to allow examination of impacts on different pests as well as examination of any potential seasonal differences in end-effector application on different insect pest types.
- Examination of end-effector impacts throughout the entire life cycle of a range of insect pest species, so as to help identify where in the lifecycle, end-effector application may have best effect, as well as allowing for examination of long-term impacts of end-effector application upon pest populations.
- Upon obtaining larger and more representative sample sets, to improve data analysis through seeking assistance from a biometrician, to initially aid in checking and adjusting the experimental design for suitability (especially with respect to the acquisition of quantifiable data), and then through development of better statistical analysis of the data (acknowledging that this may require seeking assistance from the UniSQ Mathematics department).
- Completion of the original plan to use obtained results to further develop one or more of the end-effectors through to the point at which it/they could be attached to a robotic arm.

In terms of other potential methodologies, it is acknowledged that a small-scale laboratory simulation using the constructed prototypes would have offered an alternative to the approach used. This however would have been contingent on the availability of such an environment, and upon this having been established with appropriate host plants and pest specimens prior to testing (potentially requiring access and use of an associated experimental greenhouse). That said, the benefits of a more controlled environment, where a single pest species was used with a single host plant species, where the impacts of predators, competitors, disease, environmental extremes, etc. could be minimised, are noted as likely being high advantageous in helping improve the ability to replicate and thus validate experimental findings of a project of this nature, whilst also helping to ensure that results and conclusion could be more clearly linked to respective end-effector usage. Whilst limiting the scope, and requiring greater refinement and narrowing of the project objectives, such an approach would be consistent with prior studies of a similar nature as identified during the literature review - the first simulating the application of a small laser to ground based armyworms (Obasekore et al. 2019), and the second applying lasers to aphids in potted plants (Lacotte et al. 2022).

While another alternative methodology that could have been considered was the use of computer simulations of the interaction between digitally modelled end-effectors and pest specimens, a lack of knowledge and experience in this particular field, along with a lack of necessary software, and access to sufficient computing power able to perform such simulations, made such an approach untenable. Furthermore, results from such simulations, which would have involved digitally representing the behaviour of living specimens, would be expected to have provided data of a much lower quality than that gained through the real-world testing of the interaction between the end-effectors and targeted insect species. This is based on consideration of the difficulties likely faced in accurately modelling the respective insects' behaviour as well as that of the insect-plant interactions and the prototype-plant interactions, all of which would have influenced the prototype-insect interactions and associated outcomes.

5.6 Project Conclusions

As established in Chapter 2, five research questions were ultimately derived through consideration of the literature review findings in concert with the project aims, objective and desired outcomes. These questions, as well as their answers, in consideration of the project performance analysis and findings previously discussed (as per Chapter 5.1), are as follows:

1. ***Is it possible to develop an end-effector prototype, capable of selectively removing and/or killing insect pests, that does not require the use of pesticides, and if so what types of technologies might be suitable for use in achieving this?***

   It can be concluded that this first research question has been answered in the affirmative, with it having clearly been established that the development of an end-effector capable of selectively removing and killing insect pests is a feasible proposition. This is evidenced firstly by the project accomplishing the goal of developing a number of non-chemical based end-effector prototypes; and secondly, with two of these devices demonstrating consistent success with insect removal and killing capabilities. Furthermore, all devices developed proved able to selectively target test specimens to a reasonably granular level, establishing that targeted non-chemical approaches are possible to produce in end-effector prototypes.

   While it is acknowledged that this same question was largely answered through the 2022 Lacotte et al. study, this project has established it is possible to do so with devices other than lasers, whilst also demonstrating alternative modes of operation that may prove successful against a greater range of species than those of the original study (with the Lacotte study laser based end-effectors having been identified as specific to a species of aphid against which they were tested against). Specifically, the technologies clearly identified as being suitable for use in achieving the desired insect control included a mechanical gripper based approach and a vacuum or suction based mechanical device with an incorporated fan. While the use of electric field based technologies also showed some evidence of suitability for use with insect control, further support, and thus study, was identified as still being required to confirm this.

2. ***How might mechanical, electrical or vacuum based non-chemical approaches be incorporated into a functional end-effector prototype with the ability to help control insect pests?***

Through integration of a micro servo within a relatively small 3D printed device, able to be easily manipulated and manually triggered to grasp an insect on a leaf, the Gripper device was able to clearly establish its potential for development into a mechanical based end-effector. With testing against Mealworm larvae proving the device well suited to insect removal, and testing against Cabbage White Butterfly larvae and ladybeetle adults also showing the device as having significant pest killing ability, the Gripper device clearly established its potential viability as a pest control mechanism.

Similarly, the integration of an existing electric charge generator within a simple 3D printed device, also able to be easily manipulated and manually triggered to target an insect on a leaf, established the Zapper device as having some potential for development into an electric-field based end-effector. While testing against a range of insect types indicated poor removal ability and inconsistent kill ability, the Zapper device did manage to successfully kill some test specimens, thereby indicating a degree of functionality and potential viability, though with significant development and research still needed to establish both the ability, and associated proof, to confirm its ultimate suitability as a pest control mechanism.

A vacuum based approach proved far more difficult to develop into a small, easily manipulated device. This said, through integration of a relatively simple fan-based device with a compressed air system, and some 3D printed elements, proof of the concept was established, with a medium sized device, able to engage in selective pest control, ultimately designed and constructed. Significant development of this concept, in terms of reducing its size and improving its ability to be connected to a robotic arm were, however, identified as being required before it could truly be considered suitable as an end-effector. Despite having the lowest *Build Performance*, the Sucker prototype demonstrated strong insect pest control potential, with the best *Removal Performance* of all devices, thus establishing its high level of functionality and pest control ability.

Collectively, it can be concluded that, through use of an iterative, design-based approach, mechanical, electrical and vacuum based devices were successfully able to be developed and built. Through testing, constructed prototypes were also observed as having achieved some level of success in insect removal, establishing this research question as having been partially answered. It is acknowledged, that further research, along with further design changes and testing, is still required before this question can be fully answered. Furthermore, considerations regarding potential design approach variations may also need to be considered where control efforts are applied against insect types other than those tested by this project. This said, in partially answering this question, this project can be seen as having provided some preliminary work around the control of insect pests with vacuum based, mechanical and electrical means, all areas identified as previously having limited representation in the literature, particularly in relation to agricultural RAS.

3. ***Does any one of the mechanical, electrical or vacuum based approaches, have better potential in controlling all insect pest types, when incorporated into an end-effector prototype or are particular end-effector prototype approaches better suited to particular insect pest types?***

During the establishment of device viability through testing, the vacuum based device (the Sucker), proved to have the greatest overall insect control ability, with the final developed iteration of this device consistently outperforming both other devices in removal ability and kill ability, across all species tested. Furthermore, this device showed no lasting damage to host plants after application. Support for this superior performance is clearly evidenced through examination of Figure 131, (relating to the primary testing with Mealworm larvae and pupae), as well as Figure 141 (relating to the follow-up testing with adult ladybeetles and Cabbage White Butterfly larvae). Despite poor *Build Performance*, the superior *Removal Performance* of this device, resulted in it having the best overall performance, as established in Chapter 4.6.1, with a weighted performance score of 18/24 compared with 13.9/24 for the next best performing device (the Gripper), during primary testing. This result was replicated in principle with the follow-up testing results, the Sucker device scoring highest at 17.25/24 compared with 16.33/24 for the Gripper, thus confirming its status as the best performing device overall, across all insect types tested.

Whilst establishing the vacuum based approach as having the best potential for controlling all insect pest types, analysis of the data was also supportive of particular end-effector prototypes as being better suited to particular insect types. Evidence of this was clearly demonstrated in Chapter 4.6.2, where there were noted performance difference observed for each of the prototypes when examined separately against pest type. Specifically, examination of Figure 143 clearly established a noted performance difference in the Gripper device between its performance against Cabbage White Butterfly larvae and its performance against Mealworm larvae, with a 14% improvement noted when utilised against the Cabbage White Butterfly larvae. Similarly, an 11% difference between application of the Zapper against these same two insect types was noticed, however, this time with a drop in performance against the Cabbage White Butterfly larvae. Finally, a small difference in effectiveness of the Sucker device was noted when it was used against adult ladybeetles, with a 6% drop in overall performance being observed. Drilling deeper into the noted differences, it can be observed that these results are directly related to the respective removal and kill abilities of the various devices against the different insect types, with all other parameters remaining constant.

With no comparable studies of this exact type identified, primary considerations of these findings, with respect to those found in the literature, are that this study has clearly established vacuum based technology incorporated with RAS offers far better specificity than that currently observed within systems such as those being produced by Micothon (Micothon n.d.) and the tractor mounted rigs mentioned by Koger's 2023 study. Furthermore, the findings of this study have clarified likely cause of death of impacted pests to be a result of physical trauma resulting from impact with either the vacuum passage walls, or the driving fan. With respect to the 2022 Lacotte et al. study the project results are supportive of specific approaches (and thus associated end-effector devices), being required to maximise removal performance for specific species, similar to what was noted in the previous study regarding use of particular laser types and frequencies, to maximise lethality against different aphid species, whilst also minimising potential for harm to the host plant. As previously alluded to, despite some work having been done around use of laser-based pest control, with only two species of aphid examined by the Lacotte study (2022), and a further single lifecycle stage of the armyworm examined by the earlier 2019 Obasekore simulation, far more work examining the use of laser based pest control systems and its effectiveness against different pest species and life cycle stages is still necessary to help better confirm exactly how effective different types of lasers may be in the control of particular insect pests.

As a final point, it is noted the results of this study are indicative of more broadly acting end-effector devices (in terms of specificity to particular pests), being possible for use with RAS based insect pest control. In conclusion, it can be stated that the project ultimately indicated the vacuum based end-effector prototype as having the best potential for insect pest control across all examined species, as well as strongly supporting the concept of particular end-effectors being better suited for the control of particular insect types. Further testing of more fully developed devices against greater numbers of specific insect pest species, at different stages in their lifecycles is, however, still necessary for two reasons: Firstly, to better establish the exact nature of the relationship between different end-effectors and their relative effectiveness against specific insect types; and secondly, to establish the extent of respective end-effector actions, to better prove their effectiveness against "insect pests" more broadly.

4. ***How can pesticide-free, insect controlling end-effector prototypes be optimised to improve their insect pest removing and/or killing performance****?*

   Through application of an iterative-based design methodology, using testing as stimulus for design change, the overall success of this project, in creating functional prototypes, has established this approach as being a viable path for device optimisation. Of specific note were the numerous iterations of the Sucker device, which despite still needing significant development, was able to be optimised via such an approach, such that its overall removal and kill ability changed from being almost non-existent, through to being the best performer in these two areas.

   Whilst acknowledging the role of simulations in the optimisation process, it is believed that as a result of insect controlling end-effectors ultimately being required to be used on living things in complex environments, the accuracy of results achieved through such simulations is likely to be questionable upon moving past the preliminary device design phase. This is particularly true of digital simulations, which would require the use of massive amounts of species-specific data, including behavioural analysis and predictive modelling, in order to be able to appropriately and correctly emulate pest-insect responses. With a large number of variables also needing to be considered, along with the way in which these variables are likely to interact (with the end-effectors, the pest species and each other), as well as how device application may impact other non-target species (thus requiring these to also be included within any such simulation), significant processing power and software development time, and thus high costs would also likely be required, potentially negating any savings made through reduced need for field testing.

   Despite the need for better access to large numbers of a variety of insect pest species in order to ensure high quality results, it can be concluded that an iterative design-based methodology combined with species specific testing (both laboratory and field based), provides a sound mechanism for the optimisation of pest removing/killing end-effector type devices. The use of species-specific testing combined with ensuing device modification and optimisation, is noted to be consistent with the approach utilised by Lacotte et al. (2022), whose report indicated significant work having been done prior to their study to optimise laser effectiveness against the chosen pest species, whilst at the same time ensuring minimal damage to the host plant.

5. ***Is it possible for a pesticide free, insect controlling end-effector prototype to be developed and built relatively cheaply, utilising readily available components, tools and technologies, and if so, how might this be achieved in a safe manner?***

   Whilst more work is still needed to prove the developed prototype devices can be modified, attached to, and utilised by, a robotic arm, and further work to improve the effectiveness of Prototype B (the Zapper) is required, this project has clearly established that the basis of such devices can be produced relatively cheaply and easily, within a home workshop, utilising parts readily available from electronic stores, provided access to a medium sized 3D printer exists. While the requirement of some equipment (such as the air compressor utilised within this project), may add to the overall expense of such a project, the pricing of such items, as previously established, could not be considered as being overly prohibitive. Furthermore, these items are noted as being easily acquirable, as well as a comparatively small expense (with respect to the total cost of a RAS based agricultural implement). This said, with further research and development, an alternative to replace the need for this particular item may well be established, potentially making this point moot.

Though the multiple iterations and relatively high cost (compared to the other developed prototypes), required to make the vacuum based prototype fully functional is somewhat supportive of claims presented by Keupper's 2003 work (suggesting such devices as being expensive and lacking in efficiency), the successful ability of this device in both removing and killing insects indicates that further efforts in the development of devices similar to Prototype C (the Sucker), are well justified. It is further noted that while initial costs of any new technology may be relatively high, with time, and with greater levels of production, costs typically fall, and efficiencies typically increase, making it difficult to justify not investigating options where costs are marginally higher than desired.

From a safety perspective, with the most dangerous activity required during the course of this research being the soldering, and all identified risk easily mitigated through the use of simple control measures, PPE and common sense, there was no point at which risk was considered as being more than low. Operationally, the devices themselves were also low risk, with the most dangerous undesired outcome during device operation being a small and localised shock from the Zapper terminals. In consideration of these points, there is clear support of the development and build processes used as having been safe.

In terms of how the risk level was able to be kept low during the development and build of the prototypes, this can be contributed to the use of appropriate risk management strategies. Specifically, through:

- Identification of potential hazards.
- Assessment of all key risks, through assessing the likelihood of the identified hazards causing harm.
- Management of identified risks through the application of appropriate risk management strategies, including use of the following hierarchy of controls: Elimination, Substitution, Engineering Controls, Administrative Controls and, where other options proved inadequate, the use of PPE (as per WorkSafe Victoria 2022).
- Ongoing monitoring, assessment, review and application of risk management strategies as required.

Ultimately, it can be concluded from the evidence presented that potential for the safe, simple, and relatively cheap development of non-pesticide based end-effectors currently exists. Furthermore, it is evident all the necessary technologies, materials and safety protocols necessary for such development are already in existence and readily available.

In summary, it is apparent through the meeting of the project aim and objectives, all five research questions were successfully addressed over the course of the research, though admittedly, to varying degrees, and with limitations, as described. Of significance, in consideration of the literature review findings, it is clear that in addressing these specific questions, this project has contributed positively to the work existing within this area, having begun to address a number of the identified gaps in the research, and helping to advance the field of non-pesticide RAS based insect pest control. Finally, it is clear there is still much work required within this area, and many opportunities still present for further research.

5.7 Project Implications

While an attachable end-effector was not ultimately produced by this project, it never-the-less succeeded in establishing a range of non-chemical insect control approaches existed with strong potential for development into such a device. The successful creation of such an end-effector, particularly one able to dispatch a wide range of insect pests, would significantly advance the goal of achieving pesticide-free insect control. In establishing this possibility, the project has made contributions towards a number of the United Nations Sustainability Development Goals. Specifically, by providing potential mechanisms to remove the need for pesticide based control of some insect pests, this project has contributed to:

Goal 3. Good Health and Wellbeing – through its potential in reducing pesticide exposure for agricultural operators as well as for those who consume/use agricultural products.

Goal 9. Industry, Innovation and Infrastructure – through providing an innovative approach for insect control that is inherently more sustainable than use of pesticides and their numerous problems and side-effects (toxicity, genetic damage, bioaccumulation, development of resistance in pest species, etc.).

Goal 12. Responsible Consumption and Production – by aiding in achieving more sustainable production by helping to reduce the need for pesticides in agricultural production systems, thereby decreasing associated chemical risks.

Goal 15. Life on Land – through providing a mechanism that not only reduces the need for pesticides, but one that also allows targeted removal of insect pests, thereby reducing the negative impacts of pesticides on other living things.

Furthermore, in consideration of the continuation of the development of this technology, it is believed that it is currently not far from the point where end-effectors of this nature, attached to robotic arms on field robots, could be integrated with a camera system, potentially allowing remote control of the end-effector so as to facilitate the remote destruction of insect pests. Success of such an approach would clearly prove robotic insect control without chemical use, or the on-site presence of a human, was possible, and in doing so would provide a potential mechanism for the sourcing of "manual" labour for the purposes of insect pest control, largely independent of worker location. Whilst it is difficult to establish how far this sort of technology could advance from this point, the potential for gamification of such systems to help motivate remote operators is also something that could be considered, as is the collecting of data from such remote operators, which could ultimately be used to train AI to complete these same types of tasks, and eventually help in the creation of AI driven RAS based insect pest control.

Even if it is assumed that AI does not become involved within agricultural RAS based pest control in the near future, the combination of the latest advances in RAS with the successful advancement of non-chemical based insect controlling end-effectors, suggests a clear path to the realisation of fully RAS based chemical-free insect pest control systems exists. Conceivably, upon establishing the success of remotely operated systems, the next step would involve the use of robot mounted cameras being integrated with robot vision systems (currently being developed to better identify insect pest species, as discussed in Chapter 2), along with associated control algorithms, to produce a technology able to autonomously control insect pests without use of pesticides or direct human intervention. Whilst admittedly there exists considerable work to be completed in the areas of pest identification and the automation process before such a system could be fully realised, significant progress is already being made around pest identification (as previously described, through the works of Dawei et al. (2019) and Barnes et al. (2022)), as well as with automation (through the use of DL and ROS based architectures as per Martin et al. (2021)).

As with almost all technology, it is acknowledged that such approaches, while solving problems at one level, typically come with inherent risks. What is important, is to ensure any benefits gained through the adoption of such technologies, on balance, outweigh any negative impacts. While the use of an insect destroying end-effector with a field robot, as envisaged, provides clear benefits with respect to reduced pesticide usage, and potentially helps alleviate some of the earlier identified labour issues (as discussed in Chapter 1.1), it is recognised that construction and maintenance of such robots would result in increased demand for other resources. It is furthermore acknowledged that obtaining these resources would potentially result in other forms of environmental damage. Many robot batteries, for example, require Lithium and Cobalt, both which must be mined and can be dangerous under specific circumstances. It is also possible the use of such robots would add to production costs and thus increase food prices, creating issues around access and equity. Other unintended side effects could be the inability of small operators to compete against those able to afford this technology, as suggested by Sparrow and Howard, in their 2021 paper examining how agricultural robots may impact our society in the future. Should such a thing occur, this could result in a dominance of farm ownership by larger companies, whose primary concern may be profits over stewardship. This would be extremely disruptive for many farming communities and could potentially lead to other significant issues, such as mass modification of landscapes to better suit robot operation (Sparrow & Howard 2021), and lack of local job opportunities, particularly for less technically orientated workers. Ultimately, at such an early stage in the introduction of this technology, it is difficult to predict whether robots in agriculture will, in the long-term, help contribute positively towards more sustainable agricultural practices, or in fact, be the antithesis of this, through aiding in the monopolisation of the agricultural sector by distant, large and wealthy organisations.

In conclusion, there are many unknowns, and no easy answers, as to the long-term implications of the advancement of robotic technologies in agricultural pest control. What is known, is while agricultural pests need controlling, the continued exposure of the environment, our farm workers, and the wider population, to the chemicals we currently use for this control, is unsustainable. Though acknowledging the use of non-chemical based end-effectors on agricultural robots for insect pest control is no panacea to this problem, it is believed that the results of this project have helped establish that the development of such devices are possible, and that these devices have the potential to provide at least a partial solution to the growing issues being caused by pesticide use. More specifically, through the development of three non-pesticide based pest controlling prototype end-effectors, it is hoped that this project has helped prove achievement of more sustainable insect control practices within the agricultural space is attainable.

As a final note, it is believed that while more work is clearly still needed within the non-chemical RAS based insect control space, sufficient evidence now exists to support more closely examining how non-chemical based end-effector use, combined with RAS, could be incorporated into future IPM strategies. Through doing so, a way to significantly help reduce the use of pesticides and its associated risks within agriculture clearly now exists, offering a strategy that would help reduce the exposure of farmers and farm workers to pesticides, while at the same time helping to reduce the amount of pesticide residues present in our food, fibre, and environment, benefiting not only humanity, but all life upon our planet.

CHAPTER 6: RECOMMENDATIONS

Further to, and largely in alignment with the previously mentioned suggested changes in methodology (as outlined in Chapter 5.5), there are a number of recommendations that have arisen from the completion of this project. It should be noted these recommendations are aimed at enhancing this project's primary aim of progressing the development of robotic end-effectors able to remove and/or destroy insect pests without the use of pesticides. It should furthermore be noted, that the following recommendations assume the existing project's limitations (as described earlier in Chapter 3.5.2), are able to be addressed through accessing significant financial support (either through government or industry based grants), better access to laboratory and field-testing facilities (through working in association with government, university or private sector research groups), better access to test specimens (both with respect to variety and quantity of specimens), as well as significantly greater time availability (in terms of hours of time per week and overall project duration).

First amongst these recommendations is to more widely and thoroughly test the existing devices, to establish their general effectiveness against a larger range of pest insect species, with the specific objective of establishing which device proves most effective against which pest species, and to better determine the breadth of application for each of the existing devices. Through the application of more thorough testing, via treatment of much larger numbers of test specimens (thus limiting the impacts of random error), greater confidence in the accuracy of the experimental data can be achieved, helping to further validate the preliminary findings as presented within this report. Through targeting more representative samples of insect pests, the scope of any generalisations drawn from the data should also be broader, allowing conclusions to be established that are more widely applicable than those currently able to be derived from this project.

A further related recommendation is to examine effectiveness of each device against tested pest species over greater timeframes. Specifically, it is believed that a better understanding as to the fate of treated insect pests, well beyond the 24-hour timeframe used during the primary and follow-up project testing, is likely to provide highly beneficial information in terms of long-term impacts on pest populations from the use of such devices. In support of this were early observations indicating that the electric charge-based end-effector (the Zapper), while not producing the best immediate results, had some ability in interfering with normal insect lifecycle development. The significance of this is that if lifecycle disruption can be deliberately inflicted upon a pest species, whilst immediate crop damage may still occur, the broken lifecycle would likely reduce insect pressure on the crop over the long-term.

A recommendation particular to the development of the vacuum based end-effector (the Sucker) is a redesign that incorporates an equally sized (or smaller), but more powerful fan for the development of the suction force (for example use of a small powerful electric motor with a model airplane propellor). It was noted that of the three devices developed, this device was least suited for attachment to a robotic arm, being much larger than desired and requiring access to a compressed air supply. Provision of an equally rapid air flow (and thus region of sufficiently low pressure to generate the necessary suction), would help facilitate the removal of the air compressor component thus reducing end-effector size and improving the device's potential for integration with a robotic arm on a field robot.

A recommendation specific to the Zapper device relates to the approach used by Lacotte et al. (2022), to refine their laser-based end-effectors, prior to trialling the in-field effectiveness of these devices. It is proposed that a similar approach be used in developing the electric field (EF) being used by the Zapper prototype, to better understand both the operation and effectiveness of such fields against different pest species and lifecycle stages, whilst also examining the impacts of different methods and positioning of EF application, prior to their incorporation to an end-effector. This is noted to be in line with the 2024 Jobe et al. recommendations around the need to improve knowledge around EF-insect interactions.

With regards to the different forms of end-effectors, it is recommended that initially a single pest species be targeted, with use of the end-effector proved to have the best overall insect control results. Upon achieving success with this approach, further species potentially suited for this same end-effector could be added into the pest removal regime. Where a particular species or life cycle stage showed poor device success during testing, consideration of the relative effectiveness of alternative end-effectors could then be undertaken, so as to determine (via testing) the most appropriate end-effector for their control.

A final recommendation would be to continue to develop all end-effectors further, such that attachment of each to a robotic arm is simple and achievable, thus completing the final unrealised outcome of this project. Upon completion of this, further experiments are recommended to confirm core functionality has been maintained, with manually controlled local testing of developed end-effectors performed against key pest insect species, to help validate the preliminary findings and prove their successful ability to be integrated within a robotic framework. Ideally, assuming the devices proved to be successful at this stage, further testing via remote operations, using video camera feeds and remote user input to control device application, could be performed to further establish proof of the concept. Upon perfecting this, the aim would be to adapt the robotic system further again, taking out the remote user and replacing the identification and location functions of the remote user with robot vision and an algorithm driven, automated pest removal process.

While further clearly remains to be done within the RAS insect control space, ultimately, despite considerable limitations, this project can be seen as having met its primary aim of helping to advance the state of robotic technologies, with respect to their ability in providing a potential solution to the growing problem of chemical use in the control of agricultural insect pests. Through the exploration of manual removal, electric field manipulation and pressure derived removal control approaches, embedded within end-effector devices, all proving to have the ability to be highly target specific, this project has played an important role in helping improve the compatibility of RAS and IPM based systems, helping address some of the research gaps identified within the existing literature. By attempting to address these research gaps, it is hoped that more effective and environmentally sustainable pest management solutions will ultimately be realised within agricultural systems.

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APPENDIX A – RISK MANAGEMENT PLAN

1640	RISK DESCRIPTION	STATUS	TREND	CURRENT	RESIDUAL
	Development of end-effector for non-chemical control of insect pests	Live		Low	Low

RISK OWNER	RISK IDENTIFIED ON	LAST REVIEWED ON	NEXT SCHEDULED REVIEW
Stace Rummenie	19/04/2024	22/04/2024	22/04/2025

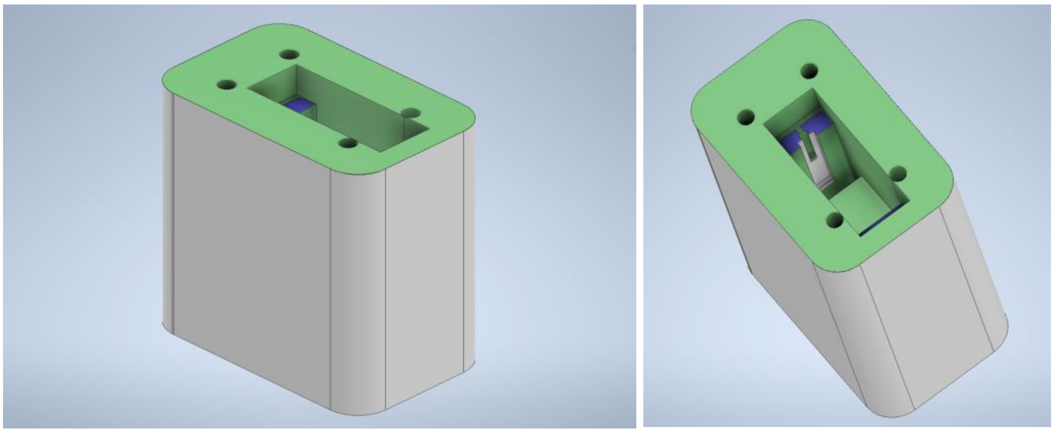
RISK FACTOR(S)	EXISTING CONTROL(S)	CURRENT	PROPOSED CONTROL(S)	TREATMENT OWNER	DUE DATE	RESIDUAL
Use of insects for testing. Use of plant material (lettuce/cabbage leaves) for testing.	Control: Avoid use of stinging and biting insects during testing. ____________ Control: Use gloves to avoid risk of allergic reaction to organic material and to minimise likelihood of stings.	Low	No Control:			Low
Use of either 12V adapter or battery packs (<= 12V). Development and use of current carrying devices. Development of current carry device with exposed wires (bug-zapper prototype). Use of electric soldering iron.	Control: Bug-zapper prototype to use double switch mechanism in order to allow operation. One switch to power up, a second one that must be held in order for current to flow. Capacitor used to generate high voltage but low current. ____________ Control: Insulate all exposed wires and cover any potential contact points in prototypes (apart from active tip of bug-zapper prototype). ____________ Control: Any 12V adapter used to be new or tagged and tested. Solder station to be new or recently tagged and tested. All batteries to be inspected for damage and not exposed to excessive heat or moisture during use. ____________ Control: Avoid contact with exposed wires. ____________ Control: Warning labels to be affixed to bug-zapper prototype to advise of shock potential if used inappropriately. ____________ Control: Wear rubber gloves to minimise chance of shock due to accidental exposure.	Low	No Control:			Low
Working alone in home workshop during construction of manipulator prototypes. Working alone in laboratory during testing of prototypes.	Control: Undertake induction at USQ laboratory prior to utlising this facility (should this be identified as being required). ____________ Control: Confirm workshop or laboratory in good working order prior to use. Check all exits clear. Ensure required safety equipment (eg fire extinguisher) is present. Inform someone else if working alone.	Low	No Control:			Low
Use of exposed very hot soldering iron, with potential for minor burns through accidental exposure.	Control: Appropriate experience and use of soldering iron. Care taken with use of soldering iron to minimise chance of materials being ignited or burns being caused. Ensure no combustible materials in vicinity of soldering area. ____________ Control: Wear leather gloves when working with hot wire/solder. Wear safety glasses if soldering.	Low	No Control:			Low

Use of lead during soldering.	**Control: Use silver solder instead of lead solder to reduce level of lead exposure.** ______________ **Control: Ensure quantities of solder used are minimal and that ventilation is adequate.**	**Low**	**No Control:**			**Low**
	Use good work hygiene to minimise contamination and possibility of lead exposure. Do not eat or drink or store food or utensils near the soldering area. ______________ **Control: Collect excess solder in labelled waste container and hold until able to dispose of as hazardous waste (noting level of waste solder expected to be <1 g and if using silver solder, lead contribution will be significantly less than this).** ______________ **Control: Wear long sleeved shirt, long pants and fully enclosed shoes. Wear safety glasses while soldering.**					
Gripper prototype will have the potential to pinch. Vacuum prototype will contain rotating fan blade.	**Control: Use low power motor to drive gripper to ensure unable to generate sufficient force to cause injury to people. Encase fan blade in chamber to ensure direct physical interaction with fan blade is not possible.** ______________ **Control: Apply labelling to gripper prototype warning of potential for pinching. Ensure prototypes not accessible by small children.** ______________ **Control: Wear safety glasses when working on prototype containing rotating fan blade.**	**Low**	**No Control:**			**Low**
Indirect effect possible where an individual attempts to avoid being pinched or zapped by prototypes. Noting this would only occur in the event of inappropriate use of the	**Control: Prevent access to prototypes by small children and remove batteries/power supply when not using/testing.** ______________	**Low**	**No Control:**			**Low**
prototypes.	**Control: Adherence to standard workshop and laboratory standards with regards to behaviour.**					

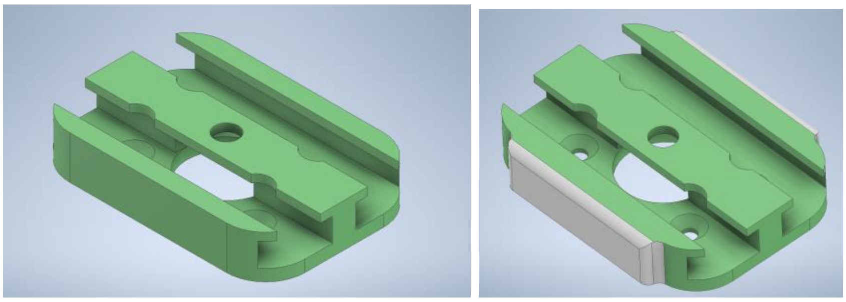
APPENDIX B – PROTOTYPE DETAILS

B.1 - Prototype A: 3D Printed Component Rendering

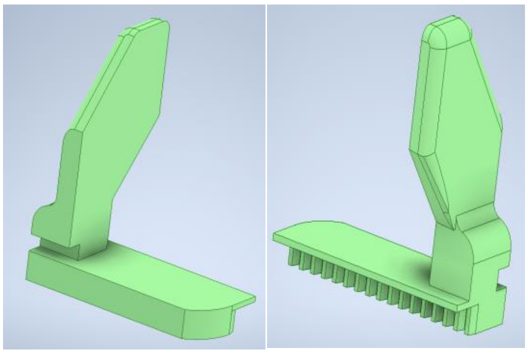
Servo Support Base (Original and Final):



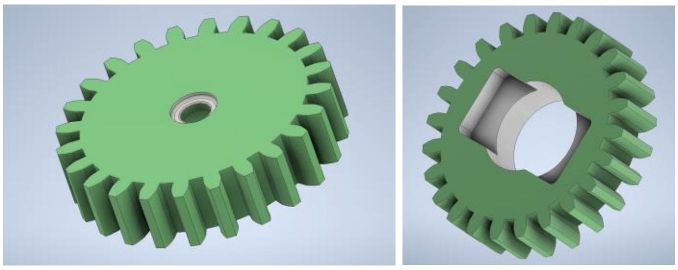
Rail Base (Original and Final):



Arms:

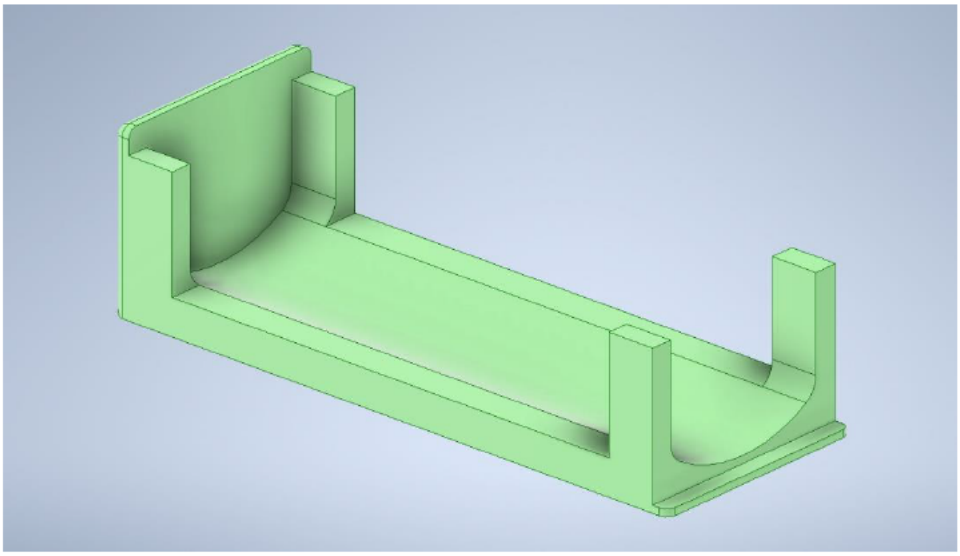


Spur Gear (Original and Final):

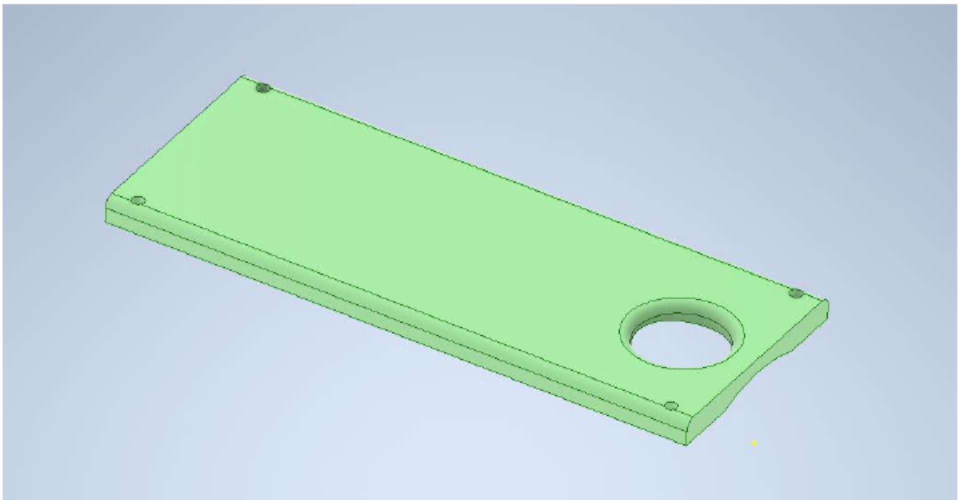


B.2 - Prototype B: 3D Printed Component Rendering

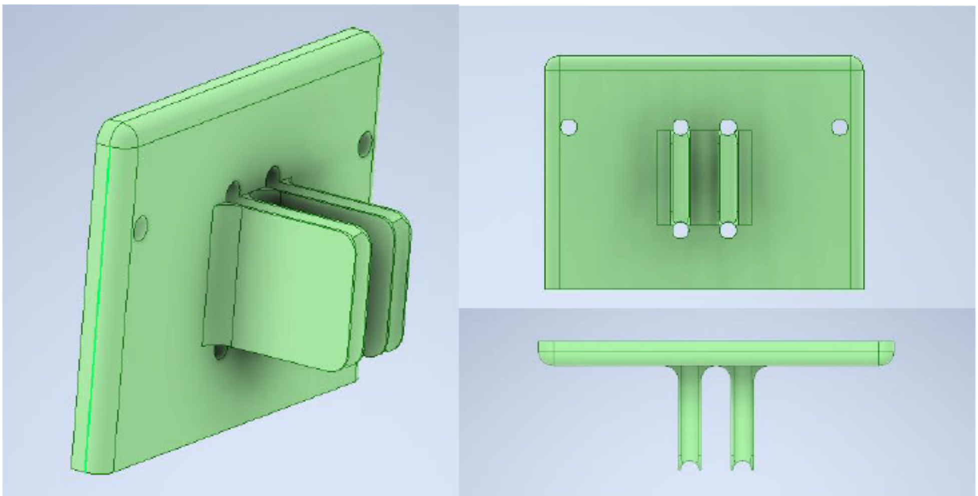
Zapper Bottom:



Zapper Top:



Zapper End Plate:



B.3 - Prototype C: 3D Printed Component Rendering

Plate 1:

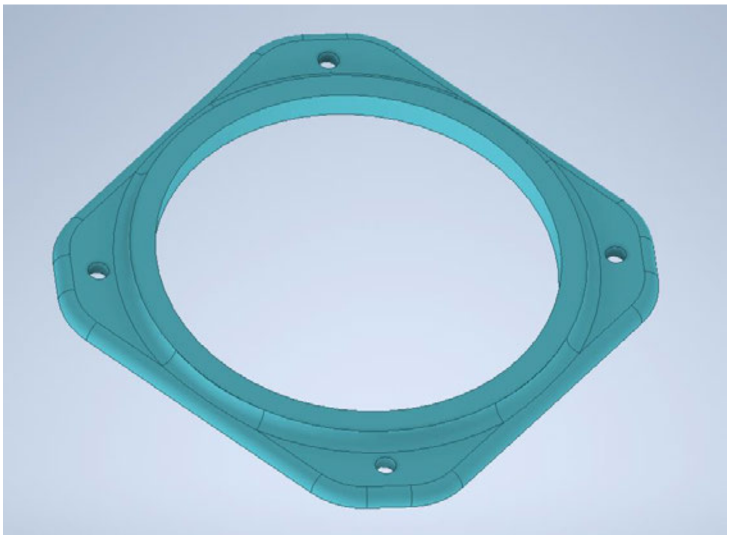
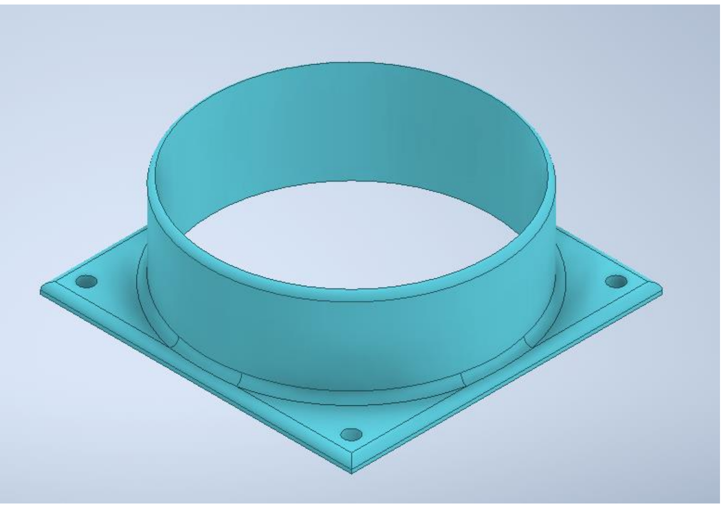


Plate 2:



Nozzle - Original (1) and Final (2):

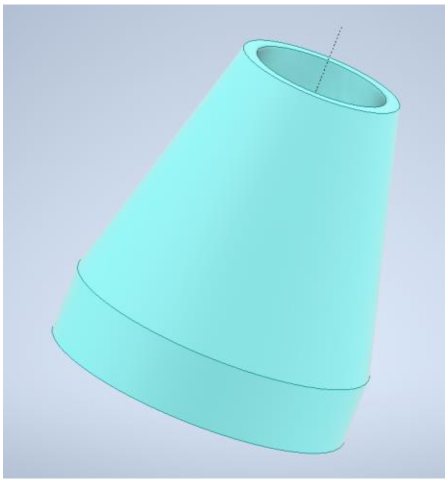
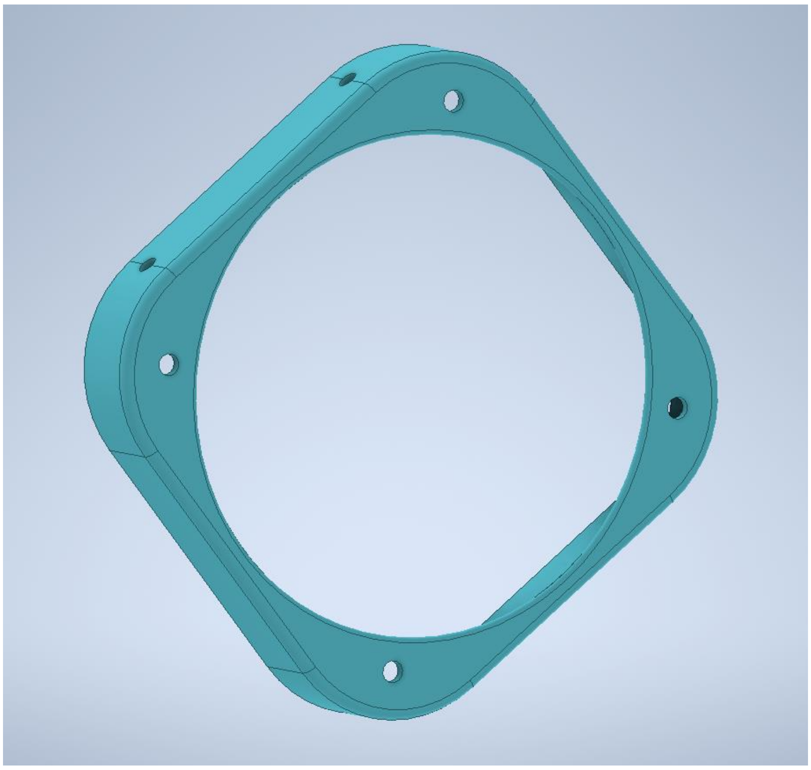
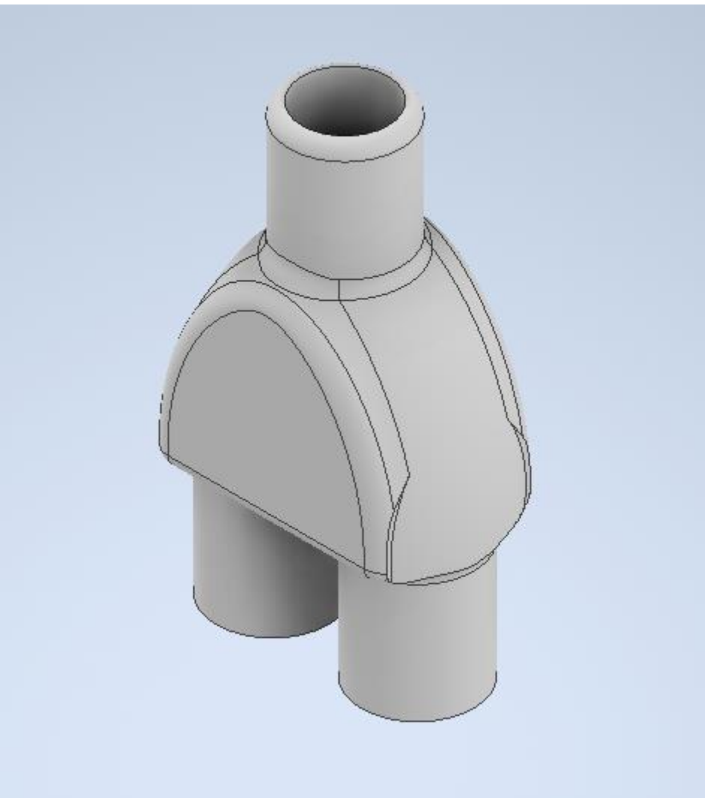


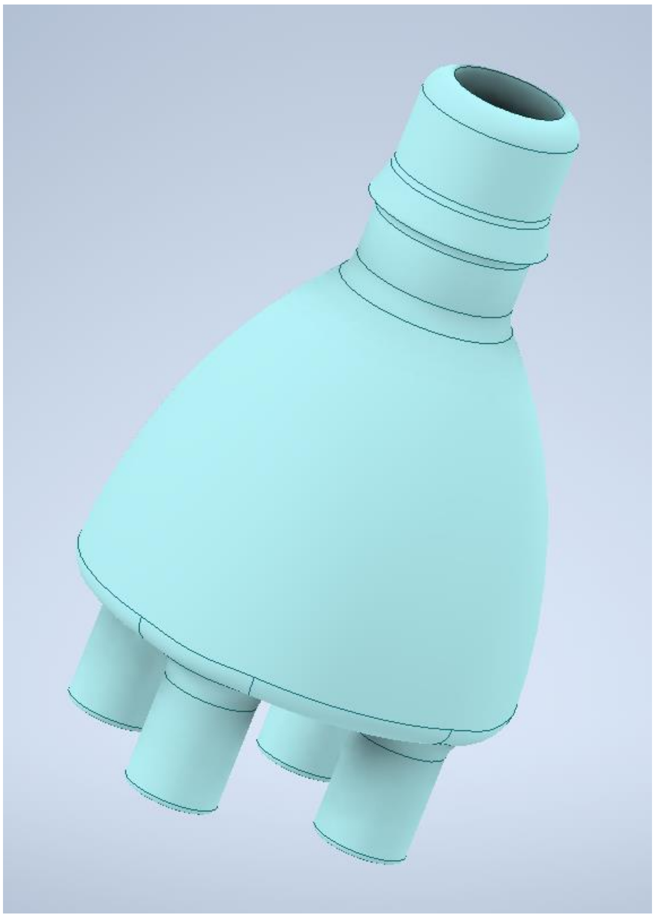
Plate 3 – Intel CPU Fan Mount Plate:



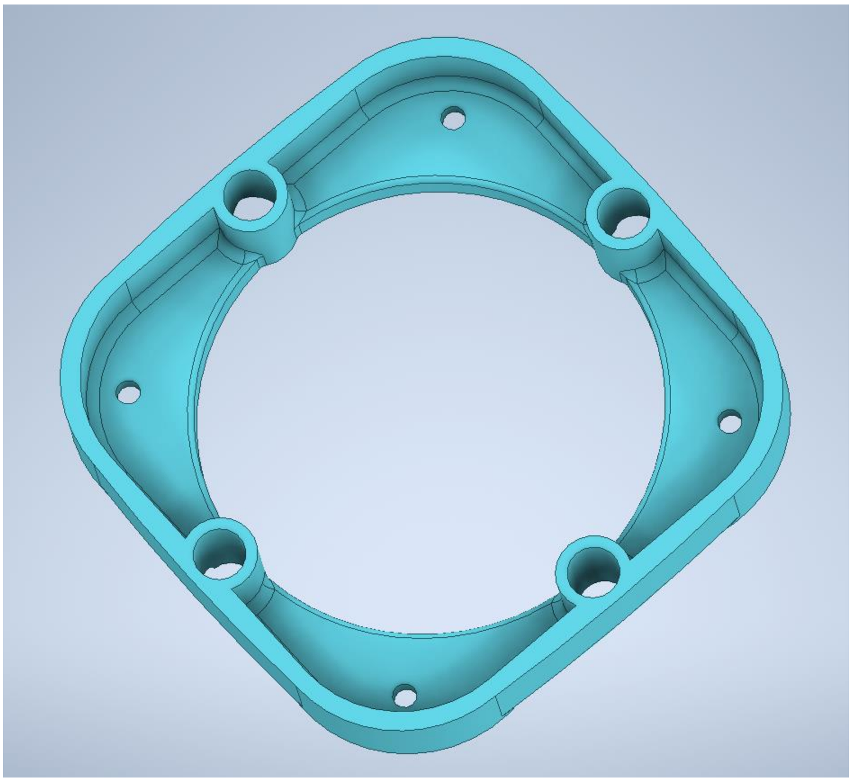
Connecting Adapter:



Four Way Air Adapter:

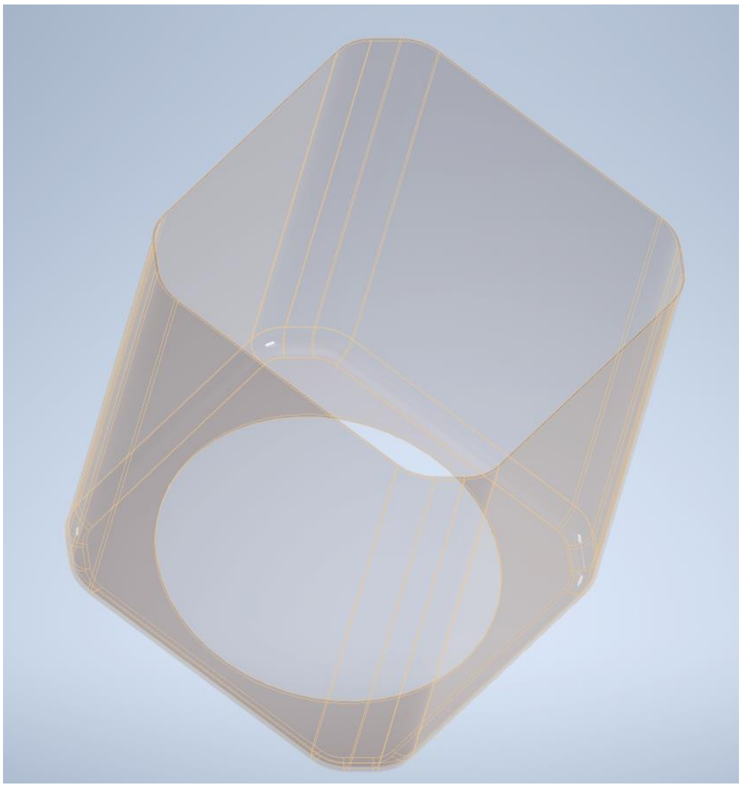


Air Connecting Plate:

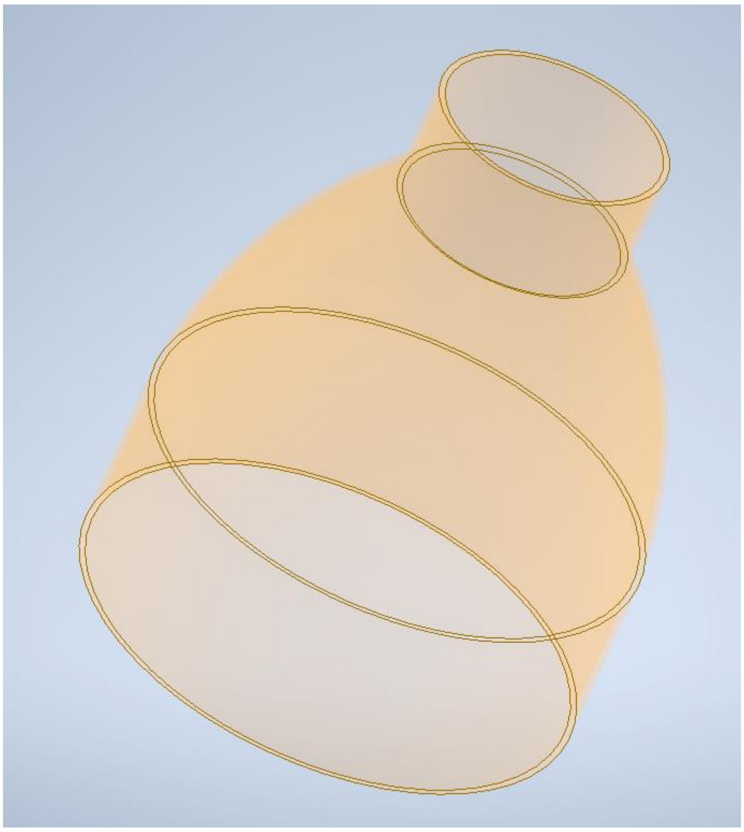


B.4 - Prototype C: 3D Rendered Non-Printed Components

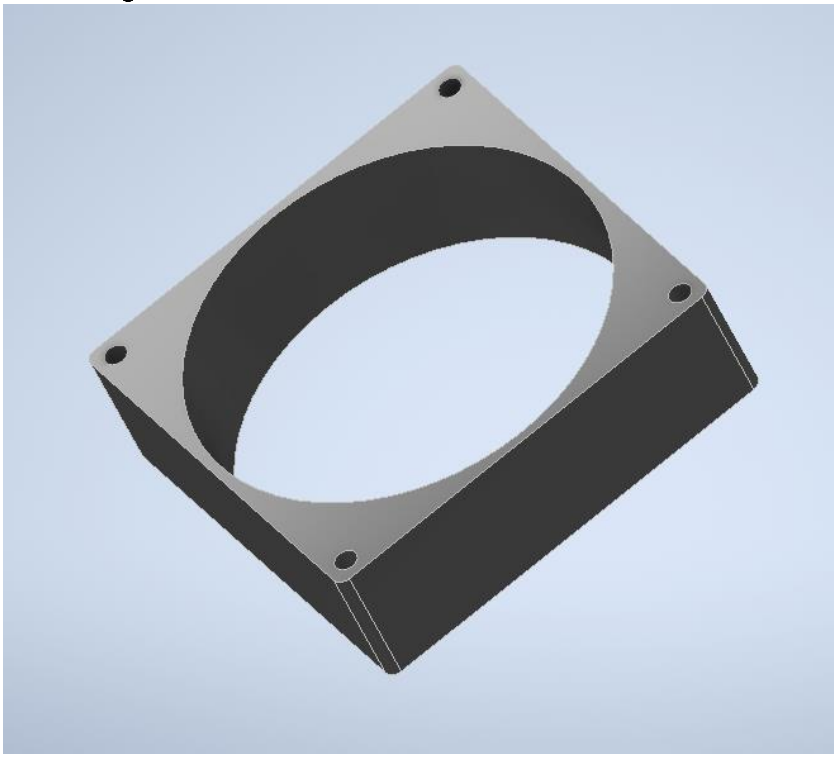
Milk Bottle End:



Juice Bottle Top:



Fan Casing:



APPENDIX C – Arduino Coding for Gripper

```
// Gripper_Driver
// Stace Rummenie.  ENP4111  University of Southern Queensland.
// 2024
//Must first include the Servo library so as to be able to utilise chosen actuator
#include "Servo.h"


Servo myservo;  // create servo object to control the servo. Name of servo "myservo"
const int buttonPin = 2;  // name 1st button input and set to use 2 on Arduino
const int servoPin = 9;  // name and set servo controller pin on Arduino
const int ledPin = 13;  //number of LED pin on Uno
int pos = 90;     // variable to store the initial servo position for gripper to be open upon initialising program
int buttonStatus = 0;  // variable for storing pushbutton status



void setup() {
 pinMode(LED_BUILTIN, OUTPUT);  //setup inbuilt led
      digitalWrite(LED_BUILTIN, HIGH);   // turn the LED on to indicate start up begun
// initialise serial port
    Serial.begin(9600);
// attach servo to pin 9 of arduino
    myservo.attach(9);
// set servo position to be fully open at start
    myservo.write(pos);
// set pinmode for button to trigger gripper to close
    pinMode(buttonPin, INPUT);
// set pinmode for Uno LED as output
    pinMode(ledPin, OUTPUT);



digitalWrite(LED_BUILTIN, LOW);    // turn the LED off by making the voltage LOW
delay(3000);  //sets delay time to 3 seconds after Arduino initialisation
}

void loop() {
  buttonStatus = digitalRead(buttonPin);  //read state of pushbutton. If pushed down, should be HIGH

  /*IF statement to check and correct position of servo, */
  if  (pos<85 && pos>95) {
  pos = 90;    // Check position of servo and if outside of set range, brings it back to fully opened position.
  myservo.write(pos);
  }

   Serial.print("Servo Angle:  "); Serial.println(pos);    Serial.println(buttonStatus);  //Servo angle reports to
serial printer for testing and initial calibration.
  // delay(50);          //Delay to allow for feedback response
```

```
  if (buttonStatus == HIGH) //Check status of button and if HIGH (pressed), close gripper by changing servo position
to 175 degrees (modify this as required)
  {
    pos = 175;
    Serial.println(pos);
    digitalWrite(ledPin, HIGH);  //activate local LED on Uno when button pressed
  }
    else    //if not HIGH, open gripper by leaving/changing servo position to 90 degrees (modify this as required)
  {
    pos = 90;
    Serial.println(pos);
    digitalWrite(ledPin, LOW);  //deactivate local LED on UNO if button NOT pressed
  }

  delay (250); // set to only check button every 0.25 seconds once running

  myservo.write(pos);
}
```

APPENDIX D – Phase 2 Test Results

D.1 - Prototype A (Gripper) Results

Subject No.	Common Name	Species	Life Cycle Stage	Size - Diameter\ Width (mm)	Size - Length (mm)
1	Cabbage White Butterfly	Pieris rapae	Larvae	2.5	12
2	Cabbage White Butterfly	Pieris rapae	Larvae	3.1	18
3	Cabbage White Butterfly	Pieris rapae	Pupae	5.5	20.5
4	Cabbage White Butterfly	Pieris rapae	Adult	60	28
5	Common Spotted Ladybeetle	Harmonia conformis	Adult	3.7	4.8
6	Black Scale	Saissetia oleae	Adult	3.8	2.7
7	Cabbage White Butterfly	Pieris rapae	Larvae	3.1	18
8	Cabbage White Butterfly	Pieris rapae	Pupae	5.5	20.5

Subject No.	Common Name	Relative Size	Removed	Incapacitated	Killed
1	Cabbage White Butterfly	small	Yes	Yes	Yes - Immediately
2	Cabbage White Butterfly	large	Yes	Yes	Yes - Immediately
3	Cabbage White Butterfly	average	Yes	Yes	Yes - Immediately
4	Cabbage White Butterfly	average	Multiple attempts required	Temporarily	Yes - Eventually
5	Common Spotted Ladybeetle	medium	Multiple attempts required	Yes	Yes - Immediately
6	Black Scale	large	No	Yes	Yes - Eventually
7	Cabbage White Butterfly	average	Yes	Yes	Yes - Immediately
8	Cabbage White Butterfly	average	Yes	Yes	Yes - Immediately

Subject No.	Common Name	Observations/Notes
1	Cabbage White Butterfly	Squashed gut contents over container and gripper jaws.
2	Cabbage White Butterfly	Squashed gut contents over container and gripper jaws.
3	Cabbage White Butterfly	Squashed gut contents over container and gripper jaws.
4	Cabbage White Butterfly	Escaped initial attempt. Took multiple attempts while fluttering around window to capture. When released stayed immobile for around an hour then flew away. Was later found dead.
5	Common Spotted Ladybeetle	At first attempt the beetle escaped. Second attempt took multiple grabs before successfully capturing and killing.
6	Black Scale	Took multiple attempts to position gripper in a fashion able to crush and kill the scale.
7	Cabbage White Butterfly	Squashed gut contents over container and gripper jaws.
8	Cabbage White Butterfly	Squashed gut contents over container and gripper jaws.

D.2 - Prototype B (Zapper) Results

Subject No.	Test Specimen	Species	Life Cycle Stage	Size - Diameter/ Width (mm)	Size - Length (mm)
1	Cabbage White Butterfly	Pieris rapae	Larvae	2.7	15
2	Cabbage White Butterfly	Pieris rapae	Larvae	3.1	18
3	Cabbage White Butterfly	Pieris rapae	Larvae	3.8	22
4	Cabbage White Butterfly	Pieris rapae	Pupae	5.5	20.5
5	Cabbage White Butterfly	Pieris rapae	Adult	60	28
6	Common Spotted Ladybeetle	Harmonia conformis	Adult	3.8	4.8
7	Common Spotted Ladybeetle	Harmonia conformis	Larvae	3.5	6
8	Black Scale	Saissetia oleae	Adult	3.8	2.7

Subject No.	Test Specimen	Size Classification	Removed	Incapacitated	Killed
1	Cabbage White Butterfly	medium	No	Yes	Yes - Immediately
2	Cabbage White Butterfly	large	No	Temporarily	Yes - Eventually
3	Cabbage White Butterfly	very large	No	Temporarily	Yes - Eventually
4	Cabbage White Butterfly	average	No	Yes	No
5	Cabbage White Butterfly	average	No	Temporarily	No
6	Common Spotted Ladybeetle	medium	No	Yes	No
7	Common Spotted Ladybeetle	average	No	Yes	Yes - Eventually
8	Black Scale	large	No	Yes	Unknown

Subject No.	Test Specimen	Observations/Notes
1	Cabbage White Butterfly	No evidence of any movement after initial terminal discharge. Observation over 24 hours confirmed dead.
2	Cabbage White Butterfly	Initially stunned and appeared dead. Several hour later it began moving about again, though slowly and not far. Next morning had clearly stopped moving.
3	Cabbage White Butterfly	Very briefly stunned. Within 15 minutes was moving again with no apparent impact. Was still alive 24 hours later. Later appeared to start building a pupal case but died part way through this process.
4	Cabbage White Butterfly	Placed back in container with leaves after discharging terminals against pupae. I week later pupal case observed to show signs of activity. Several days later butterfly emerged with no adverse effects noted.
5	Cabbage White Butterfly	Charge appears to have shorted across wings. Several attempts were required before eventually temporarily stunning. Was moving again within 10 minutes, though did not fly away. Possibility that too much damage after multiple attempts to electrocute.
6	Common Spotted Ladybeetle	Beetle was briefly stunned. Was walking around again an hour later no apparent issues. Also fine the next day.
7	Common Spotted Ladybeetle	Took multiple attempts to get device to apply to larval stage, shorting on nearby leaf. Eventually beetle larvae appeared briefly stunned. Movement evident shortly after, but was not noted to be moving later that day so
8	Black Scale	While completed a full discharnge, there is no clear way to tell if scale affected or if device has arced across leaf. It is assumed that the approach was unsuccessful. Not a good test specimen for this type of testing.

D.3 - Prototype C (Sucker) Results

Subject No.	Test Specimen	Species	Life Cycle Stage	Size - Diameter/ Width (mm)	Size - Length (mm)
1	Cabbage White Butterfly	Pieris rapae	Larvae	2.5	12
2	Cabbage White Butterfly	Pieris rapae	Larvae	2.7	15
3	Cabbage White Butterfly	Pieris rapae	Pupae	5.5	20.5
4	Cabbage White Butterfly	Pieris rapae	Adult	60	28
5	Cabbage White Butterfly	Pieris rapae	Adult	60	28
6	Common Spotted Ladybeetle	Harmonia conformis	Adult	3.7	4.8
7	Common Spotted Ladybeetle	Harmonia conformis	Adult	5	5.6
8	Black Scale	Saissetia oleae	Adult	3.8	2.7

Subject No.	Test Specimen	Relative Size	Removed	Incapacitated	Killed
1	Cabbage White Butterfly	small	Temporarily	No	No
2	Cabbage White Butterfly	medium	No	No	No
3	Cabbage White Butterfly	average	No	No	No
4	Cabbage White Butterfly	average	Yes	Yes	Yes - Eventually
5	Cabbage White Butterfly	average	No	No	No
6	Common Spotted Ladybeetle	medium	Temporarily	No	No
7	Common Spotted Ladybeetle	large	No	No	No
8	Black Scale	large	No	No	No

Subject No.	Test Specimen	Observations/Notes
1	Cabbage White Butterfly	Briefly lifted the caterpiller from the container, but fell back in shortly after.
2	Cabbage White Butterfly	No observable effect.
3	Cabbage White Butterfly	No observable effect.
4	Cabbage White Butterfly	Successfully removed the butterfly adult from the plastic container, the butterfly pulling through the fan damaging its wings and then no longer able to fly. While alive and showing no sign of distress, it was observed to be dead the next day.
5	Cabbage White Butterfly	Butterfly escaped. Device was unable to remove the adult butterfly from the window ledge that it was clinging to during the attempt. Issues with wiring disconnecting.
6	Common Spotted Ladybeetle	Initially lifted the beetle out of the the container which then swirled around in the device briefly then fell out shortly after.
7	Common Spotted Ladybeetle	No observable effect.
8	Black Scale	No observable effect.

D.4 - Prototype C (Sucker) Iteration 2 Results

Subject No.	Test Specimen	Species	Life Cycle Stage	Size - Diameter/ Width (mm)	Size - Length (mm)
1	Cabbage White Butterfly	Pieris rapae	Larvae	2.5	12
2	Cabbage White Butterfly	Pieris rapae	Larvae	2.7	15
3	Cabbage White Butterfly	Pieris rapae	Larvae	3.1	18
4	Cabbage White Butterfly	Pieris rapae	Pupae	5.5	20.5
5	Cabbage White Butterfly	Pieris rapae	Adult	60	28
6	Common Spotted Ladybeetle	Harmonia conformis	Adult	3.7	4.8

Subject No.	Test Specimen	Relative Size	Removed	Incapacitated	Killed
1	Cabbage White Butterfly	small	Yes	No	No
2	Cabbage White Butterfly	medium	Yes	No	No
3	Cabbage White Butterfly	medium	Yes	No	No
4	Cabbage White Butterfly	average	No	No	No
5	Cabbage White Butterfly	average	Yes	No	No
6	Common Spotted Ladybeetle	medium	Yes	No	No

Subject No.	Test Specimen	Observations/Notes
1	Cabbage White Butterfly	Lifted into nozzle but then stayed in nozzle swirling around until fan turned off.
2	Cabbage White Butterfly	Unable to lift until catepillar released its grip on container surface to curl up. After this successfully lifted into nozzle and stayed in nozzle until fan turned off.
3	Cabbage White Butterfly	Unable to lift until catepillar released its grip on container surface to curl up. After this successfully just lifted into nozzle throat and stayed there until fan turned off.
4	Cabbage White Butterfly	Almost able to lift from container when applied directly to pupal case, but insufficient suction to pull into nozzle.
5	Cabbage White Butterfly	Successfully removed the butterfly adult from the plastic container, the butterfly however blocked the nozzle until the fan was turned off. Some trouble removing from both the container and then the nozzle, as it appeared to have gained purchase against both. No damage noted.
6	Common Spotted Ladybeetle	Successfully lifted the beetle out of the the container, swirled around in the device and maintained in that position while device held vertically.

APPENDIX E – Sucker Pressure Determination

With an Air Compressor supply pressure of approximately 5 bar via a 40 L Ridge Air Compressor (as per Figure 149) and using Jamec-PEM Air Blow Gun with 85 mm nozzle extension (OD 6.4 mm, ID 3.2 mm), as per Figure 150. A net lifting force was generated by the sucker able to lift and suspend a mass of 48 grams.

Figure 149. Ridge 40 L Air Compressor

Figure 150. Jamec-PEM Air Blow Gun

With gravity (g) assumed 9.81 m/s^2, then as:

$$Force\ (F) = mass\ (m) \times acceleration\ (g)$$

$$F = 0.048 \times 9.81 = \mathbf{0.47\ N}$$

Assuming end of sucker nozzle having a shape approximating an oval, then with largest dimension equalling 2 cm (a = 2.0 cm) and smallest dimension equal to 1.2 cm (b = 1.2 cm):

$$Area\ of\ Sucker\ End(A_{end}) \cong \pi \times \frac{a}{2} \times \frac{b}{2} = \pi \times 1 \times 0.6 = \mathbf{1.88\ cm^2}$$

To confirm the oval estimate is a reasonable approximation of the shape, compare back against known circumference for internal pipe perimeter of 16 mm (ID):

$$C = \pi D = 1.6\pi = 5.02\ cm$$

Where pipe assumed oval, then circumference can be estimated as per Ramanujan's first approximation for the circumference of an ellipse:

$$C \approx \pi \times [3(a/2 + b/2) - \sqrt{(3a/2 + b/2)(a/2 + 3b/2)}]$$

$$C \approx \pi \times [3 \times 1.6) - \sqrt{(3 + 0.6) \times (1 + 1.8)}] = \pi \times 1.625 = 5.1\ cm$$

With the difference being less than 2%, the use of the area of an oval formula for area estimation is therefore considered acceptable.

By the known relationship between Pressure, Force and Area of force application, Pressure can be established as per:

$$Pressure\ (Pa) = \text{Force (N) / Area (m}^2\text{)}$$

$$P = 0.47 \div (1.88 \div 10000) \cong 2500\text{Pa} = \mathbf{2.5\ kPa}$$

Thus, giving an estimate for the suction pressure at the end of the Sucker Prototype, when an additional air stream is supplied, of 2.5 kilopascals.

APPENDIX F – Phase 4 Primary Test Results

F.1 - Prototype A (Gripper) Results

Subject No.	Common Name	Species	Life Cycle Stage	Size - Diameter\ Width (mm)	Size - Length (mm)	Relative Size	Removed	Incapacitated
1	Mealworm	*Tenebrio molitor*	Larvae	3.8	24	average	Yes	Temporarily
2	Mealworm	*Tenebrio molitor*	Larvae	3.8	25	average	Yes	No
3	Mealworm	*Tenebrio molitor*	Larvae	3.7	24	average	Yes	Temporarily
4	Mealworm	*Tenebrio molitor*	Larvae	3.6	25	average	Yes	Temporarily
5	Mealworm	*Tenebrio molitor*	Larvae	4	22	average	Yes	Temporarily
6	Mealworm	*Tenebrio molitor*	Larvae	3.4	23	average	Yes	No
7	Mealworm	*Tenebrio molitor*	Larvae	3.5	26	average	Yes	Temporarily
8	Mealworm	*Tenebrio molitor*	Larvae	3.5	28.5	average	Yes	No
9	Mealworm	*Tenebrio molitor*	Larvae	3.6	23.5	average	Yes	Temporarily
10	Mealworm	*Tenebrio molitor*	Larvae	3.5	26	average	Yes	No
11	Mealworm	*Tenebrio molitor*	Larvae	3.7	27	average	Yes	No
12	Mealworm	*Tenebrio molitor*	Larvae	3.8	26	average	Yes	No
13	Mealworm	*Tenebrio molitor*	Larvae	3.5	27	average	Yes	No
14	Mealworm	*Tenebrio molitor*	Larvae	3.5	25	average	Yes	No
15	Mealworm	*Tenebrio molitor*	Larvae	3.5	23	average	Yes	No
16	Mealworm	*Tenebrio molitor*	Larvae	3.4	23	average	Yes	Temporarily
17	Mealworm	*Tenebrio molitor*	Larvae	3.3	22	average	Yes	No
18	Mealworm	*Tenebrio molitor*	Larvae	3.8	23	average	Yes	No
19	Mealworm	*Tenebrio molitor*	Larvae	3.5	26	average	Yes	Yes
20	Mealworm	*Tenebrio molitor*	Larvae	3.9	27	average	Yes	No
21	Mealworm	*Tenebrio molitor*	Pupae	5.3	19.4	average	Yes	Yes
22	Mealworm	*Tenebrio molitor*	Pupae	6.1	18	average	Yes	Temporarily
23	Mealworm	*Tenebrio molitor*	Pupae	6.2	18	average	Yes	No
24	Mealworm	*Tenebrio molitor*	Pupae	5.6	19.9	average	Yes	Yes
25	Mealworm	*Tenebrio molitor*	Pupae	5.7	17	average	Yes	Temporarily
26	Mealworm	*Tenebrio molitor*	Pupae	5.5	17	average	Yes	Temporarily
27	Mealworm	*Tenebrio molitor*	Pupae	5.8	17.7	average	Yes	Yes
28	Mealworm	*Tenebrio molitor*	Pupae	5.4	17.4	average	Yes	Yes
29	Mealworm	*Tenebrio molitor*	Pupae	5.6	18	average	Yes	Yes
30	Mealworm	*Tenebrio molitor*	Pupae	5.4	16.8	average	Yes	Yes

Subject No.	Killed	Observations/Notes
1	Yes - Eventually	Appeared distressed during removal. Did not move for some time after removal. Alive but limited response to stimuli. Dead 24 hours later.
2	No	While apearing distressed during removal, no obvious impacts noted.
3	No	While apearing distressed during removal, and briefly stunned, no obvious immediate impacts noted. Limited evidence of active movement at 24 hours.
4	No	While apearing distressed during removal, and briefly stunned, no obvious immediate impacts noted. Limited evidence of active movement at 24 hours.
5	No	While apearing distressed during removal, and briefly stunned, no obvious immediate impacts noted. Limited evidence of active movement at 24 hours.
6	No	While apearing distressed during removal, no obvious impacts noted.
7	No	While apearing distressed during removal, and briefly stunned, no obvious immediate impacts noted. Limited evidence of active movement at 24 hours.
8	No	While apearing distressed during removal, no obvious impacts noted.
9	No	While apearing distressed during removal, and briefly stunned, no obvious immediate impacts noted. Limited evidence of active movement at 24 hours.
10	No	While apearing distressed during removal, no obvious impacts noted.
11	No	While apearing distressed during removal, no obvious impacts noted.
12	No	While apearing distressed during removal, no obvious impacts noted.
13	No	While apearing distressed during removal, no obvious impacts noted.
14	No	While apearing distressed during removal, no obvious impacts noted.
15	No	While apearing distressed during removal, no obvious impacts noted.
16	Yes - Eventually	Flattened during removal. Did not move for some time after removal. Stilll alive but limited response to stimuli. Not dead at 24 hours but still unable to move. Picked up leaf at same time.
17	No	While apearing distressed during removal, no immediate impacts noted. Limited evidence of active movement at 24 hours.
18	No	While apearing distressed during removal, no obvious impacts noted.
19	No	While apearing distressed during removal, no obvious impacts noted.
20	No	While apearing distressed during removal, no obvious impacts noted. Picked up leaf at same time.
21	Yes - Immediately	Crushed.
22	No	Limited response to stimuli observed at 24 hours.
23	No	Seems fine.
24	Yes - Immediately	Crushed.
25	No	Seems fine.
26	No	Seems fine.
27	Yes - Immediately	Crushed.
28	Yes - Immediately	Crushed.
29	Yes - Immediately	Crushed.
30	No	Limited response to stimuli observed at 24 hours.

F.2 - Prototype B (Zapper) Results

Subject No.	Common Name	Species	Life Cycle	Size - Diameter\ Width (mm)	Size - Length (mm)	Relative Size	Removed	Incapacitated
1	Mealworm	*Tenebrio molitor*	Larvae	3.7	22	average	No	No
2	Mealworm	*Tenebrio molitor*	Larvae	3.8	23.5	average	No	Temporarily
3	Mealworm	*Tenebrio molitor*	Larvae	3.8	28	average	No	No
4	Mealworm	*Tenebrio molitor*	Larvae	3.8	24.5	average	No	No
5	Mealworm	*Tenebrio molitor*	Larvae	3.6	23.5	average	No	Temporarily
6	Mealworm	*Tenebrio molitor*	Larvae	3.4	22	average	No	Temporarily
7	Mealworm	*Tenebrio molitor*	Larvae	4	28	average	No	No
8	Mealworm	*Tenebrio molitor*	Larvae	3.5	23	average	No	No
9	Mealworm	*Tenebrio molitor*	Larvae	3.6	24	average	No	Temporarily
10	Mealworm	*Tenebrio molitor*	Larvae	3.5	23.5	average	No	No
11	Mealworm	*Tenebrio molitor*	Larvae	3.6	25.5	average	No	No
12	Mealworm	*Tenebrio molitor*	Larvae	3.4	23	average	No	No
13	Mealworm	*Tenebrio molitor*	Larvae	3.6	28	average	No	No
14	Mealworm	*Tenebrio molitor*	Larvae	3.3	22.5	average	No	No
15	Mealworm	*Tenebrio molitor*	Larvae	3.8	25	average	No	No
16	Mealworm	*Tenebrio molitor*	Larvae	3.7	24.5	average	No	Temporarily
17	Mealworm	*Tenebrio molitor*	Larvae	3.9	31	average	No	No
18	Mealworm	*Tenebrio molitor*	Larvae	3.7	23.5	average	No	No
19	Mealworm	*Tenebrio molitor*	Larvae	3.4	24.5	average	No	Yes
20	Mealworm	*Tenebrio molitor*	Larvae	3.4	30	average	No	Temporarily
21	Mealworm	*Tenebrio molitor*	Pupae	6	20	average	No	Yes
22	Mealworm	*Tenebrio molitor*	Pupae	5.7	18	average	No	Temporarily
23	Mealworm	*Tenebrio molitor*	Pupae	5.4	16.5	average	No	No
24	Mealworm	*Tenebrio molitor*	Pupae	5.6	19.9	average	No	Yes
25	Mealworm	*Tenebrio molitor*	Pupae	5.7	17	average	No	Temporarily
26	Mealworm	*Tenebrio molitor*	Pupae	5.5	17	average	No	Temporarily
27	Mealworm	*Tenebrio molitor*	Pupae	5.8	17.7	average	No	Yes
28	Mealworm	*Tenebrio molitor*	Pupae	5.4	17.4	average	No	Yes
29	Mealworm	*Tenebrio molitor*	Pupae	5.6	18	average	No	Yes
30	Mealworm	*Tenebrio molitor*	Pupae	5.4	16.8	average	No	Temporarily

Subject No.	Killed	Observations/Notes
1	No	Appeared distressed during discharge, and activity slightly decreased afterwards. Decreased activity noted to continue to decline with time.
2	No	Appeared distressed during discharge, significantly reduced activity afterwards. Briefly stunned. Limited evidence of active movement at 24 hours - no response unless squeezed.
3	No	Appeared distressed during discharge, and activity slightly decreased afterwards. Activity noted to decline with time.
4	No	While apearing distressed during removal, and briefly stunned, no obvious immediate impacts noted. Limited evidence of active movement at 24 hours - no response unless squeezed.
5	Yes - Eventually	Appeared distressed during discharge, significantly reduced activity afterwards. Briefly stunned. No evidence of movement at 24 hours - no response when squeezed.
6	No	Appeared distressed during discharge, significantly reduced activity afterwards. Briefly stunned. Limited evidence of active movement at 24 hours - no response unless squeezed.
7	No	Appeared distressed during discharge, and activity slightly decreased afterwards. Activity noted to decline with time.
8	No	Appeared distressed during discharge, and activity slightly decreased afterwards. Activity noted to decline with time.
9	Yes - Eventually	Appeared distressed during discharge, significantly reduced activity afterwards. Briefly stunned. No evidence of movement at 24 hours - no response when squeezed.
10	No	Appeared distressed during discharge, and activity slightly decreased afterwards. Activity noted to decline with time.
11	No	Appeared distressed during discharge, and activity slightly decreased afterwards. Activity noted to decline with time.
12	No	Appeared distressed during discharge, and activity slightly decreased afterwards. Activity noted to decline with time.
13	No	Appeared distressed during discharge, and activity slightly decreased afterwards. Activity noted to decline with time.
14	No	Appeared distressed during discharge, and activity slightly decreased afterwards. Activity noted to decline with time.
15	No	Appeared distressed during discharge, and activity slightly decreased afterwards. Activity noted to decline with time.
16	No	Several attempts required with device discharging on leaf fold. Distressed during discharge, stunned after. Appeared dead at 2 hrs but was showing some response to stimuli at 24 hrs.
17	No	Appeared distressed during discharge, and activity slightly decreased afterwards. Activity noted to decline with time.
18	No	Appeared distressed during discharge, and activity slightly decreased afterwards. Activity noted to decline with time.
19	Yes - Eventually	Appeared distressed during discharge. Stunned. No activity noted at 2 hours, and no response at 24 hours.
20	No	Appeared distressed during removal and briefly stunned, no obvious immediate impact noted. Responsive at 2 hours. Little evidence of movement at 24 hours - no response unless squeezed.
21	Yes - Immediately	Thorax instantly burst on discharge.
22	Yes - Eventually	Temporarily unresponsive, fine at 2 hrs, unresponsive/dead at 24 hrs.
23	No	Seems fine.
24	Yes - Immediately	Thorax instantly burst on discharge.
25	No	Noting if zapper too close to leaf, loses charge across leaf - does not always discharge.
26	No	Pupae pushed away from discharge field. Took mulitple attempts before would discharge. Seemed dead at two hours but OK at 24 hrs.
27	No	Seems fine.
28	No	Seems fine.
29	No	Seems fine.
30	Yes - Eventually	Pupae pushed away from discharge field. Took mulitple attempts before would discharge. Temporarily unresponsive, fine at 2 hrs, unresponsive/dead at 24 hrs.

F.3 - Prototype C (Sucker) Results

Subject No.	Common Name	Species	Life Cycle Stage	Size - Diameter\ Width (mm)	Size - Length (mm)	Relative Size	Removed	Incapacitated
1	Mealworm	*Tenebrio molitor*	Larvae	3.6	26.5	average	Yes	Yes
2	Mealworm	*Tenebrio molitor*	Larvae	3.5	24	average	Yes	Yes
3	Mealworm	*Tenebrio molitor*	Larvae	3	21	average	Yes	Yes
4	Mealworm	*Tenebrio molitor*	Larvae	3.4	24.5	average	Yes	Yes
5	Mealworm	*Tenebrio molitor*	Larvae	4	28	average	Yes	Yes
6	Mealworm	*Tenebrio molitor*	Larvae	3.8	27	average	Yes	Yes
7	Mealworm	*Tenebrio molitor*	Larvae	3.7	21	average	Yes	Yes
8	Mealworm	*Tenebrio molitor*	Larvae	3.8	26.5	average	Yes	Yes
9	Mealworm	*Tenebrio molitor*	Larvae	3.6	26	average	Yes	Yes
10	Mealworm	*Tenebrio molitor*	Larvae	4	25	average	Yes	Yes
11	Mealworm	*Tenebrio molitor*	Larvae	3.7	28	average	Yes	Yes
12	Mealworm	*Tenebrio molitor*	Larvae	3.8	24.5	average	Yes	Yes
13	Mealworm	*Tenebrio molitor*	Larvae	3.5	30	average	Yes	Yes
14	Mealworm	*Tenebrio molitor*	Larvae	3.8	23.5	average	Yes	Yes
15	Mealworm	*Tenebrio molitor*	Larvae	3.6	23	average	Yes	Yes
16	Mealworm	*Tenebrio molitor*	Larvae	3.5	24	average	Yes	Yes
17	Mealworm	*Tenebrio molitor*	Larvae	3.6	28	average	Yes	Yes
18	Mealworm	*Tenebrio molitor*	Larvae	3.8	23.5	average	Yes	Yes
19	Mealworm	*Tenebrio molitor*	Larvae	3.3	24	average	Yes	Yes
20	Mealworm	*Tenebrio molitor*	Larvae	3.8	28.5	average	Yes	Yes
21	Mealworm	*Tenebrio molitor*	Pupae	5.8	17	average	Yes	Yes
22	Mealworm	*Tenebrio molitor*	Pupae	5.6	18	average	Yes	Yes
23	Mealworm	*Tenebrio molitor*	Pupae	5.7	17	average	Yes	Yes
24	Mealworm	*Tenebrio molitor*	Pupae	5.5	17	average	Yes	Yes
25	Mealworm	*Tenebrio molitor*	Pupae	5.4	17.5	average	Yes	Yes
26	Mealworm	*Tenebrio molitor*	Pupae	5.4	18	average	Yes	Yes
27	Mealworm	*Tenebrio molitor*	Pupae	5.6	18	average	Yes	Yes
28	Mealworm	*Tenebrio molitor*	Pupae	5.4	16.5	average	Yes	Yes
29	Mealworm	*Tenebrio molitor*	Pupae	5	16	average	Yes	Yes
30	Mealworm	*Tenebrio molitor*	Pupae	6	17	average	Yes	Yes

Subject No.	Killed	Observations/Notes
1	Yes - Immediately	Body smashed up.
2	Yes - Immediately	Body smashed up.
3	Yes - Immediately	Body smashed up.
4	Yes - Immediately	Body smashed up.
5	Yes - Immediately	Body smashed up.
6	Yes - Immediately	Body smashed up.
7	Yes - Immediately	Body smashed up.
8	Yes - Immediately	Body smashed up.
9	Yes - Eventually	Only one that survived relatively uninjured, though movement very much reduced. Dead within 2 hours.
10	Yes - Immediately	Body smashed up.
11	Yes - Immediately	Body smashed up.
12	Yes - Eventually	Badly damaged. Died shortly after.
13	Yes - Eventually	Badly damaged. Died shortly after.
14	Yes - Immediately	Body smashed up.
15	Yes - Immediately	Body smashed up.
16	Yes - Eventually	Did not pass through fan, but badly damaged (from side walls it is assumed). Died soon after removal from inlet chamber.
17	Yes - Immediately	Body smashed up.
18	Yes - Immediately	Body smashed up.
19	Yes - Eventually	Did not pass through fan, but badly damaged (from side walls it is assumed). Died soon after removal from inlet chamber.
20	Yes - Immediately	Body smashed up.
21	Yes - Immediately	Body badly damaged.
22	Yes - Immediately	Body badly damaged.
23	Yes - Immediately	Body badly damaged.
24	Yes - Immediately	Body badly damaged.
25	Yes - Immediately	Body badly damaged.
26	Yes - Immediately	Body badly damaged.
27	Yes - Immediately	Body badly damaged.
28	Yes - Immediately	Body badly damaged.
29	Yes - Immediately	Body badly damaged.
30	Yes - Immediately	Body badly damaged.

F.4 - Control Results

Subject No.	Common Name	Species	Life Cycle	Relative Size	Removed	Incapacitated	Killed	Observations/Notes
1	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
2	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
3	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
4	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
5	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
6	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
7	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
8	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
9	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
10	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	Yes - Eventually	Dead at 24 hours. Appears to be moulting.
11	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
12	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
13	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
14	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
15	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
16	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
17	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
18	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
19	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
20	Mealworm	*Tenebrio molitor*	Larvae	average	No	No	No	Activity slightly reduced.
21	Mealworm	*Tenebrio molitor*	Pupae	average	No	No	No	No change.
22	Mealworm	*Tenebrio molitor*	Pupae	average	No	No	No	No change.
23	Mealworm	*Tenebrio molitor*	Pupae	average	No	No	No	No change.
24	Mealworm	*Tenebrio molitor*	Pupae	average	No	No	No	No change.
25	Mealworm	*Tenebrio molitor*	Pupae	average	No	No	No	No change.
26	Mealworm	*Tenebrio molitor*	Pupae	average	No	No	No	No change.
27	Mealworm	*Tenebrio molitor*	Pupae	average	No	No	No	No change.
28	Mealworm	*Tenebrio molitor*	Pupae	average	No	No	No	No change.
29	Mealworm	*Tenebrio molitor*	Pupae	average	No	No	No	No change.
30	Mealworm	*Tenebrio molitor*	Pupae	average	No	No	No	No change.

APPENDIX G – Phase 4 Follow-up Test Results

G.1 – Prototype A (Gripper) Results

Subject No.	Prototype Used	Test Specimen	Species	Life Cycle Stage	Relative Size	Removed	Incapacitated
1	A - Gripper	Cabbage White Butterfly	*Pieris rapae*	Larvae	small	Yes	Yes
2	A - Gripper	Cabbage White Butterfly	*Pieris rapae*	Larvae	small	No	Yes
3	A - Gripper	Cabbage White Butterfly	*Pieris rapae*	Larvae	large	Yes	Yes
4	A - Gripper	Cabbage White Butterfly	*Pieris rapae*	Larvae	large	No	Yes
5	A - Gripper	Ladybeetle	*Unknown*	Adult	small	Yes	No
6	A - Gripper	Ladybeetle	*Unknown*	Adult	medium	Yes	Yes
7	A - Gripper	Ladybeetle	*Unknown*	Adult	small	Yes	Yes
8	A - Gripper	Ladybeetle	*Unknown*	Adult	medium	Yes	Yes

Subject No.	Prototype Used	Killed	Observations/Notes
1	A - Gripper	Yes - Eventually	Body only just grabbed by Gripper. Limited damage noted. Dropped on ground. Ants found it within 1/2 an hour and began killing it.
2	A - Gripper	Yes - Immediately	Unable to remove with Gripper due to location of specimen within leaf groove. Applied jaws around leaf. Body crushed. Gut contents left on leaf, caterpillar crushed onto leaf. Rain following day washed caterpillar and guts off leaf.
3	A - Gripper	Yes - Eventually	Body successfully grabbed by Gripper. Small rupture to mid body noted. Dropped on ground. Ants found it within 1/2 an hour and began killing it.
4	A - Gripper	Yes - Immediately	Unable to remove with Gripper due to location of specimen within leaf groove. Applied jaws around leaf. Body crushed. Gut contents left on leaf, caterpillar crushed onto leaf. Rain following day washed caterpillar and guts off leaf.
5	A - Gripper	No	While removed successfully, size of beetle appeared to be at limit of device and no apparent damage resulted from removal.
6	A - Gripper	No	Successfully removed and body appeared to crush slightly. Beetle showed signs of being damaged but was not dead.
7	A - Gripper	Yes - Immediately	Placing device jaws over leaf and crushing ladybeetle against the leaf provided an alternative approach that allowed for the beetle to be killed. Some parts of beetle remained on leaf after crushing.
8	A - Gripper	Yes - Immediately	Placing device jaws over leaf and crushing ladybeetle against the leaf provided an alternative approach that allowed for the beetle to be killed. Some parts of beetle remained on leaf after crushing.

G.2 – Prototype B (Zapper) Results

Subject No.	Prototype Used	Test Specimen	Species	Life Cycle Stage	Relative Size	Removed	Incapacitated
1	B - Zapper	Cabbage White Butterfly	*Pieris rapae*	Larvae	small	No	No
2	B - Zapper	Cabbage White Butterfly	*Pieris rapae*	Larvae	small	No	No
3	B - Zapper	Cabbage White Butterfly	*Pieris rapae*	Larvae	large	No	No
4	B - Zapper	Cabbage White Butterfly	*Pieris rapae*	Larvae	large	No	No
5	B - Zapper	Ladybeetle	*Unknown*	Adult	small	No	No
6	B - Zapper	Ladybeetle	*Unknown*	Adult	medium	No	No
7	B - Zapper	Ladybeetle	*Unknown*	Adult	medium	Yes	Yes
8	B - Zapper	Ladybeetle	*Unknown*	Adult	medium	Yes	Yes

Subject No.	Prototype Used	Killed	Observations/Notes
1	B - Zapper	No	Took several goes to get Zapper to effectively discharge. After discharge, reared up gripping with prolegs and waved around for a minute or so before appearing to return to prior activity. Stayed on leaf remainder of day. Not present next morning.
2	B - Zapper	No	After discharge, vomited then reared up gripping with prolegs and waved around for a minute or so before appearing to return to prior activity. Stayed on leaf remainder of day. Still present next morning. No obvious change in state or behaviour.
3	B - Zapper	No	After discharge, vomited then reared up gripping with prolegs and waved around for a minute or so before appearing to return to prior activity. Stayed on leaf remainder of day. Still present next morning, no obvious change in state or behaviour.
4	B - Zapper	No	Took several goes to get Zapper to effectively discharge. After discharge, reared up gripping with prolegs and waved around for a minute or so before appearing to return to prior activity. Not present on leaf that afteroon.
5	B - Zapper	No	Beetle too small for device. Was pulled towards one of the terminals but no discharge. No impact observed.
6	B - Zapper	No	While device discharged, and beetle appeared to be unable to correctly fold away wings, still walking around. One hour later wings folded away again. Next morning still alive and no obvious impact observed.
7	B - Zapper	Yes - Immediately	Wings exploded out from between elytra and fluid escaped from beetle body. Appeared to be immediately killed. Stayed on leaf briefly before falling with small gust of wind. Laying on back on ground with wings out. No evidence to suggest still alive.
8	B - Zapper	Yes - Eventually	Discharge blew beetle off of leaf. Beetle laying still on ground but not obviously damaged. Collected and noted moving again at 1 hour, however, not able to walk or fly. Beetle was dead the next day.

G.3 – Prototype C (Sucker) Results

Subject No.	Prototype Used	Test Specimen	Species	Life Cycle Stage	Relative Size	Removed	Incapacitated
1	C - Sucker	Cabbage White Butterfly	*Pieris rapae*	Larvae	small	Yes	Yes
2	C - Sucker	Cabbage White Butterfly	*Pieris rapae*	Larvae	small	Yes	Yes
3	C - Sucker	Cabbage White Butterfly	*Pieris rapae*	Larvae	large	Yes	Yes
4	C - Sucker	Cabbage White Butterfly	*Pieris rapae*	Larvae	large	Yes	Yes
5	C - Sucker	Ladybeetle	*Unknown*	Adult	medium	Yes	Yes
6	C - Sucker	Ladybeetle	*Unknown*	Adult	medium	Yes	Yes
7	C - Sucker	Ladybeetle	*Unknown*	Adult	medium	Yes	Yes
8	C - Sucker	Ladybeetle	*Unknown*	Adult	medium	Yes	Yes

Subject No.	Prototype Used	Killed	Observations/Notes
1	C - Sucker	Yes - Immediately	Body smashed up. Killed instantly.
2	C - Sucker	Yes - Immediately	Body smashed up. Killed instantly.
3	C - Sucker	Yes - Immediately	Body smashed up. Killed instantly.
4	C - Sucker	Yes - Immediately	Body smashed up. Killed instantly.
5	C - Sucker	Yes - Eventually	Body badly damaged and no sign of movement for first 1/2 hour. Attemtping to walking one hour later but still badly damaged. Wing broken - can't fly. Dead next day.
6	C - Sucker	No	Body damaged and no sign of movement initially. Wings mostly retracted again around 2 hours later. Successfully walking 4 hours later. Alive 24 hours later.
7	C - Sucker	Yes - Immediately	Body badly damaged, appeared dead. No sign of movement over 24 hour period.
8	C - Sucker	Yes - Immediately	Body badly damaged, appeared dead. No sign of movement over 24 hour period.

G.4 – Control Results

Subject No.	Prototype Used	Test Specimen	Species	Life Cycle Stage	Relative Size	Removed	Incapacitated
1	Control	Cabbage White Butterfly	*Pieris rapae*	Larvae	small	No	No
2	Control	Cabbage White Butterfly	*Pieris rapae*	Larvae	small	No	No
3	Control	Cabbage White Butterfly	*Pieris rapae*	Larvae	large	No	No
4	Control	Cabbage White Butterfly	*Pieris rapae*	Larvae	large	No	No
5	Control	Ladybeetle	*Unknown*	Adult	medium	No	No
6	Control	Ladybeetle	*Unknown*	Adult	medium	No	No
7	Control	Ladybeetle	*Unknown*	Adult	medium	No	No
8	Control	Ladybeetle	*Unknown*	Adult	medium	No	No

Subject No.	Prototype Used	Killed	Observations/Notes
1	Control	No	No changes observed over the 24 hour period.
2	Control	No	No changes observed over the 24 hour period.
3	Control	No	No changes observed over the 24 hour period.
4	Control	No	No changes observed over the 24 hour period.
5	Control	No	No changes observed over the 24 hour period.
6	Control	No	No changes observed over the 24 hour period.
7	Control	No	No changes observed over the 24 hour period.
8	Control	No	No changes observed over the 24 hour period.