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Development and Evaluation of a Four Fingered Robotic End Effector for Selective Apple Fruitlet Thinning

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Abstract: This paper presents the development process of a robotic system designed for apple fruitlet thinning. The study details the selection process of key components and the refinement of finger profiles to enhance the system's efficiency. The refinement of the end effector was achieved through extensive laboratory testing, demonstrating a 100% success rate in thinning single fruitlets within an operating approach angle range of 90 to 30 deg. Further testing on clustered fruitlets yielded high success rates at a 75 deg approach angle. Field trials conducted in a commercial orchard revealed a significantly lower success rate of 44%, various types of failure conditions are analysed and presented. These findings highlight the potential and challenges of deploying robotic solutions for high value crops from a controlled lab environment to a field.

Keywords: Robotic fruitlet thinning, end effector design, vision integrated automation, precision horticulture, field robotics.

1. INTRODUCTION

Automation and robotics have emerged as key solutions to tackle labour shortages in the high value crop growing sector, with significant advancements over the past three decades Bac et al. (2014). While extensive research has focused on robotic apple harvesting to address these challenges Silwal et al. (2017); Bu et al. (2020); Zhang et al. (2021); Kang et al. (2020); Kootstra et al. (2021); Jia et al. (2020), robotic apple fruitlet thinning has received comparatively less attention and remains an under explored area. Fruitlet thinning is the process of removing excess fruit from apple trees to improve fruit size, quality, and tree health. During this phase, the fruits are in tight clusters and constantly growing, unlike harvesting phase where the fruits have reached full maturation, as shown in Figure 1. Zhou et al. (2022) classified robotic systems into two primary categories: fully integrated systems and subsystems for harvesting applications. These systems typically include computer vision for crop detection, end effectors for interacting with trees or crops, and control systems. Given the multidisciplinary nature of these technologies, each subsystem represents a significant research area. Consequently, this paper focuses on the development of robotic end effectors for apple fruitlet thinning and the associated design requirements.

(a) Apple fruitlets during thinning season.

(b) Fully grown apples ready for harvest.

Fig. 1. Apples during Thinning and Harvesting.

End effectors are essential components in robotics and automation, serving as the interface between the robot and the environment or objects being manipulated Reddy and Suresh (2013). They play a direct role in executing tasks within robotic systems and are often attached to robotic arms for operations such as picking, placing, and thinning Huan et al. (2023). In agriculture, end effectors are widely

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used for selective harvesting applications. However, the development of end effectors for apple fruitlet thinning, a critical process for optimising crop yield and quality, has not been widely explored.

This paper presents the development process of a robotic end effector designed for apple fruitlet thinning and to explore the requirements and challenges associated with transitioning of robotic systems from a controlled laboratory environment to real world field conditions.

2. REVIEW OF LITERATURE

Numerous review papers on integrated harvesting systems have evaluated robots from various perspectives. Eleni et al. (2022) reviewed the evolution and current state of robotic end effectors used in agriculture, highlighting their critical role in addressing labour shortages and increasing food production demands Vrochidou et al. (2022). The study examined various end effectors designed for high value crops, including widely researched contact grasping grippers, cutting tools, and suction devices that minimise fruit contact to avoid damage. The paper discussed various detachment techniques employed by these end effectors, such as cutting, grasping, and innovative methods combining suction with mechanical manipulation. It found that the grasp and cut technique is the most effective for detachment, while two and three fingered contact grasping grippers are most frequently used in practical settings. Moreover, it suggests that different end effector types, such as suction devices and cutters, should be used collaboratively to improve effectiveness.

A scissor based kinematic robotic end effector for automated harvesting was presented by Zhao et al.(2024) Zhao et al. (2024). Although the study lacks field trials and integration with a robotic system, the simulation results predicted a 40% increase in efficiency over traditional methods. The research highlighted the iterative nature of end effector design, presenting eight novel concepts derived from the scissor mechanism. The selected concept was produced using a 3D printing process. Future work would focus on design refinement, motor selection, prototype manufacturing, control system development, and experimental testing. However, the study does not compare this method to other detachment techniques and suggests its potential application to apples as well as other crops like sea cucumbers without specific adaptation.

Gao et al.(2024) Gao et al. (2024) conducted a study on a harvesting end effector designed for robotic cherry tomato harvesting in a commercial greenhouse. The research analysed the cherry tomato's physical characteristics, such as size, mass, and fruit parameters, to determine requirements for the design. The significance of understanding manual picking patterns for developing robotic end effectors was highlighted. The study introduced four potential robotic picking patterns derived from manual picking techniques. Additionally, a dynamic measurement system was developed, incorporating thin pressure film sensors on the thumb, middle finger, and index finger to record peak forces in each manual picking mode.

The findings led to the design of two distinct end effectors: a vacuum end effector and a rotating end effector, each tailored to specific picking patterns. Both designs were tested in a commercial setting. The vacuum end effector achieved a picking success rate of 66.3% and a calyx retention rate of 75.2%, with an average picking time of 5.3 seconds and no observed fruit damage. The primary challenge was detachment failure. In contrast, the rotating end effector demonstrated a picking success rate of 70.1%, a fruit damage rate of 5.2%, and a calyx retention rate of 67.4%, with an average picking time of 6.4 seconds. The main issues encountered were localisation failures and collisions. Overall the study presented a valuable reference for future developments of robotic cherry tomato harvesting.

Rong et al.(2024) designed a cherry tomato harvesting robot consisting of a commercially available 7 DOF robotic arm, an RGB D camera, a custom designed end effector, and a mobile chassis Rong et al. (2024). The study explored environmental and crop characteristics, such as growth structures for testing the robot. Previous work by the authors involved measuring pedicel diameters of various cherry tomato clusters to inform the design of a scissor based cutting/clamping end effector Rong et al. (2023). The robotic harvester underwent testing in two commercial greenhouses, achieving harvesting success rates of 57.5% and 55.4%. The study identified major failure causes, primarily related to computer vision errors and path planning challenges of the robotic arm. Issues included inaccuracies in locating the cutting point and complications from surrounding occlusions. The study also noted that a larger scissor opening in the end effector could compensate for positional errors caused by the vision system.

HortiBot is a robotic system equipped with three 7 DOF arms designed for the selective harvesting of sweet peppers Lenz et al. (2024). The system integrates distinct functions across its arms: one for detection and localisation, another for grasping using a soft robotic end effector, and a third arm for cutting the peduncle using a cutting end effector.

The study reviewed previous challenges in robotic sweet pepper harvesting as documented in Bac et al. (2017), Lehnert et al. (2020), Arad et al. (2020), and presented strategies to overcome these issues. Although the study evaluated HortiBot in laboratory settings, details on these experiments were not disclosed. HortiBot marked a pioneering approach in selective harvesting, addressing harvesting tasks including fruit detection, peduncle localisation, active perception, environment aware motion planning, and adaptive manipulation through force sensing. Beyond harvesting, the multi arm design allows for additional horticultural tasks such as leaf pruning and pollination. The authors recorded an 83.33% success rate in harvesting of sweet pepper, with a cycle time of 27 seconds per fruit.

The literature review shows that research efforts have primarily focused on the development of specialised end effectors for robotic harvesting, with limited exploration of robotic thinning applications. This paper addresses this gap by presenting the development process of a cutting based robotic end effector for apple fruitlet thinning. It provides a detailed justification for the selection of key components and discusses the refinements made to the system based on extensive laboratory testing.

3. DEVELOPMENT OF A 4 DOF CUTTING END EFFECTOR

The development of the end effector commenced with manual field trials using an off the shelf secateur for fruitlet stalk cutting. This method proved effective and served as an initial reference point for further design. However, robotically manoeuvring a secateur to precisely cut the stalk presented significant challenges, particularly in detecting the often concealed stalk amidst dense leaves and other occlusions.

To overcome these limitations, a more adaptive, multi fingered gripper was conceptualised. During the initial development, three fingered prototypes were fabricated and tested to determine if this configuration would be sufficient. It was found that a four fingered device, arranged in a circular pattern, was ultimately required due to its consistent effectiveness in handling fruitlet clusters. This design encircles the fruitlet, utilising blades positioned at the tips of each finger to execute the cut. Each finger operates independently, adjusting its position based on the fruitlet's dimensions and contours, as determined by a computer vision system. As the gripper approaches a fruitlet, the fingers dynamically adjust to its size. Upon achieving optimal alignment with the stalk, all fingers close simultaneously to perform the cut. The additional point of contact provided by the fourth finger was required for a more consistent ability to isolate and secure individual target fruitlet within a cluster, especially when they were closely grouped or partially obscured. This advantage minimised the slippage or incomplete cuts that were more frequently observed with three-fingered designs.

To establish the required cutting force and a suitable blade for cutting, an experiment was carried out on the instron hydraulic testing machine on a sample of 40 royal gala apple fruitlet stalks. Three blade types were evaluated: a commercial shaving razor blade, a craft knife, and a custom blade laser cut from 1.2 mm 304 grade stainless steel, which was professionally sharpened.

Table 1 presents the average maximum forces required. The custom made blade was ineffective, failing to cut when the force exceeded 30 N, resulting in the stalk being crushed. The razor blade required the least force, averaging 5.37 N with a standard deviation of 2.45 N. In comparison, the craft knife required a higher average maximum force of 14.88 N, with a standard deviation of 2.59 N. These findings highlight the importance of blade sharpness.

Table 1. Average cutting max forces and standard deviations for the blades cutting sample stalks on the instron machine.

Blade type	Average max force (N)	Standard deviation (N)
Razor	5.37	2.45
Craft knife	14.88	2.59

The integrated concept for the general arrangement of the cutting end effector is shown in Figure 3. Each of the fingers will be attached to the selected actuator and a razor blade at the fingers tip. The operational sequence for the cutting end effector is shown in Figure 2.

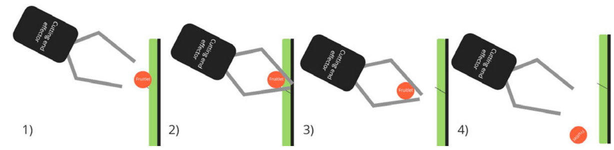

Fig. 2. Sequence of operation for the cutting end effector. 1) The end effector is ready for approach, 2) The end effectors cut the fruitlet using the finger which are actuated by servos, 3) The end effector moves away from the tree with the fruitlet and 4) The end effector drops it.

Based on the general arrangement, a cutting end effector was designed and manufactured as shown in Figure 3. Initial tests performed on the artificial fruitlet structure showed that the finger profile was slender and requires precise alignment of the fingers relative to the stalk to make a cut, as shown in Figure 3.

This alignment depends heavily on the computer vision system for precise positioning, presenting a significant challenge due to the obscured and complex growth structures common in commercial orchards. Consequently, the fingers of the cutting end effector were refined and redesigned to a hemispherical shape, enhancing flexibility in approach angle and reducing dependency on the computer vision system.

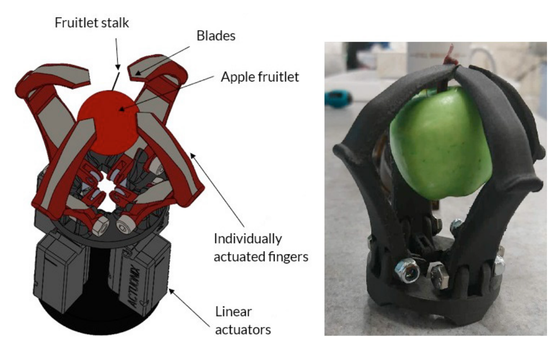

Fig. 3. General arrangement of the cutting end effectors operation mechanism.

Refinement of finger profiles for fruitlet cutting primarily focused on length and shape, as shown in Figure 4. As fruitlets expand throughout the season, their size becomes a critical design consideration. To accommodate increasing fruitlet sizes, the dimensions of the end effector's fingers must also increase. The force exerted at the fingertip is directly proportional to the finger's length; therefore, longer fingers demand higher torque to maintain the necessary force levels for cutting the stalk. A finger length of 110 mm was selected for the cutting end effector to handle fruitlets up to 50 mm in size. With this specified finger length and the selected servo, which delivers an output torque of 6.37 Nm, the end effectors finger can exert a force of 58 N.

The second factor considered was the contour refinement for the finger profile. An empirical observation was made during the fieldwork, noting that as the thinning season progressed, the fruitlets increased in size while their stalk length decreased. This reduction in stalk length rendered

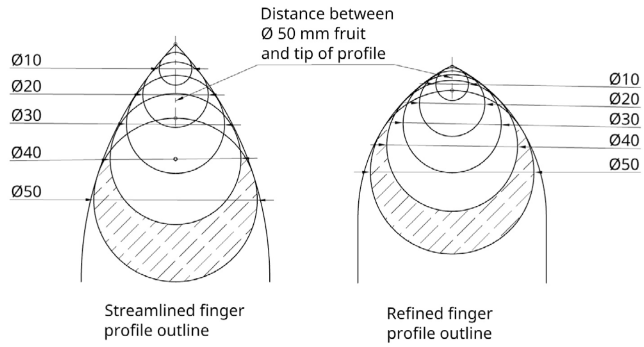

Fig. 4. Comparison of a streamlined finger profile vs a refined profile, illustrating fits of varying size fruitlets in the two profiles and the distance between a 50 mm diameter fruitlet surface and the profile tip.

the fruitlets less accessible. Additionally, the clusters of fruitlets became tighter, further complicating movement around them. Therefore, it is ideal to approach the cluster with a streamlined profile. However, if the profile is too streamlined, the fingers will be unable to accomplish closure due to the target fruit's obstruction, resulting in a failure to cut. To completely seal the fruit, as shown in Figure 4, a highly streamlined profile will need to travel deep within the cluster. During initial field trials, the streamlined profile and fingers couldn't close properly due to the short stalks and large fruitlets. A refined profile could address this issue. To achieve this, it's crucial to consider factors such as fruitlet size and the decreasing stalk length.

Thirty samples of fruitlet stalk length were recorded during week 2, revealing an average stalk length of 27 mm with a corresponding fruitlet diameter of 29 mm. Both the streamlined and refined profiles are capable of cutting the fruitlet. However, the streamlined profile's cut point needs to be positioned 12 mm from the starting point of the fruitlet to achieve a successful cut. This extended positioning is necessary because the streamlined profile's geometry would otherwise collide with the fruitlet's shape, preventing the gripper from fully closing. In contrast, the refined finger profile was specifically designed with the apple fruitlet's contours, allowing the gripper to close effectively and make a precise cut with significantly less travel along the calyx. Therefore, the refined finger profile was chosen because its tailored profile is sufficiently streamlined to navigate into the cluster, requiring a shorter effective stalk length for a successful cut compared to the streamlined profile, which offers a more efficient and reliable cutting operation.

The end effector was developed to incorporate four finger profiles, rotary servo motors, and blades, as shown in Figure 6. The overall system architecture is shown in Figure 5. The chassis and fingers were fabricated using Fused Deposition Modeling (FDM) 3D printing technology. ONYX, a high strength thermoplastic reinforced with chopped carbon fibres, was selected for its excellent surface finish, and superior mechanical properties Chen et al. (2022).

The overall dimensions of the end effector are influenced by three key factors. The first consideration is the size of the fruitlets to be processed. This informs the refinement

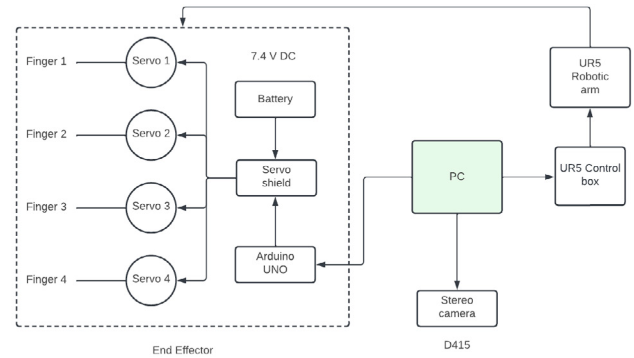

Fig. 5. Overall systems diagram for the robotic end effector system.

of the finger profile and the selection of an actuator that delivers the necessary force or torque for thinning operations. The final design phase focuses on arranging these components compactly and efficiently within the available space. The resulting end effector, with a four circular pattern configuration, has dimensions of 262 mm in length and 154 mm in width.

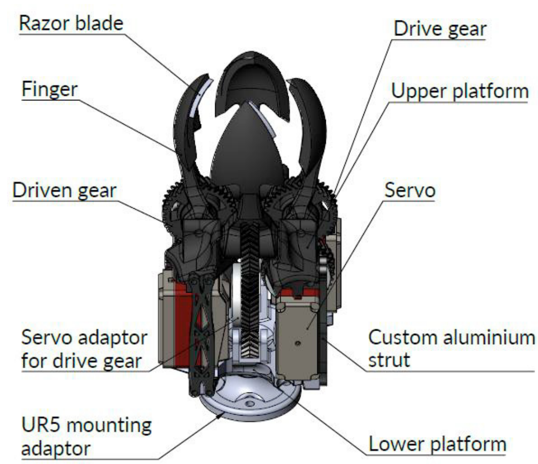

Fig. 6. CAD model of cutting end effector.

4. RESULTS AND DISCUSSION

4.1 Lab evaluation

The cutting end effector was subject to lab trials on a single and a clustered artificial fruitlets and was integrated with an off the shelf UR5 robot arm and vision system that can detect and localise fruitlets position in real time. Additionally, a path planning systems was also developed to manipulate the end effector towards the target fruitlet. The experimental setup, the vision system and the path planning system is described in this paper Jangali (2024).

For the single fruitlet evaluation, the cutting end effector was tested by approaching the fruitlet for removal 10 times at various angles, ranging from 90 to 30 deg, as shown in Figure 7. The end effector achieved a 100% success rate within the angle range of 90 to 45 deg. However, it failed to remove the fruitlet at angles below 30 deg, primarily due

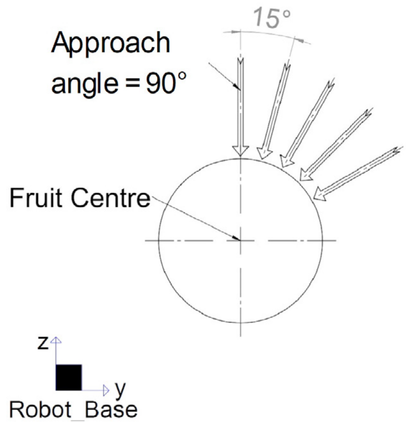

Fig. 7. Approach angle schematic of fruitlet side view.

to the path planning algorithm being unable to generate viable paths for approach angles beyond this threshold.

In the second experiment, the end effector was evaluated on a cluster of three fruitlets in five distinct positions, with the target fruitlet's spot varying with each position. Three approach angles ranging from 90 deg to 60 deg were tested for each position. The results from the second experiment are presented in Table 2. The end effector exhibited the lowest success rate at a 90 deg approach angle in position 1, achieving a 0% success rate. This failure can be attributed to limitations in the artificial fruitlet setup. As the end effector moves into the cutting position, its fingers push the surrounding fruitlets aside. Since the entire cluster is attached to a single main stem, displacing one fruitlet causes the entire cluster to move. This makes the fruitlets inaccessible to the cutting fingers, ultimately leading to the failure.

Table 2. Clustered fruitlet removal results.

Position	**90 Deg**	**75 Deg**	**60 Deg**
Position 1	0	100	90
Position 2	30	100	100
Position 3	75	75	95
Position 4	95	85	95
Position 5	100	100	15

The success rate improves as the position changes, particularly when there are no adjacent fruitlets obstructing the target fruitlet and it aligns properly within the cutting fingers. The success rate gradually increases starting from position 3, reaching 100 percent in positions 4 and 5. This improvement is primarily because the surrounding fruitlets no longer interfere with the end effector's movement into the cutting position.

At a 75 deg approach angle, the cutting success rate starts at 100 percent in position 1 and remains consistently high across the other positions. This is due to the 75 deg angle allowing the target fruitlet to align between the cutting fingers, even as the remaining fingers push the surrounding fruitlets aside. A similar trend is observed at a 60 deg approach angle, except in position 5. At this angle in position 5, the surrounding fruitlets lie directly in the path of the end effector's fingers, causing a collision during approach. This significant disruption prevents the target fruitlet from being properly positioned between the cutting fingers, leading to a failure in that specific case.

4.2 Field evaluation

This section describes the experimental methodology used to evaluate the performance and applicability of the cutting end effector in a commercial orchard setting, specifically on a two dimensional apple tree canopy. The trials were conducted during the apple thinning season in the Hawkes Bay region, spanning from the last week of November to the end of the first week of December. During this period, the fruit diameter ranged between 20 and 30 mm. The experiments utilised the apple variety "Lady in Red" for testing.

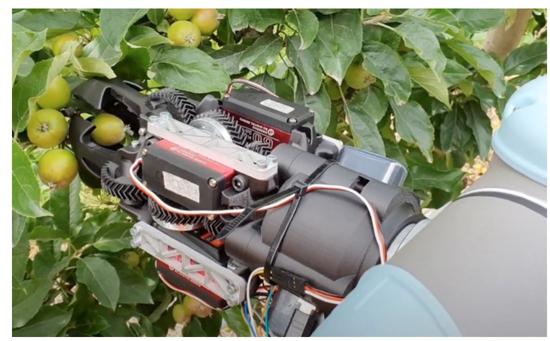

Fig. 8. Cutting end effector during field trials in a commercial orchard.

The vision system for detecting and locating fruitlets in the field was developed by our collaborators in the MaaraTech team and, therefore, was not the focus of this study. To replicate the laboratory evaluation described in the previous section, the following steps were carried out to enable a direct point to point path planning system:

(1) Position the mini rig platform within 500 mm of the apple tree canopy.
(2) Manually identify the target fruitlet.
(3) Attach the end effector being tested to the UR5 robotic arm.
(4) Manually guide the robotic arm, equipped with the end effector, to the surface of the target fruitlet.
(5) Record the surface coordinates of the fruitlet using the UR5 robotic arm's coordinate system, then move the arm away from the fruitlet.
(6) Execute the path planning program.

The cutting end effector was tested in 50 attempts to remove fruitlets from the tree, achieving success in 22 instances, resulting in a 44 percent success rate. The failures during the field trials can be attributed to three main categories: position error, occlusion, and manual positioning of the robot. Position error emerged as the most significant cause of failure across all end effectors. This was primarily due to the manual estimation of the fruitlet's center using the UR5 robotic arm and the manual alignment of the pre approach position, as no vision system was available to accurately localise the target fruitlet. These manual processes led to discrepancies between the target position and the actual position of the fruitlet, contributing to the failures.

5. CONCLUSION

This study detailed the development of a robotic end effector for apple fruitlet thinning, emphasising cutting blade selection, finger profile refinement, and iterative lab based refinement. Laboratory trials on artificial fruitlet achieved a 100% success rate on single fruitlets within approach angles of 90 to 30 deg range, while clustered fruitlet tests demonstrated high precision at 75 deg, validating the system's mechanical design. However, field trials in a commercial orchard revealed a reduced success rate of 44%, primarily due to positional inaccuracies and the absence of a vision system for real time detection and localisation. These findings underscore the critical requirement of environmental adaptability as a requirement for the end effector and sensor integration to overcome the challenged in transitioning from controlled lab settings to dynamic orchard conditions. Future work will prioritise integrating a consistent vision that can detect and localise fruitlets in the field in real time as well as integration of vision based control of the end effector based on the physical characteristics of the target fruitlet.

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