

128. Evaluation of a gripper for a dragon fruit harvesting robot

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Abstract

Dragon fruit, or pitahaya, is a tropical fruit of growing interest in the European market. This study evaluates two new robot grippers for harvesting pitahayas with a robot with two cutting devices: a vibration blade and pneumatic scissors. Four pneumatically actuated fingers were built to collect the pitahayas. Experiments revealed three main challenges for detaching and collecting dragon fruits: the high weight of each piece, the risk of physical damage at grasping, and the difficult access to the peduncle targeted by the cutter tool. Despite these challenges, over 75% of ripened fruits were successfully detached and collected, with less than 12% of 'Purple' fruits sustaining damage. In conclusion, both designs could be a possible solution for a robot harvesting delicate fruits.

Keywords: dragon fruit, fruit damage, gripper, harvesting robot

Introduction

Dragon fruit is a high-value tropical fruit with numerous healthy nutritional components (Arivalagan *et al.*, 2021). The quality rating for this fruit is essential as it is highly susceptible to damage and undergoes rapid senescence after harvesting (Huang and Zhao, 2024). Mechanical damage to various fresh fruits has been extensively studied by different authors (Li & Thomas, 2014; Opara and Pathare, 2014; Hussein *et al.*, 2020; Rashvand *et al.*, 2022). Manual fruit harvesting is costly, time-intensive, and labor-demanding (Afsah-Hejri *et al.*, 2022). Mechanical harvesting could be a viable option for cost reduction, but the risk of fruit damage restricts its development (Shewfelt and Prussia, 2022). Over the past decades, robots for harvesting fruit and vegetables have been actively developed to address limited labor resources and high harvesting costs (Xiao *et al.*, 2024). However, progress in this area remains limited, and the adoption of harvesting robots in orchards has not been broadly implemented (Rajendran *et al.*, 2023). One of the most delicate issues in robotic harvesting is the detaching and grasping of the fruit, as the gripper must handle a delicate product susceptible to mechanical damage (Sarkar, 2021; Vrochidou *et al.*, 2022). Zhou *et al.* (2022) found that 27 out of 47 applications utilized external force on the fruit, whereas 20 out of 27 picked the fruit with no pericarp contact. Contactless handling is beneficial as it reduces the rate of fruit damage and is predominantly employed in harvesting fragile fruits such as strawberries and tomatoes. Numerous methods for detaching fruits are based on the application of external force to the stems, classified into five categories: stem cutting, stem pulling, fruit twisting, fruit pulling, and vacuum application (Han *et al.*, 2024). End-effector designs are typically activated pneumatically or electrically (Davidson *et al.*, 2020). Pneumatic end-effectors are ideal for delicate or irregularly shaped objects, while electrically activated end-effectors offer precise control and integration with advanced systems (Chen *et al.*, 2014). The choice between pneumatic and electric actuation depends on the specific task and environment. The effectiveness of a gripper in harvesting depends on its design and the physical characteristics of the fruits and vegetables (Bac *et al.*, 2016). Soft grippers, made from flexible materials, are ideal for handling delicate products, minimizing the risk of bruising (Abo-Zaid *et al.*, 2024; Liu *et al.*, 2023; Navas *et al.*, 2021). Robotic harvesting of dragon fruits is challenging due to their weight, fragility, and the lignified pedicel within the flesh. This paper presents the design, construction, and evaluation of a custom robot gripper for harvesting dragon fruits.

Materials and methods

The two robot grippers' designs with two different cutting end-effectors: electrically actuated with a vibration blade and pneumatically actuated with scissors. Four pneumatic actuated 3D printed fingers were used for collecting the pitahayas. The tests were carried out in two different experiments. In a first step (July 2024), the grippers were tested manually. In a second step (October 2024), the grippers were tested mounted on the collaborative robot (Universal Robots, UR5e, Barcelona, Spain, <https://www.universal-robots.com>) fixed to a wheeled platform (Figure 1). A set of 60 fruits was collected with the robot gripper in July and 27 fruits in October.

Robot gripper with saw

The gripper, weighing 1.8 kg, has four TPU fingers made via 3D laser sintering, capable of handling pitahayas with diameters of 60–100 mm, lengths of 60–160 mm, and weights of up to 500 g (Figure 2). Its fingers adapt independently to the fruit's shape, and a PLA chassis, created through FDM printing, supports the structure. The gripper fingers have no force control, and the robot controls them through a digital signal to wrap and secure the fruit. A net prevents the fruit from falling after the peduncle is cut. The cutting system includes a vibrating saw blade powered by a 105-W brushless motor, with speed regulated by pulse-width modulation. The gripper fingers have three positions: vacuum (-0.7 MPa), atmospheric pressure, and positive pressure (0.30 MPa). The vacuum process is applied with an ejector (ZH13DSA, SMC, Kashiwanoha, Japan, <https://www.smc.eu>), increasing the opening range of the fingers. The control of these three positions is managed through a 5/3 closed-centre solenoid valve (SY5320-5LOU-01F-Q, SMC, <https://www.smc.eu>) with three positions: suction, lock, and pressure, controlled by two digital signals.

Robot gripper with scissors

This gripper (Figure 3) has four fingers working similarly to the gripper with the saw. The gripper, weighing 2 kg, uses scissor blades activated by a pneumatic cylinder (C55C40-30M, ISO 21287, SMC) at 0.45 MPa, controlled by a 5/2 solenoid valve (SY5120-5WAOU-01F-Q, SMC). The blades

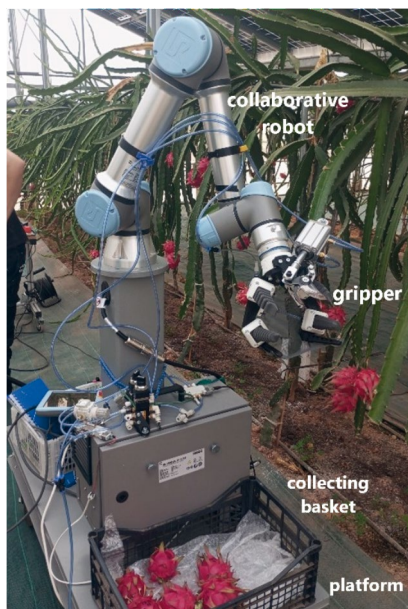


Figure 1. The platform, robot UR5e, scissors gripper and devices used during harvesting.

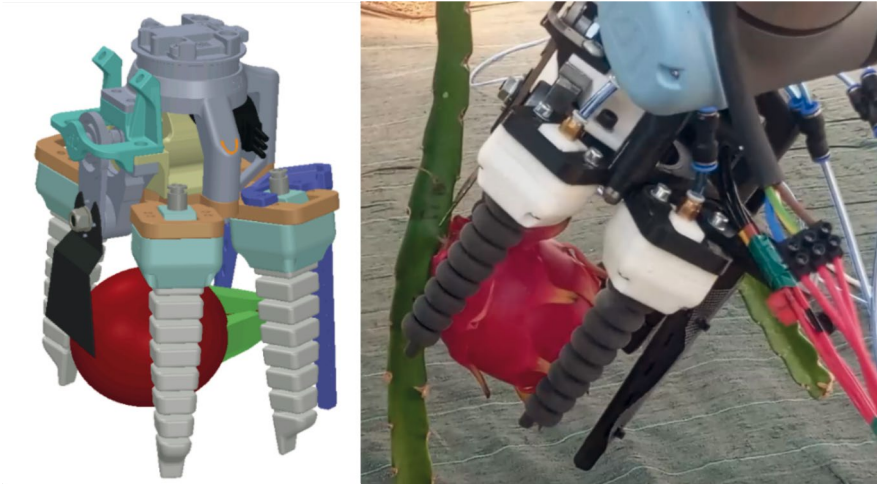


Figure 2. Robot gripper with saw blade CAD model and operation during harvesting.

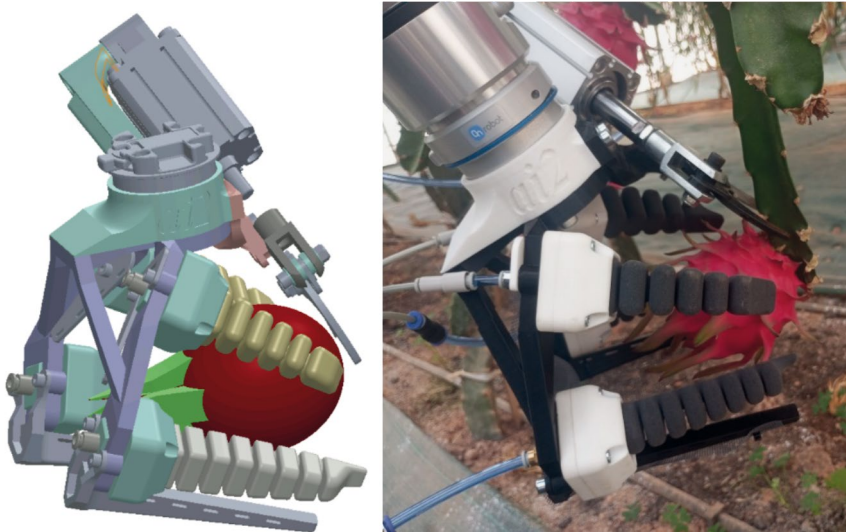


Figure 3. Robot gripper with saw blade CAD model and operation during harvesting.

have a 50 mm opening range and a 40 mm depth, which makes them suitable for handling pithayas similar in size to those harvested by vibration. A net is opposite the cutting area to prevent fruit from falling after harvesting.

Robot process and gripper operation

The process of the robot's movements and operations is shown in Figure 4. The pick position is not fixed and is determined by the robot's interaction when in force mode with the plant. For the gripper with the saw blade in phase 3 of Figure 4, the saw blade contacts the plant looking for 3N, at 45° to the stem, against the peduncle. After that, fingers secure the pithaya, the blade is activated, and the robot exerts 40N parallel to the stem until the pithaya drops. In phase 6, the robot turns the gripper around the fruit peduncle and moves back. The following phases are fixed positions where

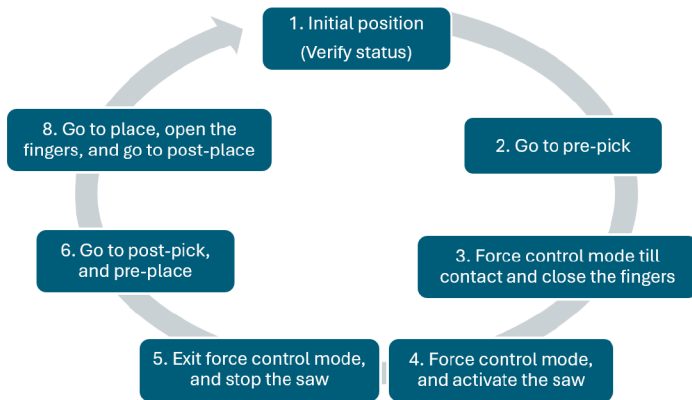


Figure 4. Robot and gripper process during harvesting.

the robot moves to deposit the pitahaya and restart the cycle. For the gripper with the scissors, the blades contact the plant, the robot activates the scissors without activating force control mode, and the process continues. In this case, it is verified that the force exerted during post-pick is not high, ensuring the fruit has detached from the plant and the cut was sufficient.

Fruit characterization

After collecting the dragon fruits, all the fruits tested with the grippers were taken to the laboratory to assess fruit damage and carry out the characterization measurements. An image analysis prototype, developed by Greenvision (GreenVision Quality Sorting Systems, Valencia, Spain, <https://www.greenvision.com>), was used to measure area, maximum diagonal, minimum diagonal, perimeter, and RGB colour coordinates. Fruit weight was measured using a digital balance (AL104 electronic balance, Mettler Toledo, Greifensee, Switzerland, <https://www.mt.com>). Fruit firmness was measured using a universal stress strain machine (model IBTH 2730 Ibertest, Madrid, Spain, <https://www.ibertest.es>), with a constant speed of 1.67 m/s. The firmness of each fruit was measured at three points of the equatorial area by using a 0.008 m probe, with (whole fruit firmness) and without peel (fruit flesh firmness). Three repetitions were carried out per test and fruit. The soluble solid content was determined with a digital refractometer (model PAL-3, Atago, Tokyo, Japan, <https://www.atago.net>).

Results

In the two seasons analyzed, significant differences were found in the descriptive magnitudes of the fruits harvested by the robot gripper between the two seasons and varieties ('Purple' and 'Nevada'), as specified in Table 1. Fruits from July were harvested in a less ripeness stage, and they had larger size and lower soluble solid content. However, external colour parameters did not show a specific profile.

The study found that 86.7% of fruits were successfully detached and collected using the gripper without the collaborative robot, with 88.9% success using the electric system and 80.0% with the pneumatic system. When using the gripper on the collaborative robot, the success rate dropped to 66.7%, suggesting positioning issues with the robotic arm. For the 'Purple' variety, only 11.7% of fruits were damaged without the collaborative robot and 8.3% with it. However, 26.7% of 'Nevada' fruits were damaged with the collaborative robot, indicating a higher susceptibility to damage. Most damages were due to cuts from the cutting end-effector, with no compression damage from the gripper fingers.

Table 1. Destructive and non-destructive fruit descriptive magnitudes (average and standard error) of the fruit harvested with the robotic gripper in July and October.

	July	October	
	'Purple' variety (60 fruits)	'Purple' variety (12 fruits)	'Nevada' variety (14 fruits)
Weight (g)	320.3 (11.34) ^a	271.2 (23.8) ^{ab}	263.8 (22.0) ^b
Area (mm ²)	8402.2 (210.6) ^a	6510.8 (446.751) ^b	716.2 (343.8) ^b
Perimeter (mm)	652.1 (13.0) ^a	288.3 (27.4) ^b	308.7 (25.4) ^b
Maximum diameter (mm)	115.6 (1.7) ^a	100.4 (3.5) ^b	113.1 (3.1) ^a
Minimum diameter (mm)	97.3 (1.3) ^a	81.2 (2.7) ^b	79.2 (2.2) ^b
Destructive firmness (N/mm)	3.30 (0.05) ^a	3.21 (0.11) ^a	3.26 (0.7) ^a
Soluble solid content (°Brix)	13.1 (0.2) ^a	14.3 (0.5) ^b	15.0 (0.2) ^b
External colour B	35.4 (0.7) ^a	37.2 (1.5) ^a	42.1 (1.5) ^b
External colour G	48.2 (0.9) ^a	26.8 (2.0) ^b	42.2 (1.3) ^a
External Colour R	107.5 (1.7) ^a	99.6 (3.6) ^a	105.3 (3.5) ^a

Values followed by the same superscript letter are not significantly different at the 5% level.

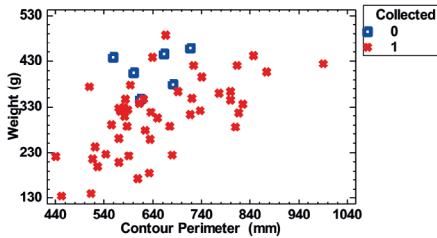


Figure 5. Damages produced by the robot gripper.

The study found no significant differences in fruit damage between two robot gripper designs with different cutting end-effectors: an electrically actuated vibration blade and pneumatically actuated scissors (Chi-square p -value >0.05). However, the electric vibration blade caused more damage (12.6%) compared to the pneumatic scissors (less than 9.2%). There was no significant difference in the gripper's collecting capacity based on the fruit's location on the plant (high, medium, low) or orientation (downwards slanted, non-slanted, upwards slanted) (Chi-square p -value >0.05).

The difficulty in collecting the fruit was not related to the positioning or orientation of the tested fruits, which were mostly isolated on the plant. A step-by-step discriminant analysis showed that for the 'Purple' variety, handled without the collaborative robot, 85.2% of dragon fruits were correctly classified based on weight and perimeter. For the 'Nevada' variety, handled with the collaborative robot, 85.7% were correctly classified based on weight alone. All non-collected fruits were correctly discriminated using size-related variables, indicating that larger fruits are more difficult for the grippers to collect.

Dispersion diagram to classify collected 'Purple' dragon fruits



Dispersion diagram to classify collected 'Purple' dragon fruits

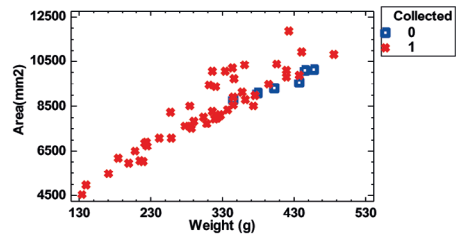


Figure 6. (Left) Dispersion diagram of the collected fruits discrimination according to weight (g) and perimeter (mm), 'Purple variety (non-collected =0; collected=1). (Right) Discriminant analysis to classify collected fruits according to area (mm²) and weight (g), (damaged fruits=0, non-damaged fruits=1).

Similar results were obtained when analyzing the fruit parameters related to producing damage during grasping and detaching. Fruits were correctly classified based on the variables Weight (g) and Area (mm²) (83.3% of well-classified 'Purple' pitahayas collected by the gripper, without the collaborative robot) (Figure 7). No effect of the variables related to the ripeness stage on fruit damage was detected. Similar results were found when studying the variety 'Nevada'. In both cases (collected fruit and damaged fruit discrimination), size related variables of the fruits were selected to perform the discrimination out of the descriptive magnitudes of the fruits listed in Table 1. These results explain the effect of the fruit size on the capability of the gripper to detach the fruit without causing damage, with failures and damages starting from 330 g. No relation was detected between the damage produced by the gripper and the ripeness stage of the fruit, considering that the fruits were collected during the harvesting maturity stage. Most of the fruits were properly detached by the gripper end effector and handled by the robot fingers without producing damage to the dragon fruit.

Conclusions

The research showed that over 75% of ripened dragon fruits were successfully detached and collected, with 86.7% success using grippers without the collaborative robot and 66.7% with the robot. Less than 12% of the 'Purple' variety fruits were damaged, indicating the grippers' potential for delicate handling. No significant differences in detachment success were found between the two powering systems, but pneumatic scissors caused less damage than the electric vibration blade. Fruit damage was not related to firmness or sugar content, but 'Nevada' variety fruits were more damaged. Fruit size significantly affected detachment success and damage, with issues starting from 330 g. Cleanliness and accessibility of the fruit are crucial for successful harvesting. The gripper's parameters should be adapted to each fruit to improve success and prevent damage. High precision in determining the peduncle's position and orientation is also necessary. The proposed designs offer feasible solutions for mobile harvesting robots for delicate fruits like dragon fruits.

Acknowledgements

This scientific article is part of the project "Recolección inteligente y automatizada de cultivos de alto valor en invernaderos sostenibles (DRAGONBOT: INNEST/2023/106)" translated in English as "Smart and Automated Harvesting of High-Value Crops in Sustainable Greenhouses" funded by "Agencia Valenciana de la Innovació (AVI)".

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