Development of the End-Effector of a Picking Robot for Greenhouse-Grown Tomatoes

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Abstract—The objective of this study is to develop a grip type end-effector for use in a picking robot designed to harvest greenhouse-grown tomatoes. The end-effector was designed with four fingers that have foam sponge pads inside to reduce damaging the fruit when bending and gripping. By controlling solenoid activation, the fingers are bent to reduce the opening of the tip, securing the fruit inside the end-effector. The center of the end-effector is a fruit suction device, which assists the fixation of fruit to the inside of end-effector, enhancing the holding performance. Test results show that the best suction performance is achieved using vacuum suction nozzles 15.0 mm in diameter and a suction force of 8.1 N/cm². The average suction attachment success rate is 95.3% and the average picking time is 74.6 s for each fruit. Future integration with robotic tomato-harvesting systems for actual field tests of tomato picking should increase the feasibility of developing automatic robotic picking systems.

Keywords: Automation, Harvesting, Vacuum suction.

I. INTRODUCTION

Tomatoes are an important crop with a high economic value; they are grown widely by farmers in Taiwan, with a total growth area of 4,762 hectares. However, greenhouse-grown tomatoes have long been harvested manually, which is a substantial drain of manpower. Thus, developing automatic harvesting robots for tomatoes is extremely necessary. The design of the picking end-effector is a crucial aspect of this development.

The research community has had a sustained interest in designing robots for agricultural harvesting. Van Henten et al. (2003) designed an autonomous robot for harvesting cucumbers in greenhouses. This robot comprises a six-axis robotic arm and a collision-free motion path planning algorithm. The average success rate for harvesting high-wire grown cucumbers was 74.4%, with an average harvest cycle time of 65.2 s per cucumber. Ling et al. (2004) used fruit identification technologies and identified the mature tomatoes using sensor signals. A lightweight four-fingered triple-jointed end-effector was attached to the robotic arm. A vacuum system was affixed to its central axis. The extension and retraction of the vacuum suction nozzle was coordinated with the bending of the fingers. The average time required to harvest one tomato was approximately 3 min 37 s. Tanigaki et al. (2008) examined cherry harvesting robots. Lasers and infrared lights were used to precisely position the fruit to prevent collisions with other fruit when the end-effector performs a deep cut. Johan et al. (2008) devised various automated apple picking robots. These robots used an industrial-grade six-axis mechanical arm and specialized end-effector for picking. The end-effector comprised a silicone funnel and vacuum suction equipment. A camera was also installed to identify, position, and assess the maturity of the fruit. The average image processing time was 8 to 10 s. The harvest success rate of this robot was approximately 80% for fruit 6 mm to 11 mm in diameter.

The terminal manipulation and operation of robotic arms and end-effectors designed to perform specific movements is crucial for successful harvesting using robots. Custom-designed end-effectors that satisfy the need to perform various movements using robotic arms are crucial to successful harvesting. Appropriate end-effector designs can enhance the operational stability and efficiency. Considering the end-effector designed by Kondo et al. (2010) for harvesting a string of tomatoes, the end-effector comprised two fingers that gripped and one light sensor kit. The harvest success rate was 50%. Applying this design in a high-wire cultivation system should increase the success rate. Reed et al. (2001) developed an automatic robotic mushroom harvesting rig that employs a monochrome camera for locating and measuring the fruit. The end-effector design includes vacuum suction and two fingers with differently sized suction nozzles that can be rotated and used for mushrooms of different sizes. Over 80% of the attempts to pick mushrooms were successful. Arima et al. (2004) developed a harvesting robot for strawberries grown in hanging plant beds. This end-effector employs vacuum suction, three pairs of photo interrupters, and cutters. The fruit is then sucked into the tip of the end-effector. Next, the end-effector tip rotates to guide the peduncle into the corner with the cutter, which then cuts the fruit from the plant. The fruit is then delivered to the tray via the transport tube.

This study designs an end-effector system for picking greenhouse-grown tomatoes, which can be installed on the self-propelling automatic tomato harvesting robot developed by Chiu et al. (2012). The end-effector was designed as a four-finger gripper. Electromagnets are employed to bend the fingers, which enhances the end-effector’s gripping capability. A vacuum suction device immobilizes the fruit to isolate it from the plant before picking.
II. MATERIAL AND METHODS

2.1 Robotic system for tomato picking

This study designs an end-effector to be integrated in the automatic tomato picking robot system. The system includes a five-axis robotic arm, a picking end-effector, machine vision, moving vehicle, and a control system. The system architecture is shown in Fig. 1. The control system is constructed using the graphic-based programming language LabVIEW version 7.1.

Fig. 1. Diagram of a tomato picking robot.

2.2 Design of the picking end-effector

Figure 2 is a diagram of the tomato picking end-effector design. The designed end-effector is a four-fingered gripper comprising fingers, a spring plate, a fruit suction device, and finger bending mechanisms. Each finger has four sections and a total length of 138 mm. The lengths of the four sections are 36 mm, 32 mm, 37 mm, and 33 mm. All the joints between the sections are flexible and provide cushioning when grabbing the tomatoes. Soft foam rubber was placed on each finger section to prevent damage to the fruit surface. The four fingers were divided into two sets, installed on the left and right open-close chucks, and controlled using the sideways open-close chuck at the tip of the robotic arm. The open-close chucks measured 140 mm x 139 mm and were designed to fit together during sideways movements. The distance between the opened and closed positions was 30 mm.

Fig. 2. The tomato picking end-effector prototype.

When the open-close chucks are open, the opening at the tip of end-effector is oval-shaped, with a horizontal width of 85 mm and vertical height of 60 mm. Because the open-close chucks move sideways at a distance of 30 m, the opening of the tip of the end-effector is 60 mm wide and 60 mm high, forming a round opening that is 60 mm in diameter. When the solenoids pull the spring plates on the inside of the fingers, the fingers bend, reducing the opening of the tip of the end-effector to a 40-mm circle. This secures the tomato within the end-effector.

To pull tomatoes inside the end-effector during picking, a twin-axis pneumatic cylinder drives the vacuum suction nozzle to extend and retract, pulling the fruit from the plant into the gripping area. This reduces collisions between the end-effector and the stalk, preventing damage. Using vacuum suction to secure fruit and prevent them from shaking enhances the holding performance of the end-effector by enabling the fruit to remain in the gripper with more stability. The fruit suction device includes an air compressor, five-way two-position solenoid valve, twin-axis pneumatic cylinder, vacuum generator, and suction nozzle. The main movements are divided into two categories, fruit suction and fruit traction. A vacuum suction nozzle is installed on a round platform, which is connected to the twin-axis pneumatic cylinder. Through the action of the twin-axis pneumatic cylinder, the suction nozzle telescopes forward and backward, drawing the fruit from the plant for rotational picking maneuvers, thereby reducing damage to the plant.

Figure 3 shows the finger bending mechanism, which includes a spring plate, wire, and solenoid. One spring plate is inserted into each of the four fingers, with a wire connecting the tip to the solenoid. When the solenoid is magnetized, it pulls the steel wire on the inside of the finger, drawing the tip in and forcing the spring plate to bend. This causes the four sections of the fingers to curl similarly to human fingers when gripping something. Limit switches that control the finger curving extent were inserted into the base of the fingers. When the four fingers curl together, the opening of the tip of the end-effector shrinks, enhancing its grip of the fruit. This study used a tubular solenoid manufactured by Shih Shin (item number SH-T2551L). The nominal voltage was DC 12V, with a nominal current of 0.83 A. The magnetic force is 1.40 gf with a 10 mm travel distance.

Fig. 3. Finger bending mechanism.

2.3 Picking action flow

Figure 4 is the overall picking action flowchart. First, an image is obtained using a binocular vision system to determine whether the fruit is sufficiently mature. If yes, the three-dimensional coordinate of each mature fruit is calculated. The coordinate information is then delivered to the robotic arm, which begins the picking operation. The robotic arm is first positioned in front of the fruit; then the open-close chuck drives the fingers to open. The twin-axis
pneumatic cylinder pushes the vacuum suction nozzle outward to grasp the tomato. To enhance the suction success rate, the mechanical arm drives the end-effector to perform vertical up and down inching movements to increase the likelihood of a good fit between the suction nozzle and the fruit surface. Once the fruit is held by the suction, the twin-axis pneumatic cylinder retracts the vacuum suction nozzle, pulling the fruit inside the end-effector. Then, the open-close chuck closes and the solenoids pull the wires, causing the four fingers to bend and clamp simultaneously, thereby securing the fruit. Next, the end-effector detaches the fruit through rotation, and then places the fruit inside the fruit basket, completing one picking cycle.

Fig. 4. Action flow of the picking end-effector with vacuum suction device.

2.4 Experimental methods

2.4.1 Tomato physical property check

The main item picked by the end-effector in this study is the Momotaro tomato. The major axis, minor axis, height, and weight of several tomatoes were measured. We measured 50 tomatoes in total. The mean and standard deviation of each measurement were calculated and used as the foundation for this experiment.

2.4.2 Test of vacuum suction force on fruit

To determine the appropriate degree of vacuum for the fruit suction device, we used a triple-fold type suction nozzle 15 mm in diameter for the suction tests. Five vacuum suction powers were tested on five tomatoes of varying size. The tested suction forces were 9.1 N/cm² (683.0 Torr), 8.6 N/cm² (645.5 Torr), 8.1 N/cm² (608.0 Torr), 7.7 N/cm² (577.9 Torr), and 7.2 N/cm² (540.4 Torr). The tomatoes used in the experiment weighed 112 g, 148 g, 186 g, 215 g, and 278 g. Each test was repeated 30 times to calculate the suction success rate.

2.4.3 Suction nozzle diameter tests

Different suction nozzle diameters produce varying levels of suction power. Furthermore, because fruit is not entirely spherical, the diameter of the suction nozzle affects the ability to create an air-tight seal between the suction nozzle and the fruit. Previous studies have shown that suction nozzles with a smaller diameter generate superior air-tightness and a higher suction attachment success rate (Ling et al., 2004). Therefore, for this study, we examined four suction nozzles of varying diameter during the experiment, namely, 15.0 mm, 17.6 mm, 18.2 mm, and 19.5 mm. The suction nozzles were made from rubber and tested during the vacuum power tests explained in Section 2.4.2. The test tomatoes weighed 112 g, 148 g, 186 g, 215 g, and 278 g. Each test was repeated 30 times to calculate the suction success rate.

2.4.4 The effect of various inching movement types on the suction success rate

Because the suction nozzle may not always attach to the fruit properly because of the contact position, angle, or surface undulation, we designed the arm to perform an inching motion when the suction nozzle contacts the fruit (vertical, sideways, and back and forth). Thus, the surface of the fruit and the suction nozzle have a greater likelihood of achieving an air-tight seal, increasing the suction success rate. The factors examined included the inching motion, inching distance, and fruit weight. Three types of inching movements are performed, namely, up/down, left/right, and forward/backward. The three tomatoes examined weighed 112 g, 148 g, and 186 g. The major axis length of each sample was 64.3 mm, 72.4 mm, and 81.8 mm. The experiments conducted in this study adopted a Latin square design; the results are shown in Table I. Each combination was tested 30 times to calculate the suction success rate.

### Table I.

<table>
<thead>
<tr>
<th>Inchering distance, mm</th>
<th>Inchering type</th>
<th>Vertical</th>
<th>Sideways</th>
<th>Back and forth</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>A</td>
<td></td>
<td></td>
<td>B</td>
</tr>
<tr>
<td>40</td>
<td>B</td>
<td>A</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>C</td>
<td>B</td>
<td>A</td>
<td>D</td>
</tr>
</tbody>
</table>

In Table I, A denotes the fruit that was 64.3-mm diameter, B denotes the 72.4-mm fruit, and C denotes the 81.8-mm fruit.

2.4.5 End-effector holding force test

Figure 5 shows a diagram of the holding force test. The primary goal of this test was to examine the end-effector’s ability to hold fruits of various sizes and weights. For this test, a test ball is held by the end-effector, and the minimum instant pull force that can pull the test ball from the grip of the end-effector is determined. One end of the force gauge was held by hand while the other end holds the test ball in a net. A video camera was used to record the change of the gauge indicator to assist in reading the data for every test record.
The end-effector was tested in three modes with different suction strengths: (1) gripper hold without vacuum suction; (2) gripper hold with 8.1 N/cm² of vacuum suction; and (3) gripper hold with 7.2 N/cm² of vacuum suction. Each test combination was repeated 20 times and assessed using analysis of variance (ANOVA). The correlation curve between the volume and weight regarding the holding capability was also established. The test balls were divided into two types according to their weight and volume:

(I) Test balls of the same weight but different volumes: Styrofoam balls with diameters of 60 mm, 70 mm, and 80 mm were embedded with a 150 g weight for grip tests.

(II) Test balls with the same volume but different weights: Styrofoam balls 80 mm in diameter were embedded with 100 g, 150 g, and 200 g for grip tests.

2.4.6 Different twisting arrangements test

To validate the suction force of the end-effector and the force required to pick tomatoes, we examined the tomato picking force in actual plantation areas. In normal picking operations, farmers first twist and then bend the peduncle of the stalk to harvest the fruit. Therefore, this study examines two methods of fruit picking, that is, with twisting and without twisting. The force gauge holds the tomato using a net, and then pulls the tomato to determine the required force. The twisting operation was categorized into three levels according to the rotation angles: (1) clockwise for 60° followed by a counterclockwise turn of 120° until the fruit is 60° counterclockwise to the starting alignment, repeated three times; (2) clockwise for 90° followed by a counterclockwise turn of 180° until the fruit is 90° counterclockwise to the starting alignment, repeated three times; and (3) clockwise for 120° followed by a counterclockwise turn of 240° until the fruit is 120° counterclockwise to the starting alignment, repeated three times. The twist angles were measured using angle plates. Each test was repeated 20 times.

2.4.7 Picking test with actual tomato plants

To examine the suction effect of the fruit suction device on fruits growing from actual plants, the vacuum force, suction nozzle diameter, and inching method investigated in Sections 2.4.2, 2.4.3, and 2.4.4 were used for suction tests on actual fruit. The robotic arm determines the coordinates of the tomato to be picked using the visual system, which drives the robotic arm to perform the picking operation. The success criterion was the adherence of the fruit to the suction nozzle, and the removal of the fruit from the plant. Tests were conducted on 25 fruits, and the success rate was calculated.

III. RESULTS AND DISCUSSIONS

3.1 Tomato physical property analysis

The tomato samples used in this study were obtained from the Zhou Deng Xiang farm in Zhuang Wei Township, Yilan County, and measured in a laboratory. We randomly selected 50 tomatoes as the study samples. The results show that the mean and standard deviation was 74.5±4.9 mm for the major axis; 68.7±6.1 mm for the minor axis; 67.5±4.5 mm for the height; and 165±23.2 g for the weight. Figure 6 shows the regression relationship between the major axis (x) and the weight(y). The regression equation was $y = 4.3185x - 156.68$, with the coefficient of determination $R^2 = 0.8368$. This shows that the volume and the weight of tomatoes are correlated. In other words, larger fruits are heavier. According to the results of the physical property test, the end-effector designed in this study is suitable for fruit with a diameter ranging between 60.0 mm and 90.0 mm and a weight ranging between 100 g to 200 g.

3.2 Analysis of fruit vacuum suction force

Figure 7 shows the suction success rate when using various suction forces and fruit weights. The curves indicate that higher suction forces provide a superior suction rate. When the vacuum suction force was increased to 8.1 N/cm², the success rate reached 86.7%. The average success rate was 94.0%. However, suction forces greater than 8.1 N/cm² offer no significant improvement. The ANOVA results show that both the suction force and the fruit weight significantly affect the suction success rate. The results also indicate that heavier fruits reduce the suction success rate. This is because the fruit tends to loosen suction when the vacuum suction attachment is retracted. No significant difference was observed for vacuum suction forces over 8.1 N/cm². Thus, we continued our study using vacuum suction force of 8.1 N/cm².

3.3 Results suction nozzle diameter tests

Figure 8 shows the suction success results for various combinations of tomato sizes and vacuum suction nozzle diameters. The results indicate that regardless of the fruit size, the suction nozzle with a 15-mm diameter had the highest success rate, with a low of 86.7% and an average of 95.3%. The average
success rates for the suction nozzles with a diameter of 17.6 mm, 18.2 mm, and 19.5 mm were 92.0%, 91.3%, and 88.0%, respectively. With larger suction nozzle diameters, larger tomatoes have higher success rates. This is because suction nozzles with a comparatively larger diameter require a greater fruit surface area, such as provided by larger tomatoes. The ANOVA results indicate that both the weight of the tomatoes and the vacuum suction nozzle diameters significantly affect the suction success rate. The laws of physics define pressure as the normal force divided by the contact area. Thus, if the vacuum suction force is fixed, smaller action areas generate greater negative pressures. Consequently, reducing the suction nozzle size increases the vacuum strength. For this study, we selected the 15-mm suction nozzle based on the above results.

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### 3.4 Test results of various inching movement types

Table II shows the results from the Latin square test of various inching movement types and their effects on the suction success rate. The results show that the vertical inching movement provides the highest suction success rate at 88.9%, followed by horizontal inching at 84.4%. The average success rate of back and forth inching was the lowest at 72.2%. Regardless of the inching movement type, the success rates are higher when the inching travel distances are further. The ANOVA results show that the inching movement type and inching travel distance significantly affects the success rate. The diameter of the fruit, however, has no significant influence. Thus, for this study, we used the vertical inching movement and a 60-mm travel distance.

<table>
<thead>
<tr>
<th>Inching travel distance, mm</th>
<th>Inching movement type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>A=83.3%</td>
</tr>
<tr>
<td>Horizontal</td>
<td>C=80.0%</td>
</tr>
<tr>
<td>Back and Forth</td>
<td>B=70.0%</td>
</tr>
<tr>
<td>20</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>B=90.0%</td>
</tr>
<tr>
<td>60</td>
<td>C=93.3%</td>
</tr>
<tr>
<td>Mean (%)</td>
<td>88.9</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>5.09</td>
</tr>
</tbody>
</table>

#### 3.5 Results of the end-effector holding force test

Figure 9 shows the results of the end-effector holding force test using test balls of the same weight but different diameters. The figure shows that for the 60-mm, 70-mm, and 80-mm test balls held by the gripper without vacuum suction, the force required to pull them free from the end-effector were 311 ± 9.5 gf, 413 ± 10.7 gf, and 539 ± 10.9 gf, respectively. When the gripper’s hold was augmented by a vacuum suction of 8.1 N/cm², the forces required to remove the test balls of varying diameters were 413 ± 10.2 gf, 530 ± 9.5 gf, and 647 ± 10.3 gf. If the vacuum force was increased to 7.2 N/cm², the required pulling force was 507 ± 9.8 gf, 673 ± 10.3 gf, and 829 ± 10.4 gf. These findings indicate that larger balls require greater forces to be pulled away. Vacuum suction of the fruits increased the end-effector’s ability to hold the fruit. Greater vacuum suction offers greater holding force. The ANOVA results show that both the vacuum suction force and test ball diameter significantly affect the holding force of the end-effector.
3.6 Results of the tomato picking force tests

Table III shows the results of the tomato picking force test. A degree of 0 indicates no twisting. The results for in-field tomato picking tests without twisting indicate that the average forces required to remove the fruit from the plant was 2,110 g, with a standard deviation of 149 g, and maximum value of 2,450 g. The minimum value required was 1,900 g, which is also a substantial force. Compared with the holding force tests in Section 3.5, the above results indicate that the end-effector cannot pull the fruit from the plant. Therefore, the tomatoes must first be twisted to enable picking.

Table III shows that when the twisting angle was 120°, the average pulling force was 401 g. However, this declined to 360 g with 180° twists. When the twisting angle reached 240°, the average pull force required was only 260 g. This indicates that significant twisting angles reduce the force required to pick tomatoes. Compared with the holding forces presented in Section 3.5, these results indicate that the pull force required is less than the forces available. This means that the end-effector designed in this study can remove the tomato from the plant regardless of the twist angle. However, greater twist angles require longer twisting times, which then increases the average picking time. Thus, we selected the 120° turning mode, that is, clockwise for 60° followed by a counterclockwise turn of 120° until the fruit is 60° counterclockwise to the starting alignment, repeated three times.

### Table III

<table>
<thead>
<tr>
<th>Twisting angle, degree</th>
<th>0(no twist)</th>
<th>120</th>
<th>180</th>
<th>240</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean, g</td>
<td>2,110</td>
<td>401</td>
<td>360</td>
<td>260</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>149</td>
<td>175</td>
<td>145</td>
<td>123</td>
</tr>
<tr>
<td>Max, g</td>
<td>2,450</td>
<td>690</td>
<td>610</td>
<td>530</td>
</tr>
<tr>
<td>Min, g</td>
<td>1,900</td>
<td>150</td>
<td>90</td>
<td>60</td>
</tr>
</tbody>
</table>

3.7 Results of picking real tomato plants

Among the 25 sample tomatoes, 23 were picked successfully and 2 were not. The success rate was 92%. The test results indicate that the vacuum suction device can generally attach to the fruit securely. The two failures were because the robotic arm was positioned too low. This placed the suction attachment point near the lower edge of the fruit, preventing the suction nozzle from fitting with the fruit surface correctly, leading to suction failure. Because the fruit could not be pulled into the end-effector correctly, the picking attempt failed. The total time required to pick 25 fruits was 1865 s, averaging 74.6 s for each fruit. The overall test results show that the end-effector designed in this study achieved its intended function and is suitable for practical application. Through further integration with the overall robotic picking system, the goal of automated tomato picking should be achieved in the future.

IV. CONCLUSIONS

In this study, we developed an end-effector for picking greenhouse-grown Momotaro tomatoes. The end-effector was designed with four fingers and a centrally located fruit suction device. The suction force helps secure the fruit to the inside of the end-effector, reinforcing the holding capability. Test results show that the 15.0-mm diameter suction nozzle has the highest suction success rate at more than 86.7%.

We also tested the suction success rate of suction nozzles contacting fruit under different end-effector inclining movements. The test results indicated that inching the end-effector vertically with 60 mm travel distances provides the highest suction success rate at 88.9%. The force required for picking by the end-effector under various twisting angles was also tested and analyzed. The results indicate that turning the end-effector clockwise for 60° followed by a counterclockwise turn of 120° until the fruit is 60° counterclockwise to the starting alignment, repeated three times before picking can effectively remove the fruit from the plant. Future integration with robotic tomato harvesting systems for actual tomato picking field tests can increase the feasibility and practical applications of robotic automatic picking systems.

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REFERENCES