Development of a Harvesting End-Effector for Eggplants

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Abstract

A robotic harvesting system, which emulates the fruit recognition, approach, and picking tasks, has been developed for the purpose of automatic harvesting for eggplants (Solanum melongena L.). In this study the harvesting end-effectors for eggplants (prototype-1 and prototype-2) were fabricated. The end-effectors were composed of a fruit-size-judging mechanism, a fruit-grasping mechanism, and a peduncle-cutting mechanism to pick the fruit selectively on the basis of fruit length after the manipulator end closely approaches. An experimental result on picking posture using prototype-1 proved that lifting the fruit at an angle of approximately 30° was effective for separating the fruit from leaves. A basic harvesting experiment using prototype-2, which was improved on the fruit-size-judging and fruit-grasping mechanism, was also conducted. It was found that the success rate of harvesting was 62.5% and the harvesting time per fruit was about 64 seconds. The main cause of unsuccessful harvesting was that the accuracy of detection of the fruit base was not sufficient. This study showed the great feasibility of automating the basic harvesting motion for eggplants.

Keywords: eggplant, end-effector, robotic harvesting, fruit size judging, peduncle cutting

Introduction

Eggplants are harvested manually after selecting marketable size and handled carefully so as not to cause damage, since external quality, such as glossiness, is important in the market. As a result, the harvesting work occupies about 40% of the total working hours. Therefore, there is much expectation for the mechanization of the harvesting work.

A harvesting end-effector is one indispensable mechanism for automatic harvesting. There are many studies on harvesting end-effectors for fruit-type vegetables. In cucumbers, the fundamental mechanism was designed1), and then the research on automatic harvesting using the inclined trellis training was conducted afterward2). In tomatoes, an end-effector with a suction pad3) and an end-effector adapting to the inverted single truss tomato produc-

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fruit size judging is also necessary, because the robotic harvesting system does not give enough accuracy on fruit size judgment using the machine vision\(^9\). Therefore, the end-effector is designed to have three functions: fruit size judging, fruit grasping, and peduncle cutting. This paper describes the mechanism of the harvesting end-effectors (prototype-1 and prototype-2) and discusses the experimental results on the picking posture using prototype-1 and the basic harvesting motion using prototype-2.

**Design of prototype-1 and Evaluation on Picking Posture**

1. **Design of prototype-1**

The harvesting end-effector for eggplants (prototype-1) composed of the fruit-size-judging, fruit-grasping, and peduncle-cutting mechanisms was fabricated for installation in the robotic harvesting system. Fig. 1 shows the mechanism of prototype-1. The fruit-size-judging mechanism was structured with the transmission-type photoelectric sensor (Omron, E 32-T 16 P) for detecting the fruit apex and the guide bars for detecting the fruit base, so that the fruit length could be estimated according to the distance between the sensor and the guide bars. An initial distance between the sensor and the guide bars was 125 mm. Two rubber actuators (CKD, XCA) and two suction pads (SMC, ZPR 13 B) were used for the fruit-grasping mechanism, because the rubber actuator can grasp various sized fruit stably\(^9\). The rubber actuators were driven by compressed air of 0.4 MPa and the grasping force to the fruit was approximately 0.7 N at this time. The harvesting scissors were used for the peduncle-cutting mechanism because the peduncle of an eggplant is tough. The scissors were opened and closed by a reciprocating motion of the pneumatic cylinder driven by compressed air of 0.4 MPa. A small-sized color CCD camera was attached in the middle of the end-effector to guide the manipulator by using visual feedback control.

2. **Picking motion using prototype-1**

After the manipulator end closely approaches the fruit, the robotic harvesting system starts the picking task. Fig. 2 shows the flowchart of the picking motion using prototype-1. The numbers [1]-[10] in the figure represent each process.

In process [1], it is first detected whether the manipulator end has approached the fruit on the basis of the pixel area of the fruit recognized using the machine
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In this detection, when the pixel area exceeds 70% of the total frame pixels, the manipulator performs the final approach to insert the fruit securely between the projector and receiver of the photoelectric sensor. After that, the picking motion starts.

In process [2], the rubber actuators and suction pads are set in motion to grasp the fruit.

In process [3], it is checked whether the fruit locates between the projector and receiver of the photoelectric sensor. In case the sensor cannot detect the fruit, the end-effector stops grasping once and moves upward 5 mm at a time with repeated grasping and releasing action until the fruit comes into the sensor. In case that the end-effector detects the fruit during this upward movement or the end-effector detects the fruit at the first grasping action, the end-effector starts moving downward 5 mm at a time. Then the position where the signal of the sensor turns off is considered as the fruit apex, and the downward movement stops.

In process [4], the manipulator assumes a posture that lifts the fruit at an angle of 30° with the center at the fruit base (lift-up 30° posture) shown in Fig. 3 to separate the fruit from leaves. However, in the case where the manipulator picks the fruit from vertical way (lift-up 0° posture), this process is omitted.

Process [5] is a motion added for prototype-2, so it will be described later.

In process [6], the guide bars are closed, and the signal of the micro-switch is checked to judge smaller fruit than marketable size (less than 125 mm in length). The guide bars hold the peduncle in the case of smaller fruit. Consequently, the micro-switch turns ON and the picking motion stops. If the fruit length is more than 125 mm, the micro-switch remains turning OFF and the next process is followed.

In process [7], the guide bars detect the fruit base. When a diameter grasped by the guide bars is big, the guide bars move upward with the motion of the pneumatic slider-1 (SMC, MXS 12-40), which can pause at an intermediate position by the three-position solenoid operated valve (Koganei, A 113-4 E 2). Then, when the diameter becomes less than 20 mm, the micro-switch turns ON and at that moment the pneumatic slider-1 stops moving upward. This position is considered as the fruit base.

In process [8], it is judged whether the fruit is bigger than marketable size. In case the micro-switch does not turn ON even if the pneumatic slider-1 moves 40 mm, the fruit length is estimated to be more than 165 mm (bigger than marketable size), and the picking motion stops.

In process [9], in the case of marketable sized fruit, the pneumatic cylinder is driven and the harvesting scissors are closed to cut the peduncle.

In process [10], the manipulator carries the fruit to the left side 540 mm away and drops it into a container. Finally, the manipulator returns to the initial position, and the picking motion ends.

3. Evaluation of the picking posture

The picking posture using the end-effector (prototype-1) was investigated. The eggplant (cv. Sensory-2) used in the experiment was planted in a pot (capacity: 13.5 l), pinched at a height of 1 m, and trained in V-shape. The samples then were carried into a laboratory and placed 300 mm away from the initial position of the end-effector. A red board was set at the back of the eggplant, and the illuminance around the fruit at this time was 450–650 lx.

The experimental method was as follows: First, 20 samples each were chosen from the smaller fruits than marketable size (less than 125 mm in length), the marketable fruits (125–165 mm in length) and the bigger fruits than marketable size (more than 165 mm in length). In this detection, when the pixel area exceeds 70% of the total frame pixels, the manipulator performs the final approach to insert the fruit securely between the projector and receiver of the photoelectric sensor. After that, the picking motion starts.

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length), respectively. Next the fruit was picked using prototype-1 after the manipulator end approached the fruit by visual feedback control. At this time the samples were classified automatically into a certain size category by the fruit-size-judging mechanism. Then it was investigated whether the end-effector caught the leaves during the picking motion. Moreover, damage to the fruit skin was observed. This experiment was performed in the lift-up 0° posture and the lift-up 30° posture, and the results in the two postures were compared.

4. Results and discussion

Table 1 shows the evaluation results on picking posture comparing the lift-up 0° posture and the lift-up 30° posture. The number of samples, which were classified into the correct category as an actual size, was 13-15 out of 20 samples, and thus the success rate of fruit size judging was 65-75%. There was no obvious difference in the success rate between the two postures. Causes of underestimation were imperfect detection of the fruit apex and the fruit base. That is, the fruit apex was detected at an upper position than its actual position. Also the fruit base was detected at a lower position than its actual position in the case of fruit with a thin base. On the other hand, causes of overestimation were imperfect detection of the fruit base and unstable grasping of the fruit. Therefore, the micro-switch did not turn ON even if the guide bars reached the fruit base in the case where its peduncle was located at the other side of the end-effector. Moreover, the guide bars elevated the fruit because of a lack of grasping force.

Next, the number of times that the guide bars caught leaves (LC) were 11 samples in the lift-up 0° posture, and 3 samples in the lift-up 30° posture. At this time some samples had scratched damage due to the upward motion of the guide bars. However, no damage was observed in the case where leaves were not caught. Consequently, it was found that the picking posture of lifting the fruit at an angle of approximately 30° is effective in separating the fruit from leaves compared with the picking posture from the vertical way. Moreover, the photoelectric sensor and the pneumatic slider came in contact with the fruit on several samples during the approach. One reason for the contact is that the threshold pixel area in detecting the state of approaching was fixed at 70% and the final approach was done afterward. This contact may lead to damage to skin.

Design of Prototype-2 and the Basic Harvesting Experiment

1. Design of prototype-2

Since several imperfections on prototype-1 were observed, prototype-2 was fabricated by modifying prototype-1. The mechanism and general view of prototype-2 are shown in Figs. 4 and 5, respectively.

Table 1 Classification of fruit length by the fruit-size-judging mechanism (prototype-1)

<table>
<thead>
<tr>
<th>Actual fruit length (mm)</th>
<th>Lift-up 0° posture</th>
<th>Lift-up 30° posture</th>
</tr>
</thead>
<tbody>
<tr>
<td>~125</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>125~165</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>165~</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>LC*</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>~125</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>125~165</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>165~</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>LC*</td>
<td>6</td>
<td>0</td>
</tr>
</tbody>
</table>

Unit: Number of samples
*Number of samples in which the guide bars caught leaves
The main modified points are the following five: (1) The pneumatic slider-2 (Koganei, TDA 6 × 40), which actuates the peduncle-cutting mechanism back and forth, was installed to reduce the contact of the peduncle-cutting mechanism with the fruit or leaves. Therefore, the peduncle-cutting mechanism stays back during the approach and goes forward at the cutting task. (2) The method of detecting the state of approaching was changed so as not to cause contact between the end-effector and the fruit by modifying the program of process[1] in Fig. 2. (3) For the same reason as point (2), the reflection-type photoelectric sensor (Omron, E 3 C-DS 5 W) was used instead of the transmission type. (4) The pneumatic slider-1 was exchanged to harvest all fruits of more than marketable size (more than 125 mm in length). However, the pneumatic slider-1 with a stroke of 60 mm (Koganei, TBDA 16 × 60) was selected because the maximum fruit length is about 185 mm even if the fruit is grown in a field. Therefore, prototype-2 would harvest fruit of 125-185 mm in length. (5) Four rubber actuators were used to increase the grasping force because the fruit was elevated during the detection of the fruit base.

2. Picking motion using prototype-2

The picking motion using prototype-2 is almost the same as that of prototype-1. The modified processes are as follows: (1) Process[1] was changed, so that the final approach of 20 mm, 10 mm, and 5 mm is performed when the recognized pixel area is 70-80%, 80-90%, and more than 90%, respectively. Then the picking motion starts. (2) In process[5], the pneumatic slider-2 was actuated to move the peduncle-cutting mechanism and the guide bars forward.

3. Basic harvesting experiment

The series of the basic harvesting motion, which is fruit recognition, approach, and picking tasks, was performed using the robotic harvesting system with prototype-2. The performance was evaluated in terms of the success rate of harvesting, the cutting position of the peduncle, and harvesting speed. The harvesting experiment was conducted only in the lift-up 30° posture under the same condition as the evaluation experiment of prototype-1. Forty samples of 125-185 mm in length were used in the experiment.

4. Results and discussion

(1) Success rate of harvesting

The results of the basic harvesting experiment using the robotic harvesting system with prototype-2 are shown in Table 2, and the harvesting scene is shown in Fig. 6. The number of cases of successful harvesting was 25 out of 40 samples, and thus the success rate of harvesting was 62.5%. No damage was observed on

Table 2 Results of the basic harvesting experiment (prototype-2)

<table>
<thead>
<tr>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Success of harvesting</td>
</tr>
<tr>
<td>Deep cutting</td>
</tr>
<tr>
<td>Judgment error</td>
</tr>
<tr>
<td>(Underestimation)</td>
</tr>
<tr>
<td>(Overestimation)</td>
</tr>
<tr>
<td>Failure of approach</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Fig. 5 General view of the harvesting end-effector for eggplants (prototype-2)

Fig. 6 Harvesting scene by prototype-2
the successful harvested fruits. On the other hand, the number of cases of deep cutting, fruit size judgment error, and approach failure were 5, 9, and 1, respectively. The main cause of the deep cutting and judgment errors was imperfect detection of the fruit base. It is necessary to improve the detection accuracy using an optical sensor, etc.

(2) Cutting position of the peduncle

The cutting position of the peduncle was defined as the distance from the fruit base to the cut section. The average cutting position was 9.3 mm with a standard deviation of 7.4 mm on the successful harvested fruit. The cutting position varied widely due to the direction of the peduncle and the diameter of the fruit base. Since the fruits are generally shipped with a peduncle of less than 5 mm, this drawback should be solved in the future by an improvement of the detection method for the fruit base.

(3) Harvesting speed

Table 3 indicates the processing time of each action by the robotic harvesting system. The average harvesting time was 64.1 seconds with a standard deviation of 11.9 seconds. This was still a low performance compared with an experienced human worker. In particular, the approach to the fruit and the detection of the fruit apex occupied the most part, so the acceleration of these actions is a subject for future study. On the other hand, the principal action of picking task (the fruit base detection and peduncle cutting) could be performed rather fast in 9.2 seconds.

Consequently the following were found:

1) The picking motion for eggplants can be automated by an end-effector composed of a fruit-size-judging mechanism, a fruit-grasping mechanism, and a peduncle-cutting mechanism.
2) The picking posture of lifting only the fruit at an angle of approximately 30° is an effective method to separate the fruit from leaves.
3) The success rate of harvesting by the robotic harvesting system with prototype-2 is 62.5%, and the main cause of unsuccessful harvesting is imperfect detection of the fruit base.
4) The end-effector cuts the peduncle at about 9.3 mm upper position from the fruit base, and the cutting position varied widely due to the direction of peduncle and the diameter of the fruit base.
5) The robotic harvesting system enables the harvesting of eggplant in about 64 seconds. The principal action of picking task (the fruit base detection and peduncle cutting) takes 9.2 seconds.
6) Subjects for further study are the improvement of the fruit base detection accuracy and the speeding up of the harvesting motion, especially the approach to the fruit and the detection of the fruit apex.

References