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Development and Evaluation of a Tomato Fruit Suction Cutting Device

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Abstract— **This paper introduces a structure and harvesting motion for the suction cutting device of a tomato harvesting robot, and reports harvesting experiments conducted in a tomato greenhouse. The suction cutting device comprises a suction part and a cutting part. The suction part separates the target fruit from a tomato cluster and the cutting part cuts the peduncle of the target fruit. A photoresistor in the cutting part assesses whether or not the target fruit is harvestable, and the cutting motion is performed only when the fruit is assessed as harvestable. The harvesting experiments were conducted in a tomato greenhouse to evaluate the suction cutting device. In this experiments, 50 tomato clusters were randomly selected as the harvesting objects, and there were 203 tomato fruits (including immature fruits). Out of the 203 tomato fruits, 114 tomato fruits were mature and within the robot workspace. Out of the 114 tomato fruits, 105 tomato fruits were recognized as target fruits by the harvesting robot. Out of these 105 tomato fruits, 65 tomato fruits were assessed as harvestable and 55 were successfully harvested (the harvesting success rate was 85%). Based on the results of the harvesting experiments, this study clarified the issues of the suction cutting device, classified the fruits according to whether they were easy or difficult to harvest, and evaluated the fruit characteristics qualitatively.**

I. Introduction

In Japan, the decrease of agricultural population is an ongoing issue. According to statistics reported by the Ministry of Agriculture, Forestry and Fisheries, agricultural workers and the proportion of those over the age of 65 amounted to 2.65 million (40%) in 1995, 2.24 million (57%) in 2005, and 1.75 million (65%) in 2015 (the proportion of those over 65 years old is in parentheses) [1]. The causes of this issue include the difficulty of agricultural work, unstable income, and lack of successors. In this context, some studies are aiming smart agriculture, which enables labor saving, high-quality production, and profitable agriculture using robot technology, information communication technology (ICT), and Internet of Things (IoT).

Some studies have focused on automation of agricultural works to realize smart agriculture. Zhang et al. have developed a multi-robot tractor system for conducting agriculture field work in order to reduce total work time and to improve work efficiency [2]. Three patterns for spatial form in traveling way of robot tractors were simulated. The authors stated that the system is more effective in a large field. In contrast to Zhang et al., Gondchawar et al. aim at making automation of the traditional methods of farming which results in low yielding of crops and fruits based on IoT devices [3]. They developed remote controlled robot, smart irrigation system, a smart warehouse management system, and showed its effectiveness in experimental tests. Studies for smart agriculture are diversifying, and various approaches utilizing robot technology, ICT, and IoT have been proposed. Furthermore, there are various agricultural fields for verification of these proposed methods. In this study, we focus on making plant factories, that realize efficient and stable production of agricultural products, smart using robot technology.

We have studied based on hearing the insights of experienced farmers in cooperation with the Hibikinada Green Farm Co., Ltd. (hereinafter, Hibikinada Green Farm) which implements long-term multi-stage cultivation of tomato plants by introducing the cultivation method of the Netherlands. In Hibikinada Green Farm, the temperature, humidity, and irrigation in the greenhouse are controlled, and stable production is realized throughout the year by the long-term multi-stage cultivation. We aim to realize a system that uses robots to automate operations from the monitoring of tomato plants to harvesting tomato fruits. [4, 5, 6]. This paper presents the automatic harvesting.

Various agricultural products have been targeted as previous studies on automatic harvesting. Zhao et al. have developed an apple harvesting robot having the spoon-shaped end-effector with the pneumatic actuated gripper [7]. They conducted laboratory tests and field experiments in an open field. The results show the harvesting success rate was 77%, and the average harvesting time was 15 seconds per apple. Based on the experimental results, they mentioned some issues for the practicality and commercialization of the robot. Feng et al. have developed a strawberry harvesting robot [8]. The robot has a nondestructive end-effector, used to suck the fruit, hold and cut the fruit-stem, was designed to prevent pericarp damage and disease infection. In harvesting experiments at the elevated-trough culture, the harvesting success rate was 86%, and the average harvesting time 22 seconds per strawberry. Arad et al. have developed a sweet pepper harvesting robot [9]. The authors carried out harvesting experiments on total of 262 fruits for long four-week testing period. The average harvesting time was 24 seconds, and the harvesting success rates were 61% for the best fit crop conditions and 18% in current crop conditions. They discussed the importance of finding the best fit crop conditions and crop varieties for

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successful robotic harvesting. In this study, we focus on the automatic harvesting of tomato fruits, which have a particularly long harvesting time among the major vegetables [10].

Regarding tomato harvesting robots, the previous studies are described. Monta et al. have studied a tomato harvesting robot from 1980s and developed an end-effector which consists of two parallel plate fingers and a suction pad [11]. The suction pad has a pressure sensor to assesses whether or not the fruit is sucked. In harvesting experiments conducted with the precondition that the robot detected the target position, the harvesting success rate was 91% (21 tomato fruits out of 23 including immature, mature and over-mature). The authors concluded that the robot could work more easily when the cultivation method was improved for the robot. Kondo et al. have developed an end-effector to harvest a tomato cluster [12]. The end-effector comprises two fingers (Lower fingers for detecting the peduncle and Upper fingers for cutting the peduncle) and a photosensor for detecting the main stem. The harvesting success rate was 50% (ten tomato clusters out of 20) at a high-density plant training system, and the failure cases in terms of the end-effector ability and cultivation environment were discussed. Yaguchi et al. have developed an end-effector, which grips one fruit using grippers and plucks it from the separation layer in the peduncle [13]. The harvesting success rate was 63% (five tomato fruits out of eight) at plant factory. As the failure case, there was a case that the calyx was removed. In addition, they noted that this harvesting success rate is inaccurate because there are not enough the number of harvesting trials. Wang et al. have developed a tomato harvesting robot having four-wheel independent steering system and carried out the picking test for 100 times in a greenhouse [14]. The harvesting success rate was 87%. They consider that the failure cases are attributed to: light intensity; the overlapping of obstacles such as immature fruits, stems and leaves; and the error between target and actual position in robot control. The number of harvesting trials and the harvesting success rate in this study are relatively high, but the details of the end-effector are not described. Feng et al. have developed a cherry tomato harvesting robot having an end-effector to hold and separate the fruit cluster [15]. The harvesting success rate was 83% (25 tomato clusters out of 30). They mentioned the failure case as the followings: the end-effector collided with the main stem; the peduncle was not holding reliably, and fruit cluster fell after being separated. Ling et al. have developed a tomato harvesting robot using a dual-arm manipulator with three degrees of freedom, a suction pad on one arm, and a cutting and gripping end-effector on the other arm [16]. They conducted harvesting experiments focusing only on single fruits cultivated in planters, and the harvesting success rate was 88% (70 tomato fruits out of 80). We have also developed a tomato harvesting robot. In a previous paper [5], we discussed the performance of three types of end-effectors. Additionally, we have developed harvesting robots with a focus on modularization and presented three tomato harvesting robots with different constituent elements [6]. In previous studies, there are three issues as the followings: 1) there is a case that the calyx was removed; 2) there are not enough the number of harvesting trials; 3) there are no discussions of fruit detailed characteristics in case of successes and failures, although failure cases focused on the harvesting environment and end-effector ability are discussed.

Based on the above issues, the purposes of this paper are evaluation of the proposed end-effector in harvesting experiments and classification of the fruits according to whether they were easy or difficult to harvest according to the experimental results. We introduce the structure and harvesting motion of a suction cutting device for a tomato harvesting robot and report the results of harvesting experiments conducted in Hibikinada Green Farm. The structure and harvesting motion of the suction cutting device are described in Section II, the harvesting experiments are detailed in Section III, the findings are discussed in Section IV, and the conclusions are presented in Section V.

II. Suction Cutting Device

A. Structure

We have referenced the end-effector developed by Monta et al. However, we mentioned the issue about the calyx. In the end effectors with suction pad developed by Monta et al. and Ling et al., and the end effectors of plucking method developed by Yaguchi et al. and Wang et al., there may be a case that the calyx was removed in harvesting. It is considered that the cause is that the force is added to the fruit at harvesting. Additionally, since the calyx is an indicator of freshness, some consumers feel that it is not fresh due to the lack of the calyx [17]. In this study, fresh market tomato fruits in the Hibikinada Green Farm are targeted for automatic harvesting, and in the discussion with the workers, they said the fruits needed to be harvested with calyx. Therefore, in the proposed end-effector, we have also referenced to the method of cutting the peduncle without touching the target fruit at the harvesting to harvest the tomato fruit with calyx, as in Kondo et al.

Figure 1 shows the structure of the suction cutting device: the side view is in Fig. 1(i) and the cross-sectional view is in Fig. 1(ii). The suction cutting device comprises a suction part and a cutting part. The suction part separates the target fruit from the tomato cluster and the cutting part cuts the peduncle of the target fruit. The suction part comprises a fan for suctioning the target fruit and a hose for the air flow. The cutting part comprises fingers (upper and lower) to cut the peduncle, a laser and a photoresistor to assess whether the target fruit is harvestable, and a stopper to prevent the harvested fruit from entering the suction part. If there is no the stopper, the harvested tomato fruit enters the suction part and damage the fruits.

Regarding the fingers, the actuator mounted onto the cutting part drives, the drive is transmitted by the timing belt, and the lower finger drives. The upper finger is fixed, and the peduncle is cut by engaging with the upper finger and lower finger. A button switch is attached to the upper finger to assess the engagement, and the switch is pushed when the two fingers engage. The fingers must have a blade to cut the peduncle. In the suction cutting device, the blade is attached only to the upper finger. If the lower finger has a blade, it may damage the tomato fruits when the lower finger is driven. Therefore, a blade is not attached to the lower finger.

Figure 2 shows the developed suction cutting device with a length of 600 mm, width of 150 mm, and height of 150 mm. The cutting part has a diameter of 70 mm to hold one medium-sized tomato. The weight is 1.5 kg. In this study, the suction cutting device was installed to the x-axis actuator of the 3-axis orthogonal manipulator, which is a component of the tomato harvesting robot [6]. To install the suction cutting device to the x-axis actuator, the hose has a length of 350 mm, which can be changed according to the components of the tomato harvesting robot. The operating voltage of the fan and actuator is 12 V, and the currents measured during suctioning and cutting are 9 A and 0.2 A, respectively. The fan, actuator, and various electronic components are connected to an Arduino UNO, which is a single-board microcomputer and controls the harvesting motion.

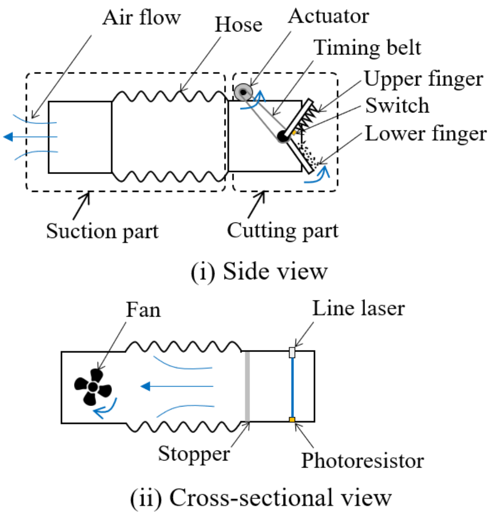

Fig. 1. Structure of suction cutting device. This device comprises a suction part and a cutting part. The suction part comprises a fan and a hose. The cutting part comprises the fingers (upper and lower), a laser, photoresistor, and stopper.

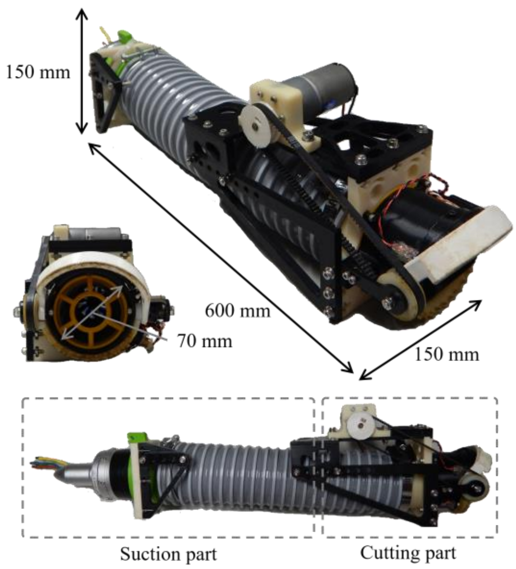

Fig. 2. Appearance of the developed suction cutting device. The length is 600 mm, the width is 150 mm, and the height is 150 mm; the diameter of the cutting part is 70 mm; the weight is 1.5 kg.

B. *Harvesting motion*

The harvesting motion using the suction cutting device is described. This motion is part of the harvesting behavior of the tomato harvesting robot, and is the motion after the robot detects a target fruit and approaches the suction cutting device toward the target fruit. Regarding the detection method, in order to recognize mature and immature tomato fruits, we referenced k-means++ method which is one of the unsupervised classification methods [18]. The RGB images acquired by the vision sensor (Microsoft Kinect) mounted on the robot are used to detect mature and immature fruits, and the positions of the detected fruit are calculated using the detection results and the depth value in the Depth images. Among the detected mature fruits, the robot targets the fruit that has the shortest distance to the robot and has no other fruits around it. When the target fruit is decided, the suction cutting device approaches to the target fruit by the manipulator. The harvesting motion is then carried out.

Figure 3 shows the harvesting motion using the suction cutting device. First, the target fruit is sucked by the suction part (motion (i) in Fig. 3). If the target fruit is sucked into the cutting part, the laser directed to the photoresistor is blocked by the sucked fruit (motion (ii) in Fig. 3). At this time, the value of the photoresistor changes, and whether or not the fruit is harvestable, that is, whether or not the cutting part holds the target fruit, is assessed according to the new value. The lower finger is driven until it engages with the upper finger (motion (iii) in Fig. 3), and when the switch attached to the upper finger is pushed, the harvesting is successful (motion (iv) in Fig. 3). In the success case of the motion from (i) to (iv) in Fig. 3, the suctioning continues. The suction part does not only separate the target fruit from the tomato cluster but also has a role in holding the target fruit. This suctioning continues until the harvested fruit is transported to the harvest box, and the suctioning stops after the fruit is placed into the harvest box.

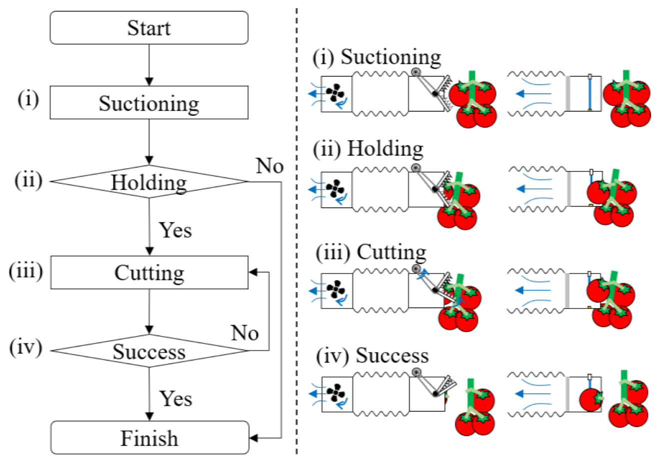

Fig. 3. Harvesting motion of suction cutting device. First, this device suctions a target fruit (motion (i)). If the target fruit is suctioned into the cutting part and assessed as harvestable (motion (ii)), the cutting motion is performed (motion (iii)). If the lower finger engages with the upper finger, the harvesting motion is successful (motion (iv)).

III. HARVESTING EXPERIMENTS

To evaluate the suction cutting device, we conducted harvesting experiments on January 17, January 21, January 22, February 24, and February 27, 2020, that is, five days in total, at Hibikinada Green Farm. The experiments were carried out on medium-sized tomato fruits (weight of 60-120 g, diameter of 50-60 mm). Figure 4 shows photos of the harvesting experiments. The tomato harvesting robot searched for tomato fruits while moving on the rail (Fig. 4(i)). The robot detected the tomato fruits and selected a target fruit (Fig. 4(ii)). The suction cutting device installed to the 3-axis orthogonal manipulator approached the target fruit (Fig. 4(iii) and (iv)). The target fruit was harvested by performing the harvesting motion shown in Fig. 3 (Fig. 4(v)). If the harvesting was successful (Fig. 4(vi)), the harvested fruit was carried to the harvest box (Fig. 4(vii)) and the tomato harvesting robot harvested the next target fruit (Fig. 4(viii)).

Table 1 describes the experimental results. In the results, 203 tomato fruits (83 immature fruits and 120 mature fruits) in 50 tomato clusters were randomly selected. Out of the 120 mature fruits, 114 tomato fruits were in the robot workspace. Out of the 114 tomato fruits, 105 tomato fruits were recognized as target fruits by the tomato harvesting robot. Out of these 105 tomato fruits, 65 tomato fruits were assessed as harvestable, 55 tomato fruits were successfully harvested, and 10 tomato fruits were damaged during the harvesting motion. In the harvesting experiments, the harvesting success rate was 85% (55 tomato fruits out of 65). The harvesting time (the time from selecting the target fruit to carrying the harvested fruit into the harvest box) was approximately 23 seconds per fruit.

IV. DISCUSSIONS

A. *Evaluation of the harvesting experiments*

Table 2 shows a comparison of the results of this study and previous studies. Regarding the parentheses of “Rate [%]” in Table 2, the denominator is the number of harvesting trials and the numerator is the number of successful harvests. Kondo et al. and Feng et al. targeted the harvesting of tomato cluster, while the other authors targeted the harvesting of one fruit. Also, the results of Monta et al. and Ling et al. are the results of the preconditions at the harvesting experiment, as mentioned in Section 1. Comparing the results without the preconditions, the number of harvesting trials and the harvesting success rate of this study is the second largest after Wang et al. Additionally, in this experiments, all 55 fruits that were successfully harvested had a calyx on them. So, the suction cutting device, which sucks the fruit and cuts the peduncle without touching the fruit, is useful in terms of harvesting fresh market tomato fruits.

However, note that the suction cutting device cannot be harvested the target fruit unless the fruit is sucked, and there were failure cases that the harvested fruits had scratches on surface as mentioned in Section IV-B. Regarding the former, the harvest success rate was 52% (55 out of 105 tomato fruits), considering the case where suction was not possible. In order to improve the harvesting success rate of the robot with the suction cutting device, it is considered that the following is necessary: 1) quantify the harvestability (easy or difficult to

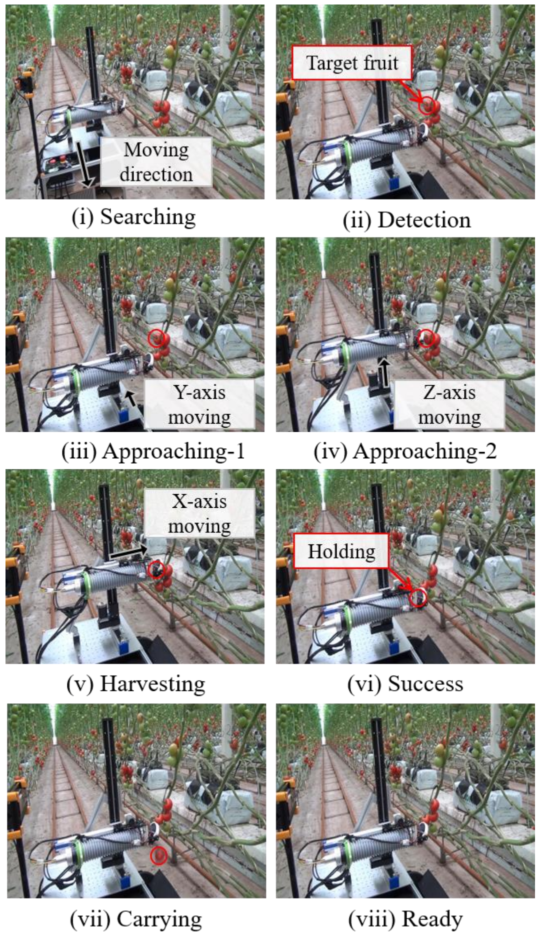

Fig. 4. Harvesting experiment in tomato greenhouse. The tomato harvesting robot moves on the rail and decides a target fruit ((i) and (ii)). The suction cutting device is moved toward the target fruit ((iii) and (iv)), and the harvesting motion is performed ((v)). If this motion is successful ((vi)), the harvested fruit is carried to the harvest box ((v)). The tomato harvesting robot harvests next target fruit ((viii)).

Table 1. Results of the harvesting experiments.

Number of clusters	50
Number of tomato fruits	203
Number of immature fruits	83 / 203
Number of mature fruits	120 / 203
Number of fruits in robot workspace	114 / 120
Number of fruits recognized by the robot	105 / 114
Number of fruits assessed as harvestable	65 / 105
Number of successfully harvested fruits	55 / 65

Table 2. Comparison of the experimental results.

First Author	Rate [%]	Targeting type
Monta [11]	91.3 (21/ 23)	Large-sized fruit
Kondo [12]	50.0 (10/ 20)	Cluster (Max mass: 400g)
Yaguchi [13]	62.5 (5/ 8)	Medium-sized fruit
Wang [14]	87.0 (87/ 100)	Not mentioned
Feng [15]	83.3 (25/ 30)	Cluster of cherry tomato
Ling [16]	87.5 (70/ 80)	Not mentioned
Fujinaga (this study)	84.6 (55/ 65)	Medium-sized fruit

harvest) and apply a harvesting strategy based on the harvestability; 2) increase the degree of freedom of the manipulator or the suction cutting device, and make the harvesting direction (approach direction to the target fruit) variable. The points are discussed in IV-C.

B. *Harvested fruits with scratches on surface*

In the experimental results, 10 fruits out of the 65 that were assessed as harvestable had scratches on their surface. Figure 5 shows examples of these scratches. Figure 5(i) shows scratches caused by sandwiching the target fruit between the upper and lower fingers during the cutting motion. Figure 5(ii) shows scratches caused by colliding the blade while the suction cutting device approaching the target fruit in the x-axis direction ((v) in Fig. 4). For scratches like Fig. 5(i), it is considered that this can be prevented by increasing the number of the photoresistors for assessing the suction of fruits. To prevent scratches like Fig. 5(ii), the visual feedback control of the hand position by a hand camera is necessary.

C. *Qualitative evaluation of harvesting ease or difficulty*

We quantitatively evaluated the characteristics of fruits that are easy or difficult to harvest for the suction cutting device based on the experimental results. To this end, we examined the fruits that the robot assessed as harvestable and were successfully harvested, and fruits that the robot assessed as un-harvestable. In this study, the former were fruits that were easy to harvest, and the latter were fruits that were difficult to harvest. Figure 6 shows images of fruits that were easy or difficult to harvest. These images were captured from the front of the target clusters using a commercial camera. The characteristics of the fruits that were easy to harvest were considered as the calyx of the fruit facing the back (Fig. 6(i)-1, and (i)-2) and the calyx of the fruit facing upward, sideways, or diagonally upward (Fig. 6(i)-3). The characteristics of the fruits that were difficult to harvest were considered as the calyx of the fruit facing the front (Fig. 6(ii)-1) and the existence of a stem and peduncle in front of the fruit (Fig. 6(ii)-2 and (ii)-3). Figure 7 shows images of the fruits and the harvesting experiment when the target fruit was assessed as un-harvestable. In this case, an obstacle (peduncle) existed in front of the target fruit (Fig. 7(i)), and during the suctioning, the upper finger collided with the peduncle and the target fruit could not be suctioned (Fig .7(ii)).

Out of the 105 mature fruits recognized by the robot, 38% (40 out of 105 tomato fruits) of the fruits were assessed as un-harvestable. In other words, with the current suction cutting device, 38% of the fruits (at least) could not be suctioned in the tomato greenhouse. For the fruit that could not be sucked, obstacles (calyxes, stems, and peduncles) existed in front of the target fruit. To harvest that 38% of such fruit, it is necessary to quantify the harvestability and change the approach direction of the suction cutting device to the target fruits according to their harvestability, which is an index that quantifies the harvesting ease or difficulty. As one of the harvestability factors, we consider the occlusion ratio. The occlusion ratio of obstacles to the target fruit is calculated, and the harvestability in the current approach direction is quantitatively evaluated based on the calculated ratio.

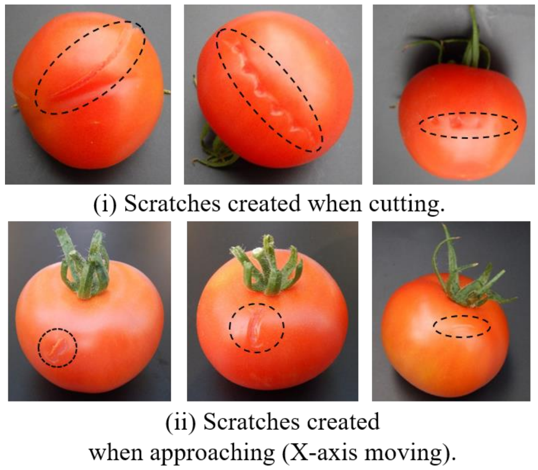

Fig. 5. Scratches on harvested fruits surface caused during harvesting motion: (i) scratches caused by sandwiching the target fruit with the upper and lower fingers; (ii) scratches caused by colliding the blade.

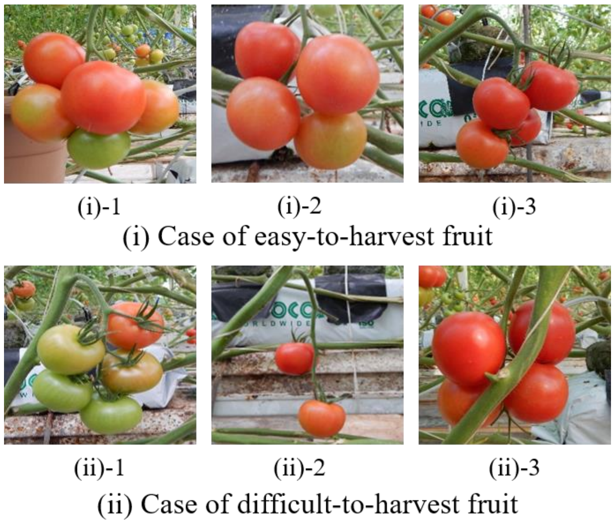

Fig. 6. Characteristics of fruits that were easy or difficult to harvest: (i) easy to harvest; (ii) difficult to harvest. The comparison of these cases shows that, in the case of fruits that were easy to harvest, there were no obstacles in front of the tomato fruits.

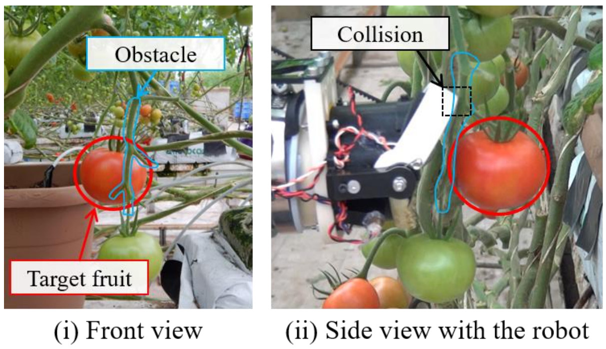

Fig. 7. Case assessed as un-harvestable: (i) an obstacle (peduncle) existed in front of the target fruit; (ii) during the suctioning, the upper finger collided with the peduncle and the target fruit could not be suctioned.

If the harvestability is low, the suction cutting device is moved toward the target fruit from a different direction. To this end, it is necessary to mount a hand camera, and increase the manipulator's degrees of freedom or mount an actuator on the suction cutting mechanism to vary the suction direction.

V. Conclusion

This paper described the structure and harvesting motion of suction cutting device, and presented the results of harvesting experiments conducted at a tomato greenhouse. The suction cutting device succeeded in harvesting 55 mature fruits out of 65, and the harvesting success rate was 85%. We showed that the proposed end-effector is effectiveness for harvesting fresh market tomato fruits because it can harvest a tomato fruit with the calyx. However, noted that the premise is to suck the fruit, and harvesting is difficult when there are fruits outside the robot workspace or when there are obstacles such as leaves and stems, etc. in front of the target fruit.

Additionally, issues relating to the suction cutting device were discussed. Out of the 65 mature fruits, 10 fruits had scratches on their surface during the harvesting motion. Hence, it is necessary to add photoresistors for assessing the suction of fruits and implement the visual feedback control of the hand position. Out of the fruits recognized by the tomato harvesting robot, 62% of the fruits were assessed as harvestable and 38% were assessed as un-harvestable because they could not be suctioned owing to the existence of obstacles (calyxes, stems, and peduncles) in front of the target fruits. To solve these problems, it is necessary to mount a hand camera and quantitatively evaluate the harvestability of the target fruit. If the harvestability is low, it is necessary to change the suction direction toward the target fruit from other directions. Also, at present, as a concept for installing this robot into the greenhouse, it is assumed that the robot works at night or on holidays when humans do not work.

The scope of future work will be to improve the intelligence of the tomato harvesting robot, and investigate and develop a tomato harvesting robot that can perform more efficient harvesting motion through more long testing period.

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