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REVIEW

Development of a Stationary Robotic Strawberry Harvester with a Picking Mechanism that Approaches the Target Fruit from Below

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Abstract

A stationary robotic strawberry harvester, combinable with a movable bench system, was developed. Initially, the features of strawberries, such as the visibility of fruit, the picking force required, and spectral reflectance were investigated. Subsequently, a machine-vision system was constructed, comprising units to measure position and coloration respectively. Considering the visibility of strawberry fruit, these units were optimally located to detect mature fruit and estimate their coloration. White, red, and green light-emitting diodes were installed for more accurate coloration measurement. The average error was 5.4%, and its standard deviation was 10.8%. We developed an end-effector with three functions: 1) to prevent the fruit adjoining the target fruit from being touched during the approach, 2) to force adjoining fruit away from the target fruit during the picking motion, and 3) to remove peduncles from harvested fruit, as done manually. The performance test confirmed that the stationary robotic harvester outperformed the conventional robots, namely, the harvester achieved a stable high harvesting success rate of 67.1%, and was able to successfully remove the peduncles from 88.0% of the harvested fruit.

Discipline: Agricultural engineering

Additional key words: end-effector, machine vision, movable bench system, plant factory

Introduction

The gross production value of strawberries in Japan is about 1.6 billion US dollars, which is approximately 17% of the global value (FAOSTAT 2010). However, strawberry production is heavily dependent on human labor, with working hours exceeding 2,000 h/10 a, which is over 60 times higher than those for rice production in Japan. Above all, harvesting operations occupy a quarter of all working hours. To cope with the labor shortage, considerable effort has gone into developing a robotic harvester for strawberries grown via hilltop culture (Kondo et al. 2000, 2001; Cui et al. 2006), and a practical field test was conducted at the table-top culture (Hayashi et al. 2010). These robots detect and approach a fruit from above the hilltop plants or from the aisle side of the table-top plants. However, new clusters of immature strawberry fruit generally tend to overlap the previous clusters of matured fruit from above one after another at the hilltop or table-top cultures through most of the harvesting season. These immature fruit naturally significant hinder the robotic harvesters from picking the targeted fruit. To avoid this, inside-approach harvesting robots which pick the fruit from inside benches at the table-top culture have been studied (Arima et al. 2001, 2003; Hayashi et al. 2012), and performance was improved significantly when the obstacles in front of the target fruit were reduced. However, all developed robots have a common issue: their performance drops radically when many fruit or peduncles are crowded together. For instance, they cannot find mature fruit that are occluded by immature fruit or other obstacles, nor can they separate the target fruit from adjoining fruit during the picking motion. This may mean they leave mature fruit in the greenhouse, harvest unripe fruit along with the target fruit, or cut the peduncles of other fruit. The major cause of this problem is their lack of flexible vision or a high-performance end-effector because they are strictly limited by size from moving effectively around the green-

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house. The average harvesting success rate during the practical field test was reportedly 41.3% with a simple end-effector, which cuts and holds the peduncle of a strawberry fruit (Hayashi et al. 2010). To improve the working accuracy of a robotic harvester for strawberries, we focused not only on existing obstacles but also on simplicity for detecting and approaching the target fruit. Namely, the shape of a fruit is almost round and its peduncle and calyx are hidden by the fruit when observed from below at the table-top culture. Accordingly, observation from below should reduce the influence of crowded calyxes. In terms of approaching, it was thought that the larger the target becomes, the easier the picking operation would be, which means holding the fruit body from below seemed more reliable than cutting and holding its peduncle from a horizontal direction.

From the perspectives of safety and reliability of food production, plant factories have been drawing widespread attention. Like industrial factories, plant factories essentially require high efficiency for vegetable or fruit production. With this in mind, a movable bench system for strawberries has been developed to increase land productivity and decrease labor load at the plant factory (Hayashi et al. 2011). Unmanned spraying is also possible with the system; in addition, operators can plant, deleaf, and harvest without walking long distances between narrow aisles because the plants on the movable bench are transported to them one after another. Obviously, the robotic harvester can operate in a fixed position with the system, and it need not be simple and compact like conventional robots: the stationary robotic harvester can be equipped with considerable hardware like a high-performance end-effector and flexible vision system to enhance automatic harvesting operations.

This study thus has three aims: 1) to design a machine-vision system that observes fruit from optimal angles using multiple cameras, 2) to develop a high-performance end-effector that can keep the target- and adjoining fruit apart during the picking operation, and 3) to construct a stationary robotic harvester and evaluate its performance. This study could lead to the development of an automatic harvesting system in a plant factory for strawberries.

Features of the target plant

Before designing a stationary robotic harvester, we investigated the features of strawberry plants from the automatic harvesting perspective. First of all, the visibility of the target fruit from three directions, namely, aisle side, bench side, and below, was classified and analyzed using table-top plants, namely, cv. *Beni hoppe*, cultured in greenhouses in February and March. The number of observed fruit ranged from 227 to 305 and more than half had adjoining fruit. The percentages of fully visible fruit were 40, 90, and 75% from the aisle side, bench side, and below, respectively (Fig. 1). It was considered that the bench side would provide optimal visibility, and that visibility from below would be far superior to that from the aisle side. It also seemed that the image-processing algorithm used to detect target fruit would be substantially simplified when the image was taken from below because the fruit shapes were almost round and peduncles and calyxes were hidden by the fruit (Fig. 2).

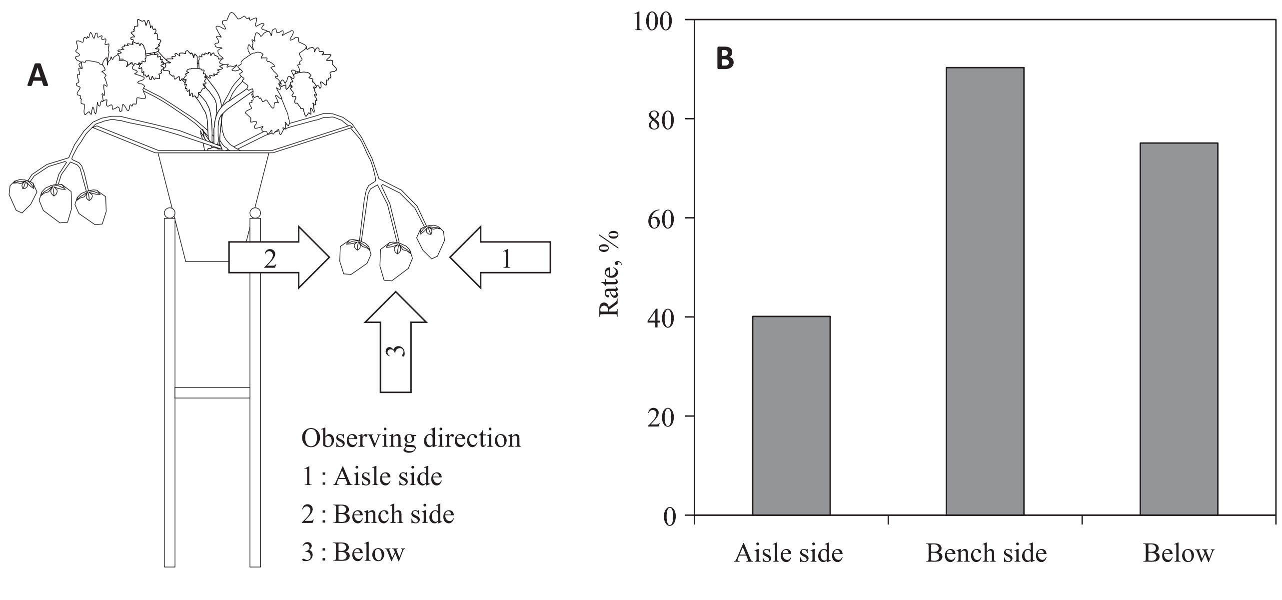


Fig. 1. Difficulty in approaching the target fruit
A) diagram of the observation direction, B) rates of the number of fruit that were completely visible and unhindered by obstacles

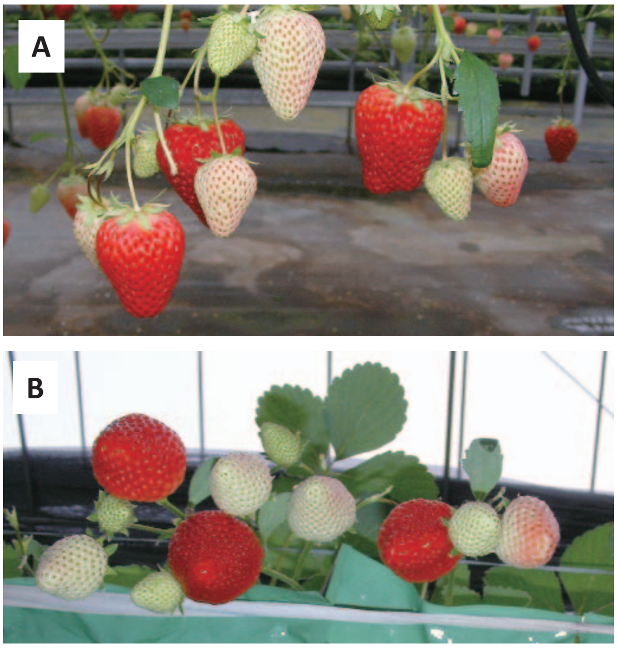


Fig. 2. Comparison of fruit shapes
A) image from aisle side, B) image from below

Next, the force required to pick a fruit from its peduncle was measured. In general, a harvesting robot cuts the peduncle with a cutter to harvest the fruit. With this method, the cut peduncle that remains on the fruit might damage other fruit when they are packed. Most farmers therefore harvest strawberries by hand, and some can harvest a fruit without the peduncle by tilting it before pulling. To design an end-effector capable of harvesting a fruit without its peduncle, we measured the maximum force required to separate the fruit from their peduncles. A fruit cv. *Beni hoppe* was fixed in a jig, whereupon the peduncle was pulled at constant velocity (50 mm/min) until the peduncle and fruit separated. The pulling force was measured as the peduncle was pulled, and the pulling angle was set to 0, 45, or 90 degrees. Figure 3 shows the maximum separating forces plotted versus the diameter of the peduncles. When the fruit was pulled straight, the peduncle sometimes broke in the middle, and part of it remained on the fruit. When it was pulled at 90 degrees, however, the peduncle rarely broke, and the fruit and peduncle separated at the abscission layer with relatively little force. The results clearly showed that the force required to separate a fruit from its peduncle could be reduced by tilting the fruit before pulling it. Therefore, we wrote the harvesting robot software such that the robot could be instructed to tilt the end-effector when harvesting the fruit.

Finally, we investigated the spectral reflectance of a fruit and leaf of a strawberry cv. *Beni hoppe*. Figure 4 shows that the spectral reflectance of the fruit increased when the wavelength was around 650 nm but that the value of the leaf was otherwise low there. When the wavelength

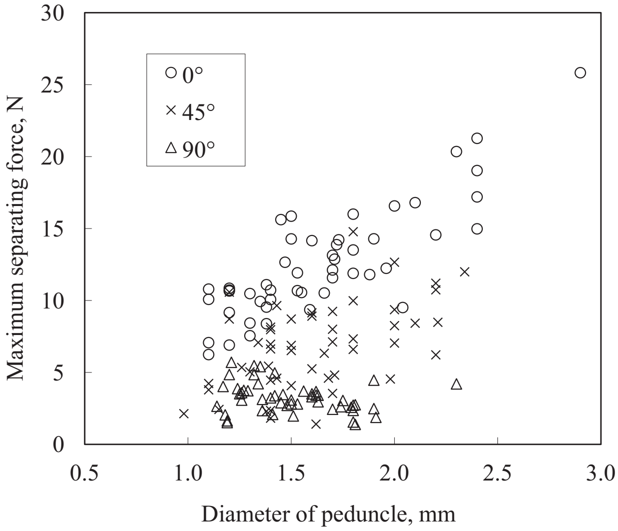


Fig. 3. Plot of diameter of peduncle and maximum separating force with pulling angles of 0, 45, and 90°

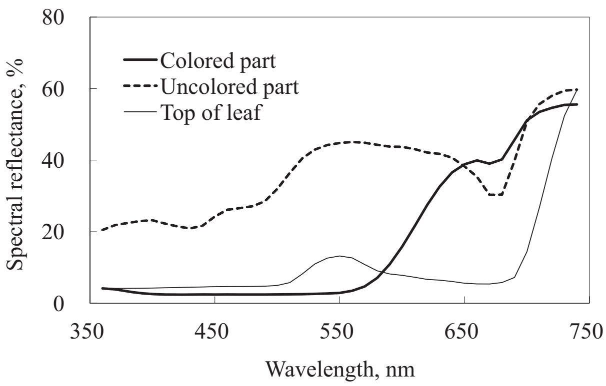


Fig. 4. Spectral reflectance of the strawberry fruit and leaf

was approximately 550 nm, only the colored part was low. It was considered that emphasizing the reflectance property using monochromatic red and green light would facilitate efforts to recognize colored and uncolored parts of a strawberry fruit.

Development of a stationary robotic harvesting system

1. Experimental system and harvesting procedure

Figure 5 shows a schematic diagram of a system used for experimental harvesting. The stationary robotic harvester was placed in front of the movable bench unit, which carried a strawberry bench 1 m long at a velocity of 0.03 m/s. The automatic harvesting procedure is as follows: 1) the movable bench unit starts to move, and the robot starts to search for mature fruit; 2) if the robot detects mature fruit, the movable bench unit stops, and the three-dimensional (3D) positions of the detected fruit are calculated; 3) their

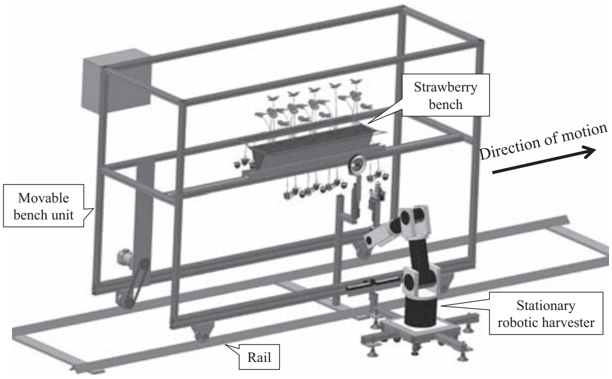


Fig. 5. Schematic diagram of the system used for experimental harvesting

maturity is estimated by the coloration measurement, and if the value is at least 80%, the target fruit is judged as mature; 4) if there is mature fruit, the robot starts the picking motion; 5) after picking, when the robot's manipulator has returned to the initial position, the movable bench restarts. When the movable bench unit touches a limit switch at the end of the rail, automatic harvesting is completed.

2. Machine-vision system

Figure 6 shows the components of the machine-vision system and their layout. Each unit has a polarizing filter to directly reduce reflected light. Considering the visibility of the fruit, as shown in figures 1 and 2, the position measurement unit was set to capture images from below. However, the coloration, which indicates the maturity level of a fruit, seemed difficult to measure from below because the top part of the strawberry fruit generally turns red, and its upper half cannot be observed. Thus, the coloration measurement unit was set to grab images from the bench side. The distance between the coloration measurement unit and fruit was sometimes very small. Under these circumstances, the coloration measurement unit had to be set in front of the fruit due to the camera range. Thus, based on the height information provided by the position measurement unit, we mounted the unit on the electric actuator with a stroke of 100 mm to keep the unit in front of the fruit.

Considering that more than half the fruit had adjoining fruit, it was necessary to detect individual fruit accurately, especially for stereomatching. If some fruit was bunched together and could not be individually recognized, the calculated positional data would include some errors. In response, we applied general particle detection and labeling methods in the image-processing field to the position mea-

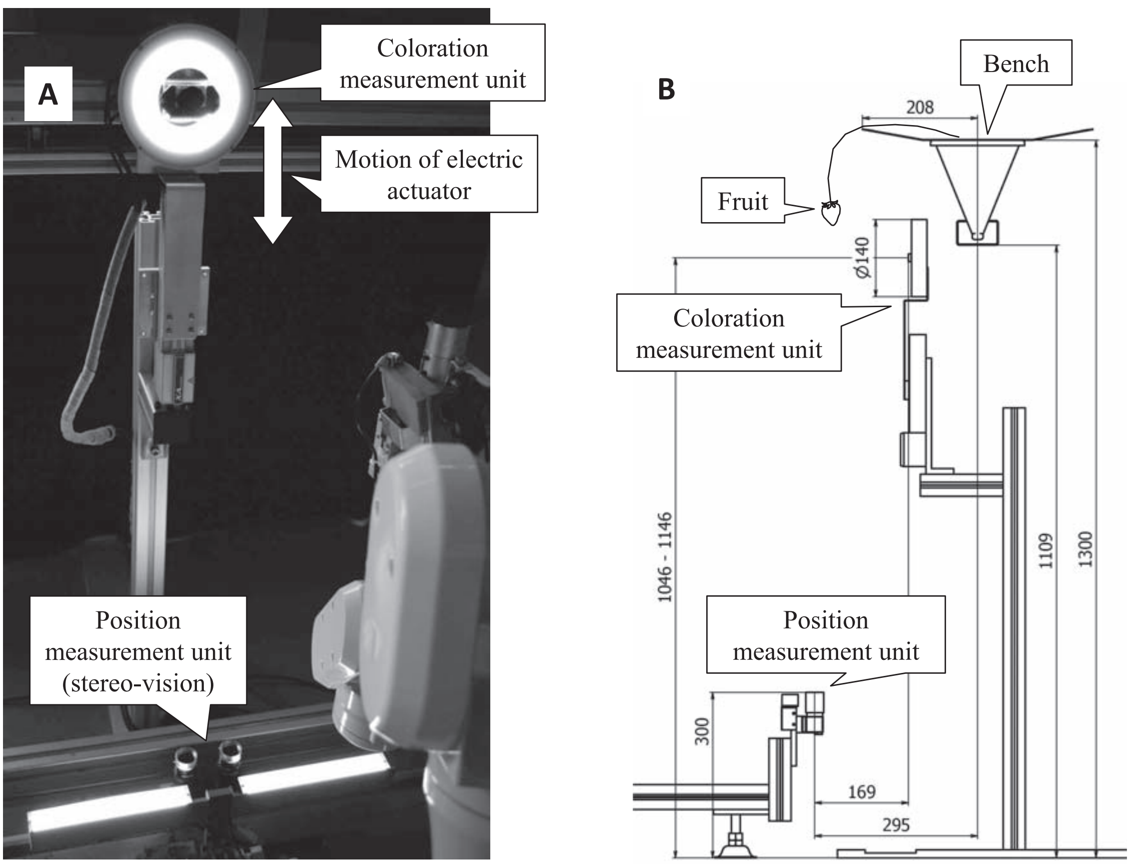


Fig. 6. Schematic diagram of the machine-vision system
A) components, B) layout of the units

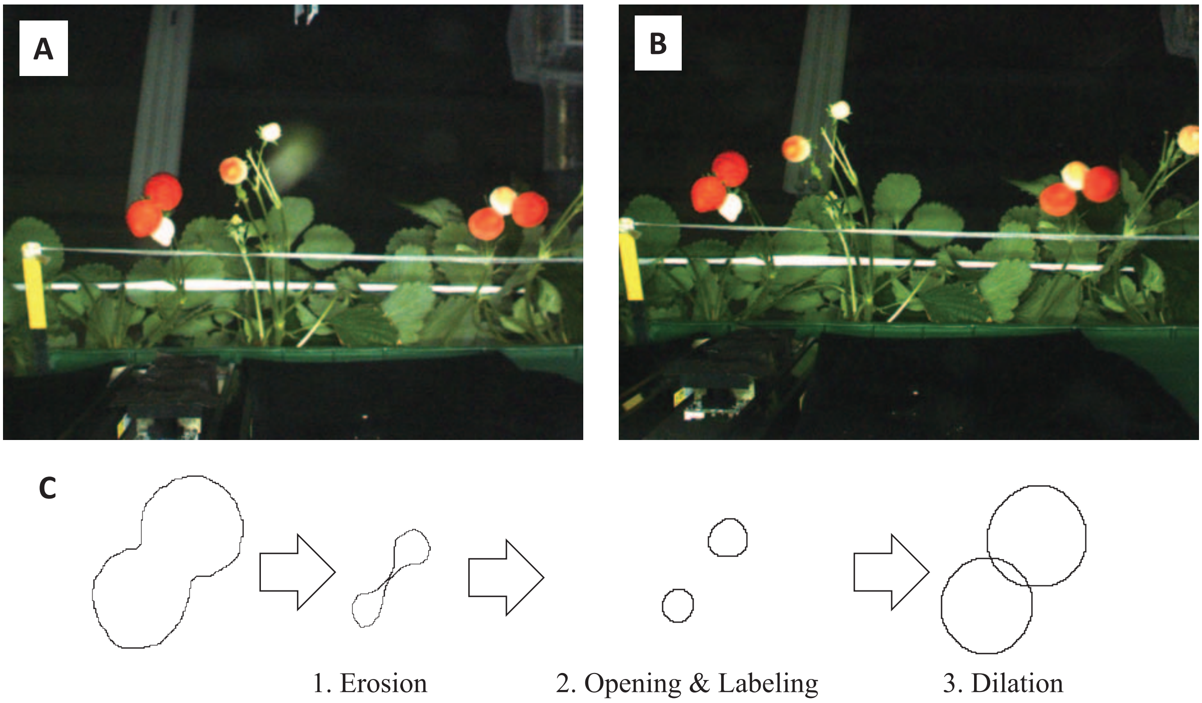


Fig. 7. Particle detection and labeling method with position measurement unit
A) image from left camera, B) image from right camera, C) labeling method for adjoining fruit

surement algorithm. Using the latter, the fruit regions are eroded, separated and labeled, and finally dilated, as shown in Figure 7. The erosion parameter influenced the labeling performance: if it was too big, small fruit were erased by the eroding procedure and could not be detected, and if it was too small, a relatively large region could not be separated and labeling performance declined. To detect crowded fruit of various sizes, the erosion parameter was set to be small during the initial labeling stage, and then expand while recursively evaluating the circularity of the fruit regions. It took approximately 0.05 s for the unit to detect, label, and calculate the positions of the fruit with a 2.4-GHz CPU. If there were few fruit in the range, the fruit nearest the bench side was selected as the target fruit because it should be exposed to the coloration measurement unit.

When assessing maturity, it is difficult for accurate coloration measurement to determine the threshold if there is a pink-colored part on the fruit surface with white illumination. Considering the foregoing spectral reflectance of a strawberry fruit, we applied not only a white light-emitting diode (LED) but also red and green LEDs to improve the coloration measurement accuracy by emphasizing colored and uncolored parts. Figure 8 shows the image-processing method used to segment the colored part and calculate the coloration rate. This method needs three images captured under red, green, and white LEDs respectively. Initially, the color image captured under a red LED was broken down into R_r, G_r, and B_r images. The whole fruit without a leaf (region A) was segmented from the R_r image applying discriminant analysis, whereupon the G_g image was broken down from the image of a green LED. Similarly, the white and pink part was segmented. It was sometimes observed that part of the leaf was included in region B. Accordingly, the segmented part from the G_g image was processed with the logical product conjunction with region A, and the uncolored part without a leaf (region B) was calculated. The R_w and G_w images were broken down from the image of a white LED and the red and pink region (C) was segmented from the image representing the difference between the R_w and G_w images. The intersecting area of regions B and C is colored pink (region D), while the red region (E) is segmented from the region obtained by subtracting the pink region from the red and pink regions. Finally, the coloration rate is calculated using the numbers of pixels in the regions. To evaluate the machine-vision performance, we compared the maturity level assessed by human observation and that assessed by the coloration measurement unit using 118 fruit of cv. *Beni hoppe*. The results showed that the average measurement error of the coloration was 5.4%, and the standard deviation of the error was 10.8%.

When these two units were combined, matching the position was used to detect the fruit and measuring coloration of the fruit seemed difficult, because the labeling procedure in the coloration measurement unit required an advanced algorithm, as previously discussed. A masking process was therefore used to hide the adjoining fruit in the images of the coloration measurement unit. The masking region was calculated based on the position and diameter of

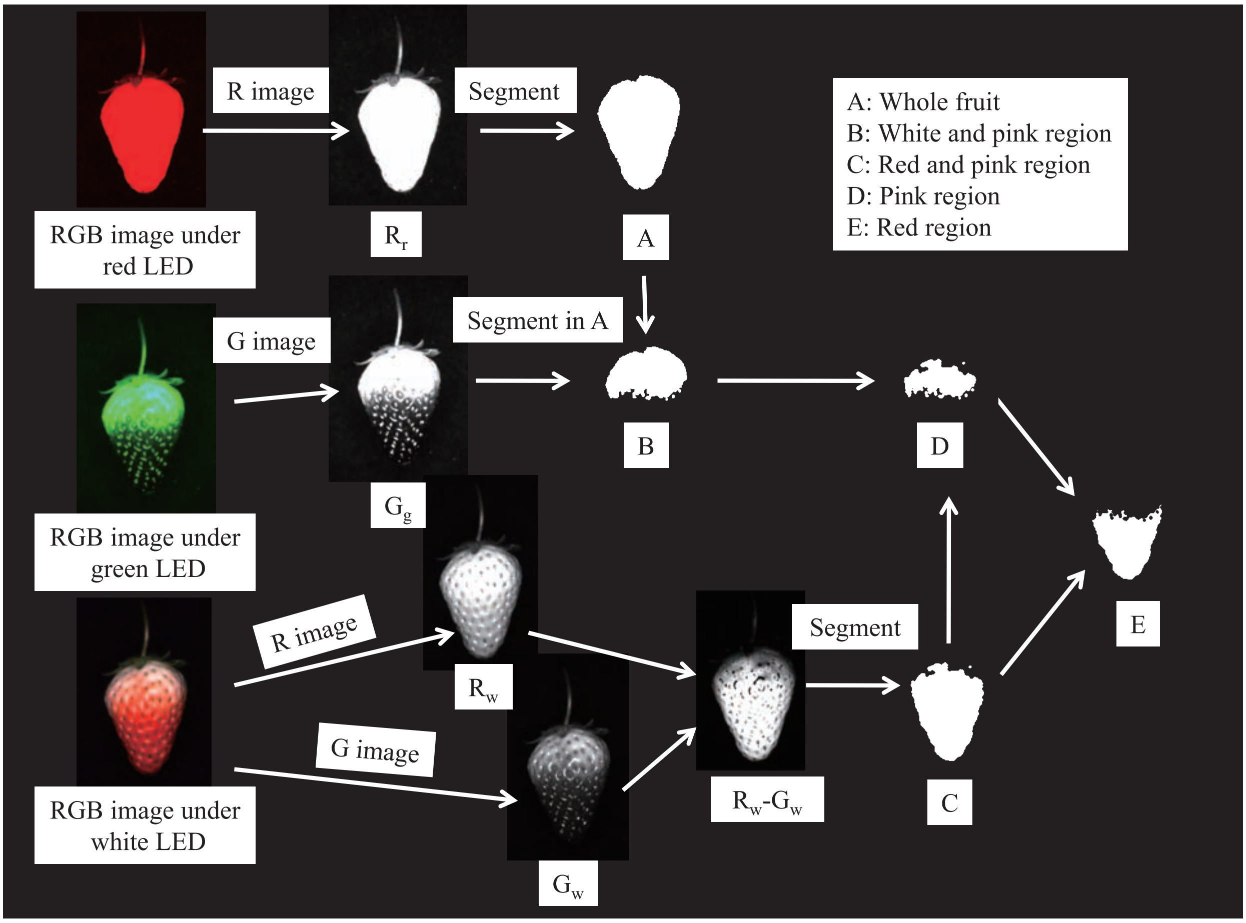


Fig. 8. Image and segmented region to measure coloration

the target fruit, which, in turn, were estimated using the position measurement unit.

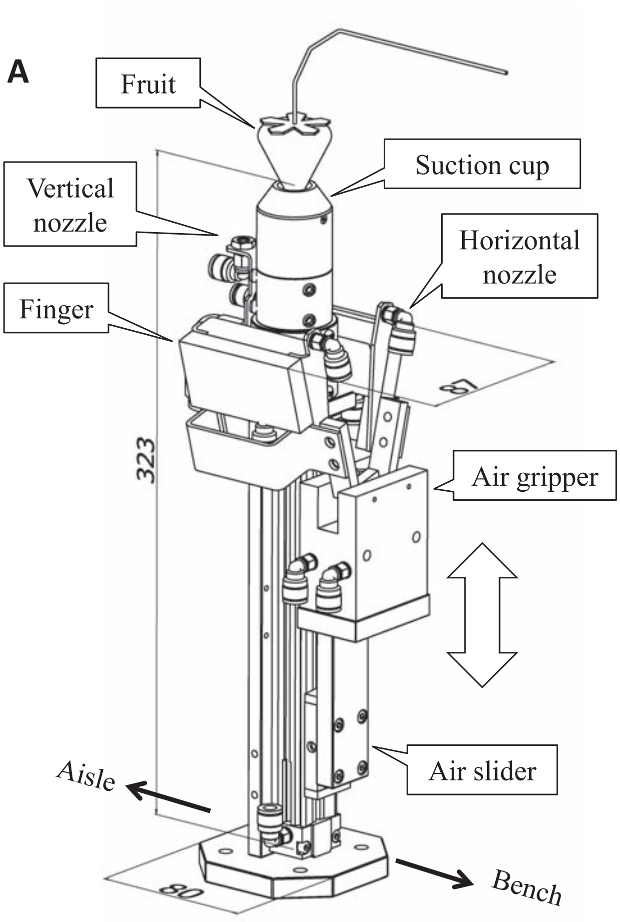
3. End-effector

Because there is generally insufficient space under the movable bench system for a bench-side approach, we decided to design an end-effector that would approach the fruit from below. Considering the fact that more than half the fruit in a greenhouse have adjoining fruit, it seemed necessary for the end-effector to pick the target fruit without affecting them. Figure 9 shows the end-effector, which comprises a suction cup, two fingers, three nozzles, an air gripper, and an air slider. An air pressure sensor was connected to the suction tube to check for the presence of fruit on the suction cup, while the suction cup and fingers were covered in cushioning material to avoid damaging the fruit. The end-effector firstly approaches the target fruit from below. To prevent the fruit adjoining the target fruit from being touched during the approach, the suction cup was set at the tip and the fingers were set at the lower position along with the air slider. If the target fruit is aspirated by the suction cup, and the pressure sensor detects it, the manipulator mounted with the end-effector stops the upward motion and then extends the fingers to the fixed fruit via the air slider. Subsequently, the fingers are closed by the air gripper, and the fruit is held between the cushions on the fingers. To avoid picking adjoining fruit around the fixed fruit, two nozzles blow air from the bench side to the aisle side, and the remaining one blows air to the upper side, as shown in Figure 10. The air blowing starts when the fingers are extended, and stops when they are closed. The airflow was 270 L/min, and the air consumption during the picking motion was 10 L. Finally, the fruit was tilted to 70° and pulled to separate it from the peduncle. Figure 11 shows the tilting motion by the manipulator with seven degrees of freedom. The tilting angle of the manipulator should be 90° considering the force required to separate a fruit from its peduncle. The angle, however, was set to 70° to avoid collision between the manipulator and the planting bench. The mean time to pick a fruit was 31.5 s.

Basic harvesting experiment

1. Materials and methods

A basic performance test was conducted in a laboratory from April to May in 2007 using 50 benches on which



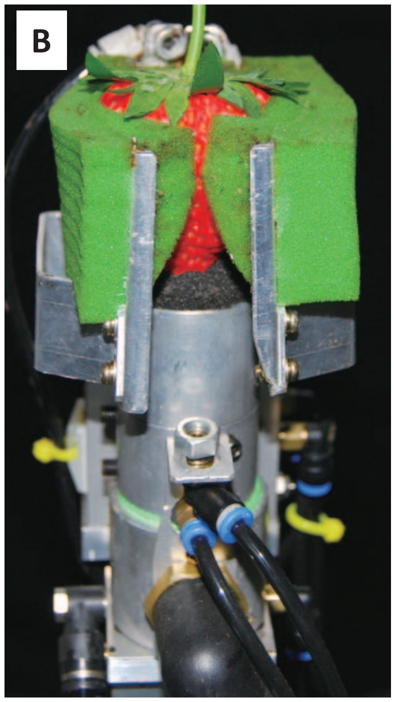


Fig. 9. Schematic diagram of the end-effector
A) general view, B) scene of extending fingers and holding fruit

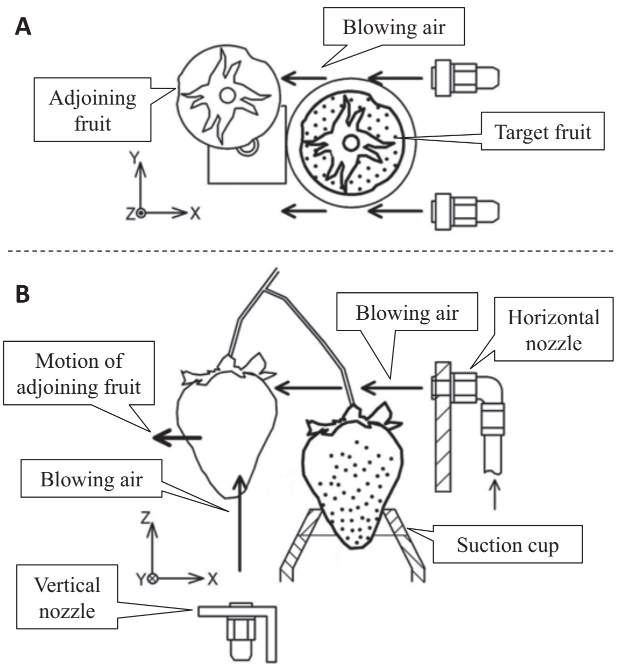


Fig. 10. Separation of adjoining fruit by blowing air
A) top view, B) side view

ten plants of cv. *Beni hoppe* were grown. The coloration rate of the tested fruit exceeded 5% and a total of 536 fruit were tested, 467 of which (87.1%) were in the position range for possible harvesting, 237 were assessed as mature, and 230 immature following visual inspection. The conditions of the adjoining fruit were defined as follows: A: no adjoining fruit, B: adjoining fruit on the aisle side to the target fruit, C: adjoining fruit on the bench side to the target fruit, and D: intervening adjoining fruit under the target fruit. If there were adjoining fruit on both sides, the condition was considered C. The portions of mature fruit under each condition were 31.6, 31.2, 12.2, and 24.9% respectively. During the test, the fruit coloration, condition of the adjoining fruit, success or failure of position detection, judgment of ripeness by machine vision, and picking operations were all recorded. The number of damaged target and adjoining fruit, the harvesting error, in which the robot harvested the adjoining fruit simultaneously, and the number of fruit with attached peduncles were counted.

2. Performance of the stationary robotic harvester

The harvesting success rate for mature fruit was 67.1% of the 237 mature fruit tested. In terms of the conditions of

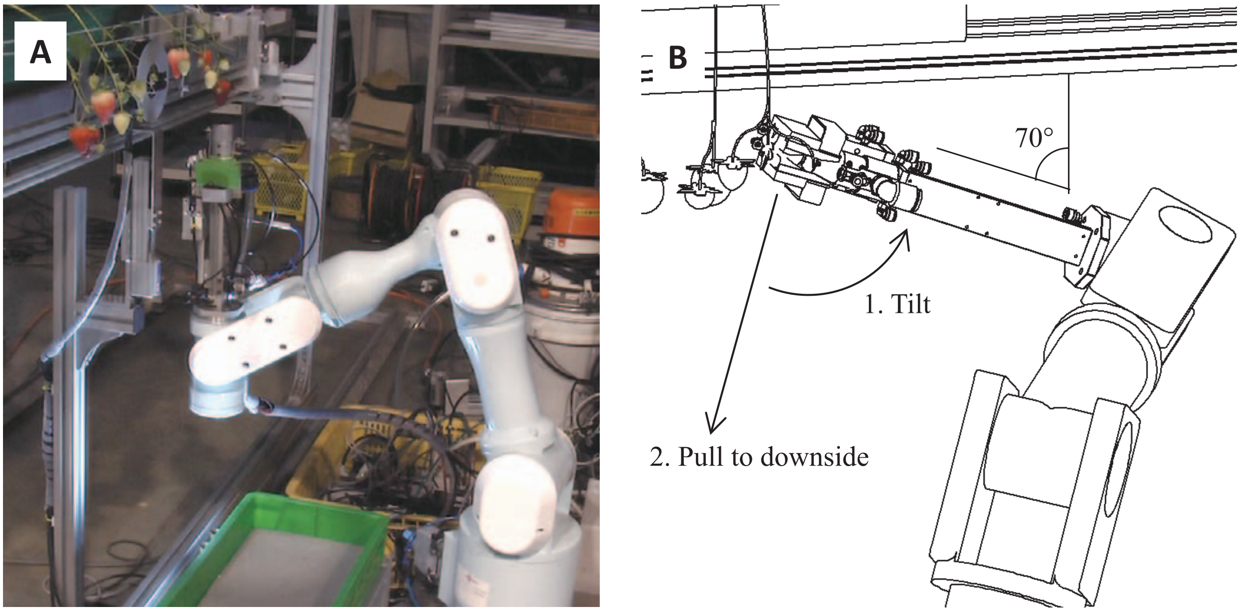


Fig. 11. Tilting motion by the manipulator
A) general view of end-effector and manipulator, B) scene of tilting motion

Table 1. Harvesting success rate and breakdown of each condition

Fruit condition	Portion of matured fruits, %	Success rate*2, %			
		Harvesting W	Detection X	Maturity assessment Y	Picking Z
A	31.6	69.3	93.3	81.4	91.2
B	31.2	75.7	91.9	88.2	93.3
C	12.2	51.7	86.2	68.0	88.2
D	24.9	61.0	81.4	87.5	85.7
Total	99.9*1	67.1	89.0	83.4	90.3

*1 Total of values rounded to one decimal place.
*2 W = X × Y × Z / 10000

the adjoining fruit, the success rates were 69.3, 75.7, 51.7, and 61.0% for conditions A, B, C, and D, respectively (Table 1). The harvesting success rate is the collective value for the following rates: the rate of fruit successfully detected, the rate of mature fruit correctly identified with coloration, and the rate of mature fruit picked, which equated to 93.3, 81.4, and 91.2% under condition A. The values under condition B were, however, almost the same or superior compared with that of condition A. It was observed that strawberries under condition A tended to swing at greater amplitude than those under other conditions, when the movable bench unit stopped. Accordingly, it was thought that the error in positioning fruit became excessive due to the swing motion to measure coloration and the picking operation under condition A. Under condition C, the adjoining fruit on the bench side to the target fruit obviously affected the coloration measurement results under that condition. Under condition D, the successful detection and picking rates were relatively low due to the presence of intervening adjoining fruit under the target fruit. The rate of harvesting immature fruit was 21.3% of 230 immature fruit tested, and the rate of immature fruit incorrectly identified was 36.1%. The main reason for the error was the pendulum motion of the immature fruit detected when the movable bench unit stopped.

The percentage of damaged fruit among that harvested was 12.5%. The rate of picking adjoining fruit was 13.9% of all picked fruit, and the rate of damaged adjoining fruit at the time of picking was 3.4%. The rate of fruit for which the peduncle was removed successfully was 88.0%. The mean weight of the harvested fruit with peduncles was 7.8 g, which was less than the average weight of the whole harvested fruit of 14.8 g. It seemed that small fruit tended to retain their peduncle when the developed end-effector was used. When the average number of mature fruit was 2.3 per bench length of 1 m, the average processing time per bench was 126.7 s.

Conclusion

As a unique approach to improving the performance of conventional automatic harvesting techniques, we envisioned a plant factory for automated strawberry production, which comprised a movable bench system and a stationary robotic harvester. The experimental automatic harvesting system was studied as an initial step toward an industrial strawberry production system. At the beginning of this study, the features of strawberries were investigated to develop a stationary robotic harvester. The visibility of the strawberry fruit on table-top culture was observed in the greenhouse, and the view from below seemed superior to that from the aisle side. The force required to separate a fruit from its peduncle was evaluated, and it emerged that a lower force was required if the angle between the fruit and peduncle was increased. The spectral reflectance of the strawberry fruit and leaves was measured and the results indicated the potential to enhance the colored and uncolored parts of fruit using monochromatic red and green light for more accurate coloration measurement.

A machine-vision system for the stationary robotic harvester was constructed; comprising units to measure the position and coloration. Based on the foregoing investigation, these units were located optimally to detect the mature fruit and estimate their coloration. For the coloration measurement, red and green LEDs were used in addition to white LEDs. The average coloration measurement error was 5.4%, and the standard deviation of the error was 10.8%. To enhance the accuracy of the picking motion of the robotic harvester, we developed an end-effector with three unique functions: 1) the suction cup was set at the tip, and the fingers were set in the lower position with the air slider to prevent the fruit adjoining the target fruit from being touched during the approach, 2) compressed air was blown toward the adjoining fruit to force them away from the target fruit, and 3) the peduncle was removed with a motion involving tilting and pulling the target fruit. The end-effector was set on the manipulator and a program for the picking motion was installed.

The performance test confirmed that the stationary robotic harvester outperformed the conventional robotic harvester because it had a stable high harvesting success rate of 67.1%, with both the unique end-effector and machine vision. Even when there were adjoining fruit on the aisle side of the target fruit, the harvesting success rate reached 75.7%. Peduncles of the harvested fruit were removed in 88.0% of the fruit via the tilting sequence of the robot. However, reducing the damage to picked fruit and improving the working speed remained issues to be resolve. Based on these results, we expect that an industrial strawberry production system not only including a stationary robotic harvester but also a system for monitoring and controlling plant growth, unmanned plant protection system, and an automatic sorting and packing system will be realized in the near future.

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