New strawberry harvesting robot for elevated-trough culture

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Abstract: In order to improve robotic harvesting and reduce production cost, a harvesting robot system for strawberry on the elevated-trough culture was designed. It was supposed to serve for sightseeing agriculture and technological education. Based on the sonar-camera sensor, an autonomous navigation system of the harvesting robot was built to move along the trough lines independently. The mature fruits were recognized according to the H (Hue) and S (Saturation) color feature and the picking-point were located by the binocular-vision unit. A nondestructive end-effector, used to suck the fruit, hold and cut the fruit-stem, was designed to prevent pericarp damage and disease infection. A joint-type industrial manipulator with six degrees-of-freedom (DOF) was utilized to carry the end-effector. The key points and time steps for the collision-free and rapid motion of manipulator were planned. Experimental results showed that all the 100 mature strawberry targets were recognized automatically in the harvesting test. The success harvesting rate was 86%, and the success harvesting operation costs 31.3 seconds on average, including a single harvest operation of 10 seconds. The average error for fruit location was less than 4.6 mm.

Keywords: strawberry harvesting robot, elevated-trough culture, machine vision, nondestructive end-effector, autonomous navigation system, manipulator, sensor

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1 Introduction

Because of the nice taste and high yield, strawberries are widely grown all over the world. In China, the cultivated area of the strawberry is more than one billion hectares. However, the harvesting of mature strawberries has been a hard and heavy task in a long time. To protect the taste and appearance of the fruits, strawberry harvesting has to be done at a cool time of the day by hand[1-4]. According to the investigation, the labor cost on harvesting contributes more than 1/4 of the total production cost[2]. Developing harvesting devices/machines to improve the harvesting efficiency and reduce the labor cost in strawberry production is an active demand.

Since the 1990s, the harvesting robots for cucumbers and tomatoes have been researched in Holland and Japan, and some prototypes have been developed[1-7]. While a lot of problems are still unsolved, due to the complicated structure and unstable illumination conditions of the working environment. Recently, researchers have started using new cultivation methods to reduce the executing difficulty of mechanical harvesting. An elevated substrate culture for strawberries is drawing more and more attentions with its good performances on fruit-leaf separation and fruit regular distribution. The first strawberry harvesting robot for the elevated-trough culture was developed by Japanese researchers in 2002[1]. The robot could finish one harvesting circle in 11.5 seconds with a success rate of 41.3%. Besides, robotic

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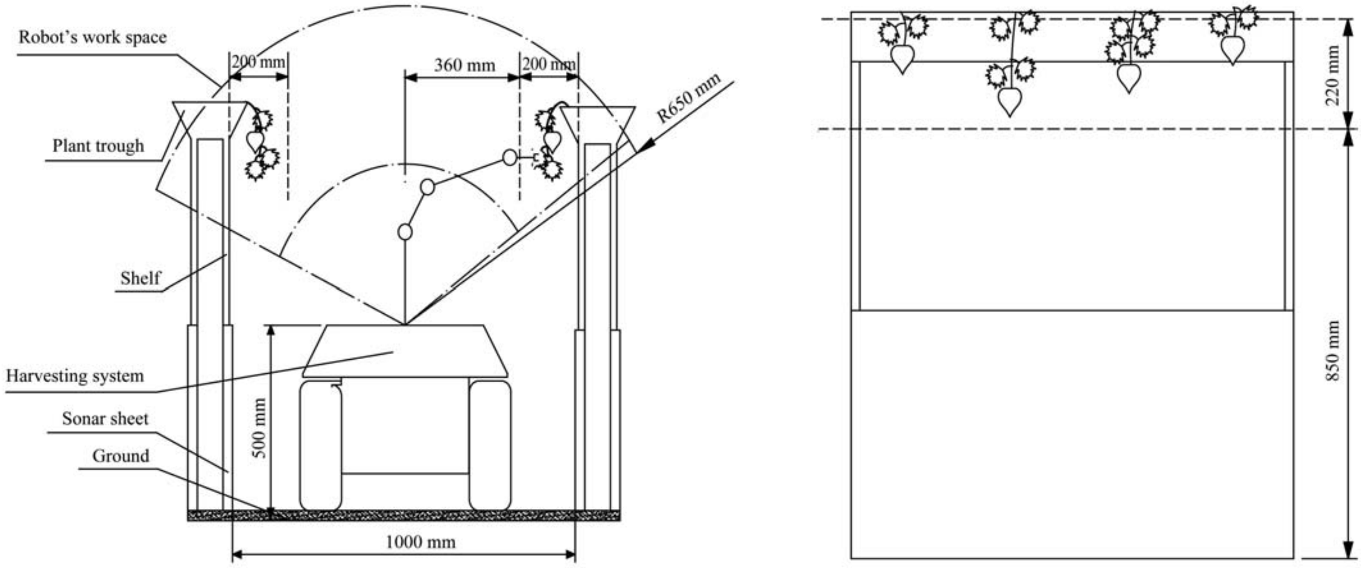
harvesting machines for mound planting were also developed in China[8-11].

In this study, a harvesting robot system for the elevated-trough culture is developed. The system is composed of a manipulator, an end-effector, an automatic vehicle, and a machine vision unit. The robot can move along an aisle between two cultivation shelves under the guidance of the automatic navigation system, and pick fruits on both sides by itself. Experiments have been performed to prove the outstanding harvesting capability of the robot. As a further step to commercial use, the strawberry harvesting robot is expected to serve for the sightseeing agriculture show or high-tech education.

2 Working environment of the robot

The elevated-trough culture has been becoming more and more acceptable for farmers because of its potential advantages. As shown in Figure 1, the strawberry plants are grown in the trough which is braced by the shelves. The iron-sheets (500 mm high) cover on the shelves, which are used for sonar-navigation of the robot. The strawberry fruits distribute in the space of 850-1 070 mm above the ground and 0-200 mm away from the grown trough.



a b

Figure 1 Strawberry grown on elevated-trough culture

3 Robotic system components

Based on the concept of automatic harvesting machine, the following design specifications are defined. Firstly, the mature fruit should be recognized and located accurately under the unstable illumination in greenhouse. Secondly, the collision against the crop, the culture troughs and the robot itself, should be avoided to ensure successful harvest. And then the operation on the fruit should be safe so that the soft pericarp would not be hurt. The intact appearance is extremely important for the strawberry's storage and taste. Finally, the work efficiency and success rate should be raised as much as possible.

The modular harvesting robot is optimally constructed to meet the requirements above-mentioned. As shown in Figure 2, it mainly consists of six components: a four-wheel mobile platform, a 6-DOF manipulator, a

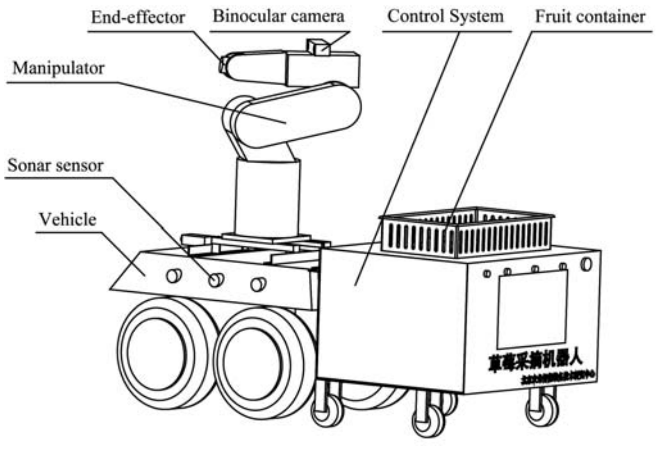


Figure 2 Modular strawberry harvesting robot

harvesting end-effector, a binocular vision unit, a fruit container and a controller. The total weight is 105 kg and the dimension is 1 500×700×1 600 mm^3. In addition, the control instructions can be sent by a remote control device under the voice-prompt guidance, which ensures the simplicity and safety of the farmer/master's operating process.

3.1 Mobile platform

The mobile platform is a four-wheel-drive vehicle, which makes the robot move with strong loading capacity and perfect mobility on the uneven terrain of the greenhouse at a speed of 0.3 m/s. Sonar sensors and a camera play the role of active perception device in the autonomous navigation. When the robot moves among the cultivation shelves, sonar sensors fixed on both sides of it will detect the distances between the vehicle and the iron-sheet on the shelves and help the control system to keep the vehicle moving forward in a straight line. The camera in the front of the mobile platform will capture the color guide line on the ground and lead the robot to turn around when coming to the end of a crop line. The moving trajectory of the robot is shown in Figure 3. Due to the hybrid sensing strategy of sonar sensors and a video camera, the robot can move independently without other devices (e.g. steel rails).

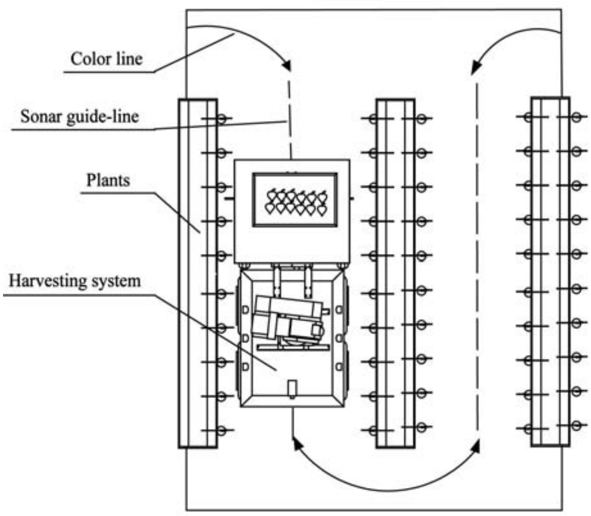


Figure 3 Moving trajectory

3.2 Manipulator

A Denso VS-6556G manipulator is determined to approach the fruit's space of the culture mode. It is fixed on the vehicle 500 mm high from the ground shown in Figure 1, and is used as an arm for positioning the end-effector during harvesting operation. Its bottom joint can rotate in an angle range of 0-345° and the working space looks like a hemisphere with the diameter of 650 mm, which is feasible to handle the fruits on both sides of the robot. The manipulator has 6 degrees of freedom (6-DOF), and can carry 5 kg max-load (heavier than the end-effector designed by us) with steady-state accuracy of ±0.02 mm. Besides the rotation-joint mode structure satisfies the requirement well for working in the limited space between crop and robot. The controller communicates with the robot controller by RS232 bus to receive the fruit position data. In summary, the manipulator's geometrical and physical properties are sufficient for performing harvesting operation in the elevated-trough culture.

3.3 End-effector

The soft surface of strawberries is easily damaged by mechanical stress. Hence, to develop a nondestructive end-effector is vital for automatic harvesting performance. Our end-effector contains two fingers forming a pneumatic gripper for peduncle-grasping, a suction cup for fruit-holding and an electrical heating knife for peduncle-cutting. Figure 4 and Figure 5 show the details of the end-effector. When the end-effector approaches the fruit target, the bellows-shaped suction cup will be pushed out 100 mm to hold the fruit by vacuum, and then pull it back to make the peduncle stay between two fingers. The fingers are closed to grasp the peduncle, and the elastic urethane layers pasted on fingers are used to prevent pinching off the peduncle. The electrical heating cord and the cutting board are respectively fixed above the two fingers. As the two

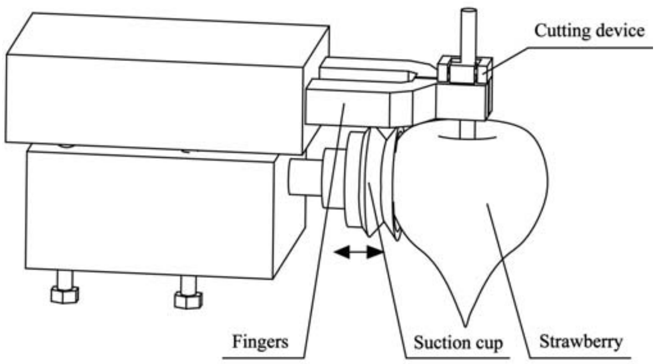


Figure 4 End-effector

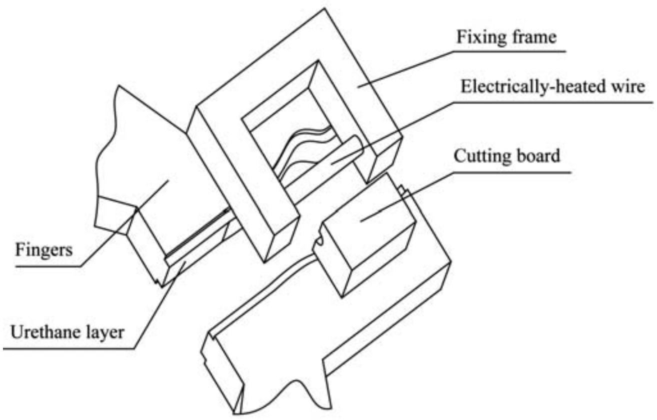
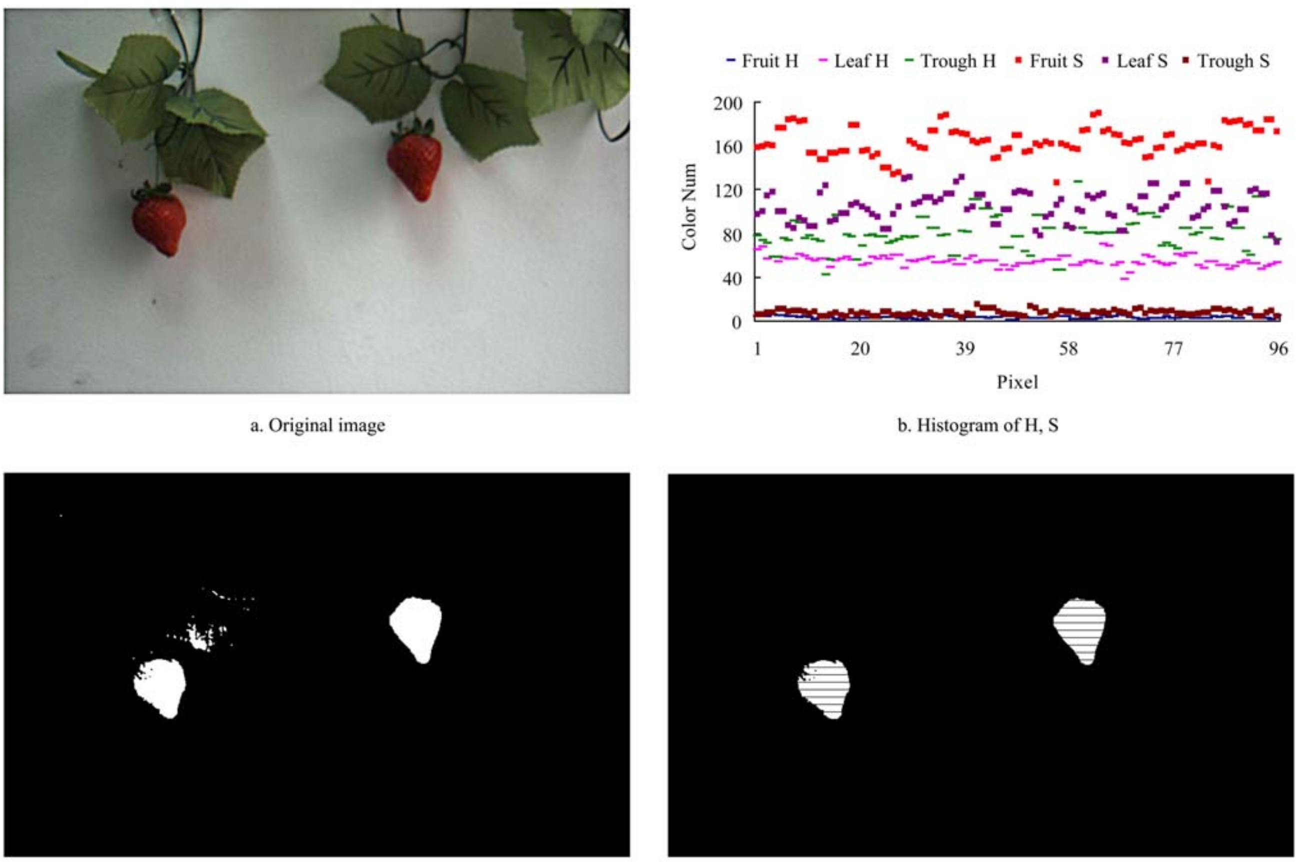


Figure 5 Cutting device

fingers are closed, the cord is electrically heated to 200℃ to cut the peduncle. Heat-cutting kills viruses at the cutting surface and prevents plants from disease infection.

3.4 Machine vision unit

The Point Grey Bumblebee2 binocular camera is employed to recognize and locate the mature strawberries. The commercial vision unit is proved to be practical for reducing the developing cost, while meeting the demands on target detection. As shown in Figure 2, the camera was mounted on the manipulator between the third and fourth joint, and acquired the targets image of both sides at the appropriate height. It has a resolution of 1 024 (H) × 768 (V) pixels and a focal length of 6 mm. At the average distance of 700 mm between the camera and the strawberries, the view field of camera has a width of 670 mm and a height of 500 mm. The image processing algorithm for strawberry detection and location is presented in Figure 6. It consists of four steps:



a. Original image b. Histogram of H, S

c. Binary image d. Picking-point extraction

Figure 6 Target image processing

1) The original image captured is shown in Figure 6a. The H (Hue) and S (Saturation) values of 100 pixels from fruits, leaves and troughs are surveyed (Figure 6b). In the ripe fruit area, the H value falls in the range from 5 to 50) and S value falls in the range of (120, 210), which is distinct from the areas of leaf and trough. So the threshold segmentation for the ripe strawberry region could be done. The binary image is shown in Figure 6c.

2) However, the noise pixels from the leaf remain in the binary image after threshold segmentation in Figure

6c. Fortunately, the target features of size and shape are available to distinguish the target from noises. If S_i denotes the total pixel number of one target and L_i is the edge length, the circularity R_i can be obtained as $R_i = {}^{4\pi S_i}\!/_{L^2}$. As the fruit S_i ranges between 3000 and 5000 and the circularity between 0.3 and 0.6, the area of fruit can be identified effectually and the noise is deleted. The ripe strawberry is extracted from the original image in Figure 6d.

3) In order to locate the picking-point of fruits, the whole target region is divided into several small parts and each part has a height of 10 pixels. The fruit pixels in each part are counted as Num_i, and the center of the part with the maximum Num_i is considered as the picking-point among the image pixels.

After the picking-point (x_r, y_r) are determined in the right image from the binocular vision unit, the other (x_l, y_l) can be matched in left image based on the binocular structure parameters. Finally, the 3D coordinate (x, y, z) is calculated as the following equations:

$$\begin{cases} x = zx_l \ / \ f_l \\ y = zy_l \ / \ f_l \\ z = \dfrac{f_1(f_r t_x - x_r t_z)}{x_r(r_7 x_l + r_8 y_1 + f_l r_9) - f_r(r_1 x_l + r_2 y_1 + f_1 r_3)} \\ \quad = \dfrac{f_1(f_r t_y - y_r t_z)}{y_r(r_7 x_l + r_8 y_1 + f_l r_9) - f_r(r_4 x_l + r_5 y_1 + f_1 r_6)} \end{cases}$$

where, f_l, f_r is the focal length of the right and left camera, (x_r, y_r), (x_l, y_l) is the image coordinate of the picking-point in the right and left image, respectively, t_x, t_y, t_z, $r_{1...9}$ are the parameters of the binocular stereovision system.

4) However, (x, y, z) means the coordinate under the binocular coordinate, which need be translated into the manipulator coordinate. The position data is intelligible for the manipulator controller. The vision unit fixed on the manipulator captures the images and locates the targets only when the manipulator stops at the settled original gesture. Hence, the transformation relation is constant between the binocular and manipulator coordinate. The transformation matrix T, containing rotation and translation vector, can be easily determined through calibration. Then the 3D location (X, Y, Z) of the picking-point in the manipulator coordinate could be derived as:

$$\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = \mathbf{T} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

4 Robot control system

The system controller executes the processes of navigation, target recognition, manipulator motion and end-effector control, which compose the robotic harvesting task schedule. A reasonable schedule is important to make the automatic operations high-performance and cooperative.

4.1 Operational flow of harvesting

A task sequence of harvesting operation is presented in Figure 7. After startup and initialization, the telecontrol instruction sent from people will make the harvesting system move ahead independently. Once the moving time reaches 2 seconds, the navigation system will stop moving. After that the vision unit begins to identify and locate the ripe strawberries in its view field, and the 3D position data of the available fruits is sent to the manipulator. The end-effector is positioned to the target, and separates the strawberry from plants with the operation of suck, grasp, and cut. Finally the fruit will be carried above the container and released. At the moment, a single pick cycle is finished. After all the ripe fruits in the left side are harvested, the bottom joint of manipulator will turn 180° to the right side to pick fruits.

When completing the harvesting operation in both sides, the robot will move ahead to pick other fruits in the front, till receives tele-control instruction for stop. If a fruit is not successfully separated from the plant because of position error or collision, it will still exist in the same area of the view field when the manipulator returns to the initial gesture after a harvesting cycle is completed, the robot will attempt for 5 times before giving up to harvest another one.

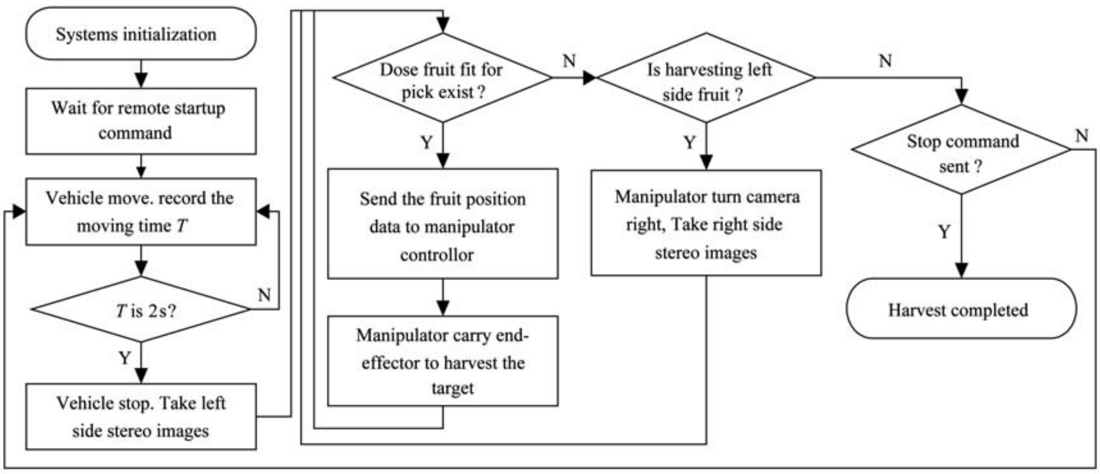


Figure 7 Task sequence of the harvesting operation

4.2 Manipulator trajectory plan

Because the space between the strawberry troughs in the greenhouse is limited for the manipulator motion, as well as the obstacles such as plants, shelves and troughs exists irregularly, the manipulator's motion trajectory should be rectified timely during picking targets for well fruit-holding and collision avoidance.

In this study, the collision-free motion was planed through the key-points defined in the motion path to make the end-effector operate fruits in the right gesture and prevent collision, as shown in Figure 8. During the harvesting operation, the center of the suction cup on the end-effector carried by the manipulator, should pass through the key-points $P_i(i=0, 1, 2, 3, 4)$. The center is moved from the initial position of P_0 to P_1 in 3 seconds, where the end-effector is carried to face horizontally with the target fruit from 100 mm away. Then it approaches horizontally from P_1 to P_2 to grasp the fruit in one second, then the fruit is held and separated after delaying two seconds to insure the vacuum press powerful enough. After separating the fruit, the end-effector moves back to P_1 in one second, and then approaches to P_3 above the container in two seconds. Finally the fruit is released to the container after one second, so that the vacuum pressure for sucking the fruit is weakened completely.

The time list of the key-points in one harvesting cycle is shown in Table 1.

Table 1 Time step of manipulator motion (s)

Key-points	P_0	P_2	P_2	P_2	P_1	P_3	P_3
Time Step	0	3	4	6	7	9	10

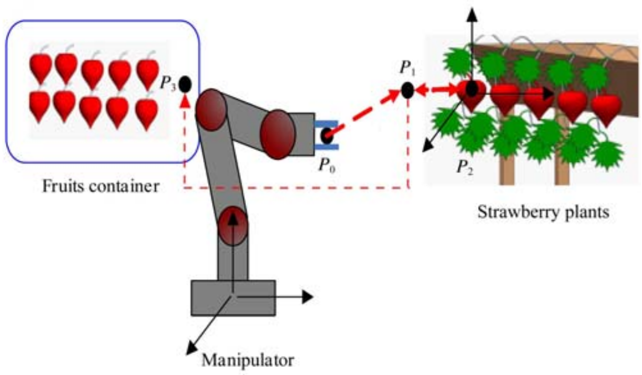


Figure 8 Motion point of manipulator

5 Functional test

Figure 9 shows the integration of the robotic system. The field test was carried out to verify the accuracy and efficiency of the harvesting performance in 7:00-9:00 a.m of 18th October, 2011. The plant culture is shown in Figure 10, and the growing density is about 30 cm. Twenty mature strawberries in the same plant line were set as one series to harvest, and a total of 100 target fruits were picked in the field test. Because the research on dealing with the targets partially covered had not been done adequately, the strawberries overlapping each other were eliminated manually before the test. The test result was noted, including 20 sets of location error between the center of the suction cup on the end-effector and the fruit picking-point, the time cost in harvesting test, the number of harvesting cycles and the success rate.

Firstly, the statistics of location error is shown in Figure 11, in which D means the distance between the manipulator coordinate origin and the fruit picking-point, *e* is the position error measured during the harvesting operation. Among the 20 sets of error measured, the average is less than 4.6 mm and the maximal is 7.7 mm. The longer the harvesting distance is the slightly more error occurs. The error more than 6 mm will possibly cause failure of harvesting.

Figure 9 Functional model of harvesting robot

Figure 10 Strawberry plant for test

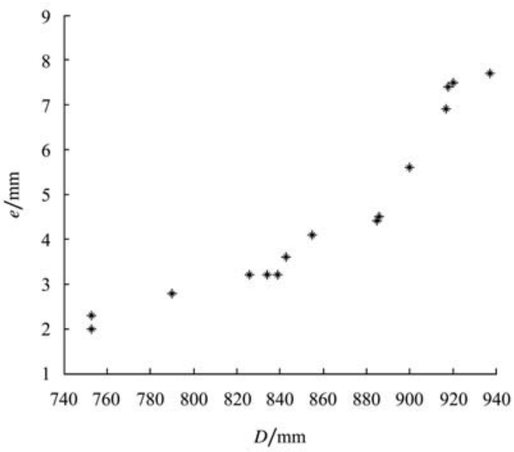


Figure 11 Position error statistics

Secondly, the 100 targets were all detected by the vision unit, but 86 fruits were successfully harvested after harvesting attempt for 121 times because of the operation faults. Besides, the harvesting process including the 86 successful cycles, the 35 unsuccessful cycles, the vehicle moving and the rotation of the manipulator from the left side to the right, cost 45 min in all. So one harvesting attempt needs averagely 22.3 seconds, and one successful attempt costs 31.3 seconds, among which a single harvesting cycle needs 10 seconds according to the motion planning. Among the 14 fruits unsuccessfully harvested, 10 fruits could not be held by suction cup because of the greater error or the smaller fruit size, and 4 fruits dropped down before transported to the container. In addition, the 35 additional attempts were all caused from unsuccessfully sucking the smaller targets.

6 Conclusions and future research

A strawberry harvesting robot was built for the elevated-trough culture, aimed to meet the requirement for automatic production. Based on the sonar-camera sensor, the intellective navigation along the plant trough was completed. The mature fruit was detected from the complex background according to the saturation and hue threshold and the shape feature, which efficiently weakened the influence of the unstable illumination in greenhouse. In addition, the 3D position was located based on the binocular unit. The end-effector's operations (sucking the fruit, holding and heatedly cutting peduncle) avoided damage on the pericarp and the virus infection on the cutting surface. The 6-DOF industrial manipulator satisfied well the need for harvesting strawberry, and the trajectory key-points made the end-effector pick the target in right gestures and prevent collision. The functional test in greenhouse showed that the robotic harvesting system successfully picked 86 out of the 100 mature fruits, and 31.3 seconds for picking one on average. Beside the average position error was less than 4.6 mm; however the error more than 6 mm would result in the harvesting failure. The future research will focus on the improvement of end-effector for sucking the smaller fruits and the optimization of the control program to increase the harvesting efficiency.

Acknowledgments

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