JARQ 36 (3), 163 – 168 (2002) http://www.jircas.affrc.go.jp

Robotic Harvesting System for Eggplants

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Abstract

The harvesting operation for eggplants is complicated and accounts for a little less than 40% of the total number of working hours. For automating the harvesting operation, an intelligent robot that can emulate the judgment of human labor is necessary. This study was conducted with a view to developing a robotic harvesting system that performs recognition, approach, and picking tasks. In order to accomplish these tasks, 3 essential components were developed. First, a machine vision algorithm combining a color segment operation and a vertical dividing operation was developed. The algorithm could detect the fruit even under different light conditions. Next, a visual feedback fuzzy control model to actuate a manipulator was designed. The control model enabled the manipulator end to approach the fruit from a distance of 300 mm. Furthermore, an end-effector composed of a fruit-grasping mechanism, a size-judging mechanism, and a peduncle-cutting mechanism was developed. It produced enough force for grasping the fruit and cutting the tough peduncle. Finally, the 3 essential components were functionally combined, and a basic harvesting experiment was conducted in the laboratory to evaluate the performance of the system. The system showed a successful harvesting rate of 62.5%, although the end-effector cut the peduncle at a slightly higher position from the fruit base. The execution time for harvesting of an eggplant was 64.1 s.

Discipline: Agricultural machinery
Additional key words: machine vision, manipulator, end-effector

Introduction

Fruit vegetables such as eggplants are carefully harvested to avoid damage, after a worker selects mature fruits. The worker estimates empirically the maturity taking account of the growth of the plant, the market tendency, the varietal characteristics and so on. Since it is difficult for conventional agricultural machines to perform such intellectual judgment, the harvesting operation is conducted by hand at present and is not fully mechanized. According to a statistical report, the total number of working hours for eggplant production in Japan is about 200 h/a, and the harvesting operation accounts for a little less than 40%. The total number of working hours is about 50 times that for mechanized rice production in Japan using a tractor, a rice transplanter, a head-feeding combine, etc. Furthermore, the shortage of farmers has become a serious problem due to the concentration of the population into urban centers associated with industrialization.

Under such circumstances, it is essential for Japan to develop a mechanized operation system for stable supply of safe vegetables. As an approach to mechanization, fundamental studies on robotic harvesting were undertaken with the use of advanced technology[8]. As for vegetable production, a basic system for harvesting tomato was developed in the 1980s[6]. Thereafter, robotic sysems for harvesting cucumber[1], cherry tomato[7] and strawberry[2] were developed. Machine vision technology has been used for detecting fruit in robotic harvesting. Each crop needs a distinctive machine vision algorithm. Considering the robotic harvesting of eggplants, the machine vision has to distinguish fruit from stems and leaves, which are similar in color to the fruit. Moreover, judgment of the fruit size is necessary. This function is intro-

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Received 17 December 2001; accepted 28 January 2002.

duced into the end-effector. The end-effector must grasp softly the fruit and cut a tough peduncle.

In the current study, the harvesting operation of a human laborer was divided into 3 tasks, namely, recognition, approach, and picking. These tasks then were performed using a machine vision unit, a manipulator control unit, and an end-effector unit. A robotic harvesting system was developed with the combination of these system components. If the development of an intelligent agricultural machine could be extended to complex crop management operations such as training, trimming, etc., a convenient farming system may eventually be developed. Moreover, this could pave the way for the development of new vegetable production systems worldwide.

Target variety and training method

Many local varieties of eggplants have been bred and widely cultivated in Japan. The sizes and shapes vary considerably. Among the varieties, those with a middle size have been popular in the market along with the progress in transport technology and practical use of F_1 hybrids. Therefore, the middle-sized variety 'Senryo-2' was used in this study. Eggplants are usually cultivated in soil outside or in a greenhouse. Soil-less culture also has been studied. For the introduction of robotic harvesting, production in a greenhouse seems to be suitable due to the availability of power and the dustproof environment. Meanwhile, the training technique of eggplants differs from area to area in Japan. The V-shape training method, as shown in Fig. 1, is well known and enables the fruit to face the passage area. Therefore, the robotic harvesting system was designed to run in an inter-ridge space in the V-shape training method in a greenhouse.

Development of the robotic harvesting system

System components

The robotic harvesting system was composed of a machine vision unit, a manipulator unit, and an end-effector unit, as shown in Fig. 2. The general view is shown in Fig. 3. The machine vision unit (CCD camera, image processing board, and PC-1), corresponding to human eyes, performed the task of detecting the fruit from an image. The manipulator unit (manipulator, controller, and PC-2), corresponding to the human arm, performed the task of approaching the fruit. The articulated manipulator with 5 DOF (degree of freedom), which is widely used for parts assembly in a factory, was selected. Moreover, the end-effector unit (end-effector and I/O board), corresponding to the human hand, performed the task of picking the fruit. The CCD camera was attached to the center of the end-effector. These system components were linked to LAN to communicate with each other.

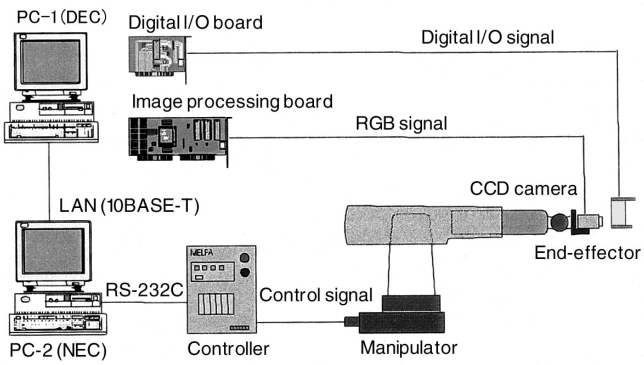

Fig. 2. Schematic diagram of the robotic harvesting system

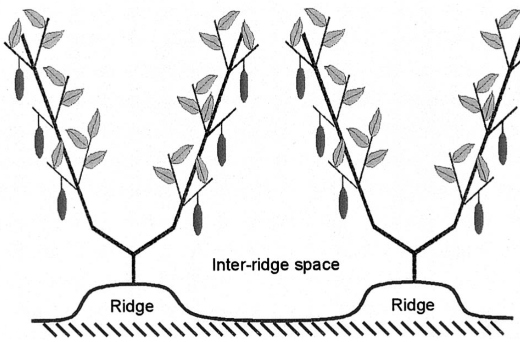

Fig. 1. V-shaped training method

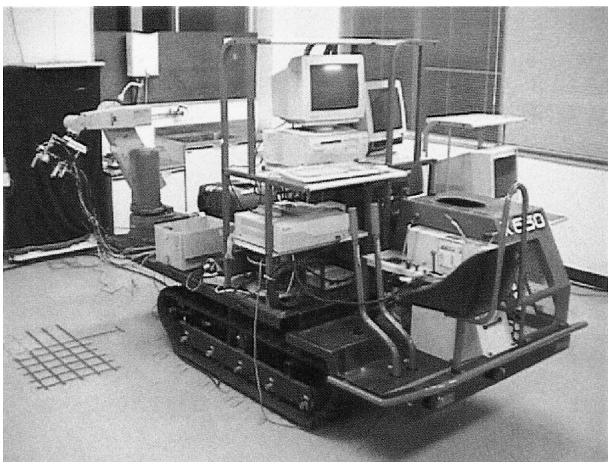

Fig. 3. General view of the robotic harvesting system

Machine vision algorithm[3]

The machine vision algorithm for detecting the eggplant fruit was based on color characteristics and morphological features. Fig. 4 shows the procedure of image processing. First of all, the original image (Fig. 4-a) was captured, and the low gray-level pixels were segmented (Fig. 4-b) with the use of color characteristics whereby the brightness of the fruit was relatively low compared with that of other parts. Here, since some parts of the leaves and stems could be detected by mistake in this process, the morphological features of eggplants were used. In short, the vertical long portion was recognized as fruit part. Therefore, the segmented image was vertically divided by a logical operation (AND) with 2 templates (Fig. 4-c, d) and vertically divided objects (Fig. 4-e, f) were obtained. The objects with a maximum area (Fig. 4-g, h) remained out of the vertically divided objects to eliminate the short objects. A logical operation (AND) between these 2 images was performed, so that several long lines were obtained (Fig. 4-i). Finally these lines were joined by a swelling operation, and the final object was recognized as the fruit (Fig. 4-j).

Fig. 5 shows examples of image processing. It was confirmed that the algorithm could be used under different light conditions, although the algorithm detected a part of the fruit in the case of direct sunlight conditions.

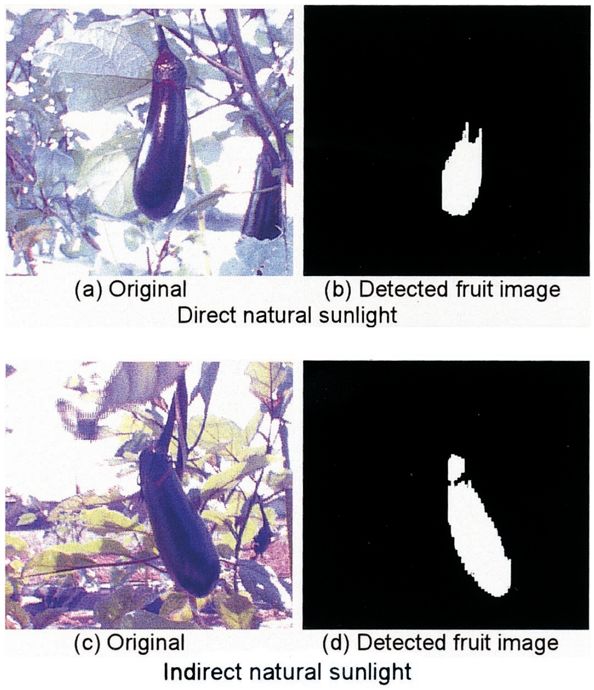

Fig. 5. Examples of image processing under natural sunlight (camera distance: 400 mm)

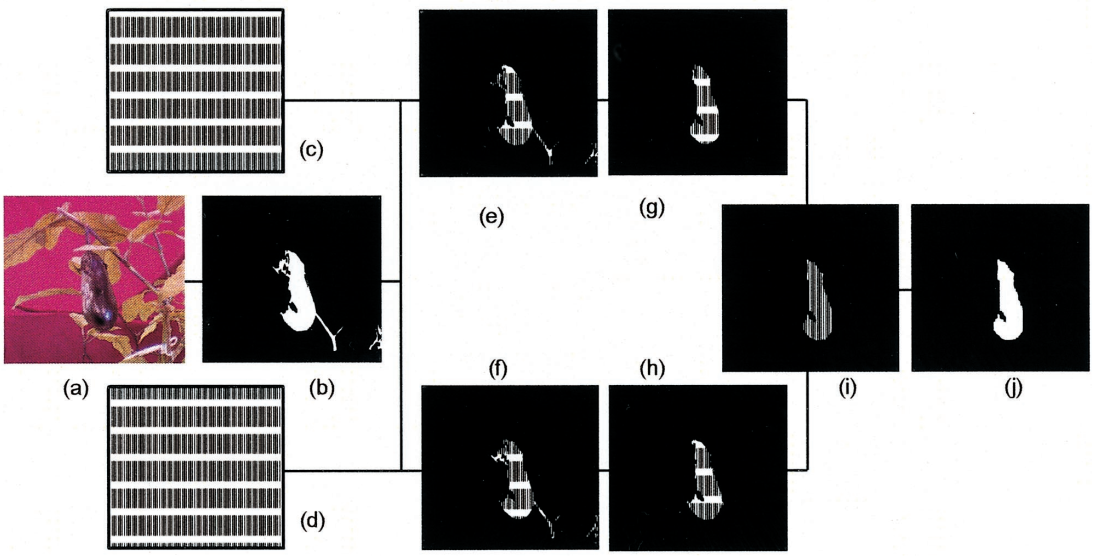

Fig. 4. Machine vision algorithm for eggplant detection

(a): Original image, (b): Low gray-level pixels, (c): Template A, (d): Template B, (e): Vertically divided image using Template A, (f): Vertically divided image using Template B, (g): Maximum area of object, (h): Maximum area of object, (i): Vertical long lines, (j): Detected fruit.

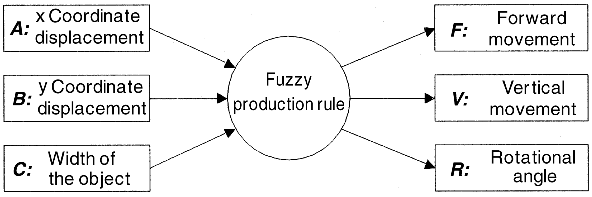

Fig. 6. Schematic diagram of the manipulator control

Manipulator guidance to fruit by fuzzy logic[4]

After detection of the fruit by the machine vision unit, the manipulator approached the fruit with the use of machine vision data. A fuzzy logic was adopted for the manipulator guidance, since the machine vision algorithm would not always detect the whole part of fruit. Therefore the visual feedback fuzzy control model shown in Fig. 6 was designed to determine the forward movement, vertical movement and rotational angle of the manipulator based on the position of the detected fruit in an image frame. Consequently, the manipulator end approached the fruit so that the target region (the portion around the maximum diameter) was located at the center of the image frame. The area of the detected fruit increased along with the approach of the end-effector. When the area occupied more than 70% of total image pixels, the system stopped approaching as the manipulator end reached the fruit.

Harvesting end-effector[5]

The harvesting end-effector is an important tool to pick up the fruit after the manipulator end reaches the fruit. It was composed of a fruit-grasping mechanism, a size-judging mechanism, and a peduncle-cutting mechanism. Fig. 7 shows the general view of the end-effector. The grasping mechanism could hold softly the fruit with the 4 rubber actuators and the 2 suction pads. The judging mechanism could select a fruit with a size of 125–185 mm based on the distance between the photoelectric sensor for detecting the fruit apex and the guide bars for detecting the fruit base. The cutting mechanism, moreover, was able to cut the tough peduncle. All the mechanisms were actuated with 0.4 MPa of compressed air.

Harvesting procedure

Integrated software for performing the harvesting operation was developed with the functional combination of the system components. The harvesting procedure is as follows. First, the manipulator end was controlled vertically, horizontally, and in the forward direction by the visual feedback fuzzy control model. After the manipulator end reached the fruit, the system started the picking task. The photoelectric sensor, attached at the bottom of the end-effector, was checked to determine whether it detected the fruit apex. The end-effector then moved downward or upward until the fruit apex became located in front of the photoelectric sensor, and grasped the fruit. The manipulator lifted the fruit at an angle of 30° with the center at the fruit base to separate the fruit from adjacent leaves. The guide bars were closed and slid up. When the guide bars reached the fruit base, they stopped sliding up. The scissors used for harvesting were closed to cut the peduncle. Finally the fruit was transferred to a container, which was placed beside the manipulator.

Basic harvesting experiment

Materials and methods

A basic harvesting experiment was conducted in the laboratory with 40 samples to evaluate the performance in terms of successful harvesting rate, cutting position,

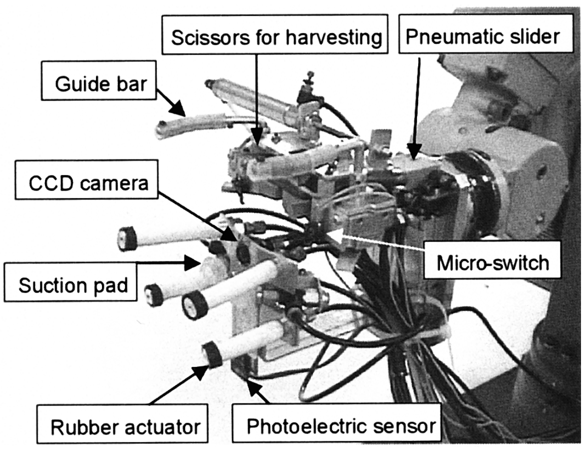

Fig. 7. General view of the harvesting end-effector

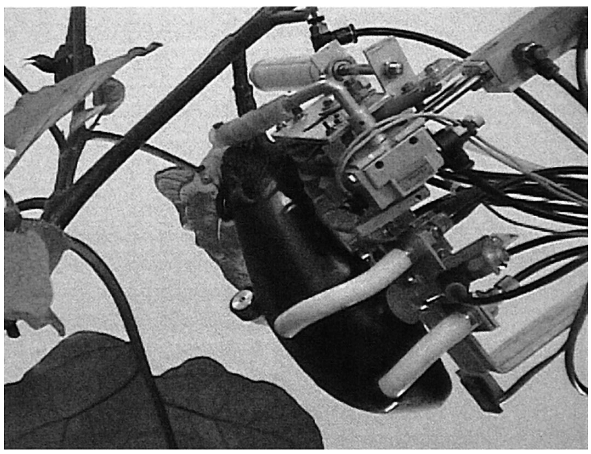

Fig. 8. Harvesting scene with the end-effector

Table 1. Basic harvesting experiment

	No. of samples
Successful harvesting performance	25
Deep cutting	5
Judgment error	9
(Underestimation)	(2)
(Overestimation)	(7)
Failure of approach	1
Total	40

Table 2. Execution time of each task in the basic harvesting operation

	Execution time (s)
Approach	29.5
Fruit apex detection	16.6
Fruit base detection and peduncle cutting	9.2
Release to a certain area	8.8
Total	64.1

and execution time. Eggplants (variety: Senryo-2) were planted in a pot, trimmed at a height of 1 m, and subjected to V-shape training. The fruit sample with a size of 125–185 mm was placed at a distance of 300 mm from the original position of the manipulator, and the integrated software was used. Here, the leaves in front of the fruit were removed to avoid disturbing the visual sensing. The illumination around the fruit was about 450–600 lx.

Performance of the robotic system

A harvesting scene for eggplant with the end-effector is shown in Fig. 8, and the results of the basic harvesting experiment are shown in Table 1. The system could harvest 25 samples out of 40, with a successful harvesting rate of 62.5%. However, in 5 samples, the system cut the fruit portion (deep cutting) and in 9 samples the fruit size was misjudged. These failures were mainly due to the unsuccessful detection of the fruit base, which should be improved by the use of an optical sensor. Moreover, failure of approach occurred in one sample because the machine vision algorithm did not detect the fruit during the approach.

The average cutting position of the peduncle was 9.3 mm higher from the fruit base in the samples harvested successfully. The cutting position varied widely with the direction of the peduncle and the diameter of the fruit base. Since eggplants are generally shipped with a peduncle of less than 5 mm, it would be necessary for human labor to cut the peduncle again, considering the practical use of the system in the future.

Moreover, Table 2 shows the execution time of each task in the basic harvesting operation for the samples harvested successfully. It was found that the robotic harvesting system required 64.1 s to harvest one eggplant. Especially, the execution time for judging the fruit size, to which the approach and the fruit apex detection were added, was 46.1 s and accounted for most of the time. The speeding up of this task may lead to a significant improvement of the performance. Moreover, further studies for the practical use of the system should be carried out, including control with a traveling device, enhancement of system compactness and coordination with human labor.

Conclusion

The harvesting operation for eggplants is complicated and requires a great deal of time. As a fundamental study for automation, the robotic harvesting system for eggplants was developed with the use of advanced technology. The system developed comprised a machine vision unit, a manipulator control unit and an end-effector unit, and could perform automatically the basic harvesting operation, namely, recognition, approach, and picking tasks. The rate of successful harvesting performance was 62.5%, although the end-effector cut the peduncle at a slightly higher position from the fruit base. The execution time for harvesting an eggplant was 64.1 s. Consequently, the fundamental design of robotic harvesting for eggplants was developed and should contribute to the development of techniques for stable vegetable production.

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