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Development of a Three-degrees-of-freedom Robot for harvesting Lettuce using Machine Vision and Fuzzy logic Control

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In Korea, research projects on year-round leaf vegetable production systems are in progress, most of them focused on environmental control. Therefore, automation technologies for harvesting, transporting and grading are in great demand. A robot system was developed for harvesting lettuce plants, comprising of a three degrees of freedom manipulator, an end-effector, a lettuce-feeding conveyor, an air blower, a machine vision device, six photoelectric sensors and a fuzzy logic controller. Fuzzy logic control was applied to determine appropriate grip force on lettuce plant. Leaf area index and height were used as input variables and voltage as an output variable for the fuzzy logic controller. The success rate of lettuce harvesting was 94·12%, and the average harvesting time was approximately 5 s per lettuce plant.

1. Introduction

Greenhouse cultivation area in Korea had been increased from 1·9% in 1990 to 4·8% in 1997. Moreover, glasshouses to which new technologies could be applied had greatly prevailed. However, only a few new technologies including automatic seeder, compositive environment control and automatic nutrient-solution management system have been automated. Most tasks such as transplanting, sorting and harvesting were still dependent on manual labour (Yun, 1996). Researchers in Rural Development Administration investigated input labour per hour of greenhouse lettuce in each stage of tasks and reported that 47% of the total working hours was applied to harvest. Therefore, shortage of labour could be ameliorated by automation of harvesting work.

Research on the design of an end-effector, a core technology of an agricultural robot system, is actively in progress in the agricultural engineering area. Kondo and Monta (1999) developed a robotic cutting–sticking system consisting of four sections; a cutting providing system, a machine vision system, a leaf-removing device and a sticking device. Kondo *et al.* (1996) developed a cherry tomato harvesting system, which includes a stereo machine vision device and an articulated robot with approximately 70% accuracy. A harvesting robot system composed of a machine vision device, Cartesian robot, and an end-effector with a suction cup was also constructed by Reed and Tillett (1994), showing 67% success rate. A lettuce-harvesting system was developed by Uchida *et al.* (1994) for a plant factory to harvest 1800 heads per hour. However, as the pot used in the system was disposable and was cut off along with the lettuce roots, another process was necessary to remove it. Moreover, the waste plant material in the pot became an issue in that it could cause environmental pollution. Weber *et al.* (1991) and Simonton (1991) applied agricultural harvesting robot systems to melon and geranium, respectively. However, most systems were not cost-effective since they were developed with an industrial robot. To overcome such problems, Tillet *et al.* (1995) fabricated a robot with two degrees of freedom and a pneumatic device, and developed a tomato-packing robot system competitive in terms of accuracy and cost.

This study was conducted to develop and evaluate a competitively low price system for automatic harvesting in a plant factory.

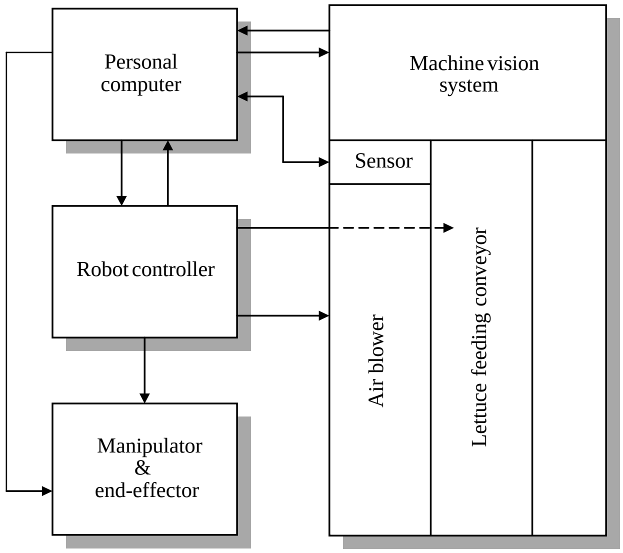

Fig. 1. Schematic representation of a robot system for harvesting lettuce

2. Materials and methods

2.1. *Construction of lettuce-harvesting robot system*

A lettuce-harvesting robot system included a machine vision system to acquire lettuce image, photoelectric sensors for measuring lettuce height, a lettuce-transfer device to feed the plants into harvesting position, a manipulator with three degrees of freedom (3-DOF) and an end-effector for harvesting lettuce, an air blower for lifting drooping leaves when an end-effector approached the lettuce, and a controller for achieving these processes. The schematic representation of a lettuce-harvesting robot system is given in *Fig. 1*.

2.2. *Procedure for harvesting lettuce*

The procedure for harvesting lettuce was as follows (*Fig. 2*):

(1) The machine vision device took the image of the lettuce, and photoelectric sensors detected the height.

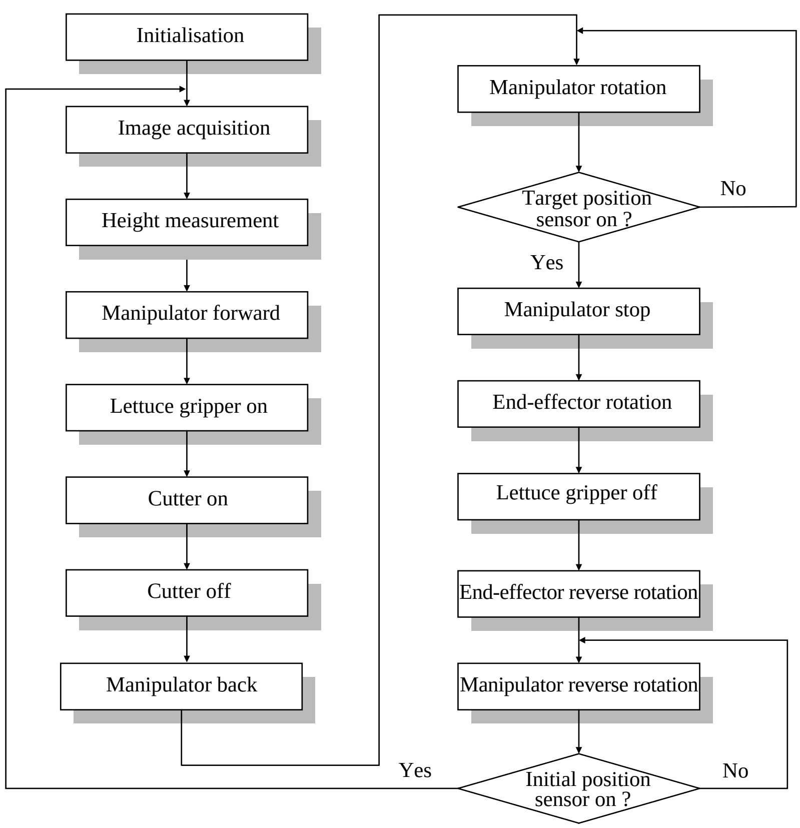

Fig. 2. Procedure for harvesting lettuce

(2) The lettuce-transfer device placed lettuce plants into the appropriate position one by one.
(3) The air blower in the lettuce-lifting device lifted drooping leaves when the end-effector approached the lettuce.
(4) The lettuce was held in a gripper, whose grip force was controlled by fuzzy control, and the root removed by a cutting blade.
(5) The cut lettuce was sent on a lettuce-transporting conveyor through the rotation of the manipulator.
(6) The five steps in this procedure were repeated after the manipulator returned to the initial position.

2.3. *Manipulator*

A 3-DOF manipulator based on a cylindrical coordinate system was fabricated. As shown in *Fig. 3*, the manipulator was rotated about the *Z*-axis to move the cut lettuce on the packing conveyor using an AC servomotor controlled by proportional-plus-integral (PI) controller, and its position was controlled with photoelectric sensors. The manipulator was moved linearly forward and backward to harvest the lettuce using a pneumatic cylinder. And the end-effector was rotated with a stepping motor about the Y-axis to put the harvested lettuce on the packing conveyor. If the end-effector was not rotated, the leaves may be damaged by cutting blades or grippers when the lettuce was put on the packing conveyor.

The following was considered when the pneumatic cylinder moved back and forth.

In the operation of the pneumatic cylinder, deflection of the rod resulting from the weight of the end-effector was coordinated by the use of cylinder rod guide. The stroke clearance of the cylinder rod was acquired to prevent damage on the drooping leaves when the manipulator approached.

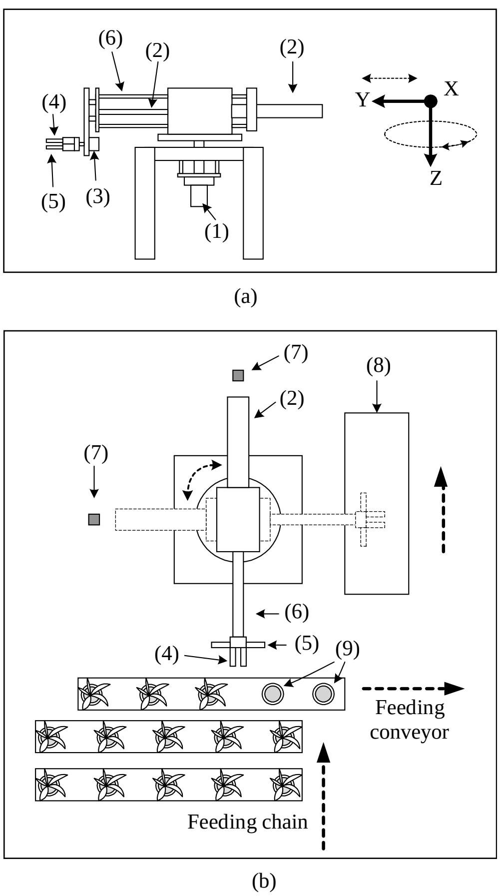

Fig. 3. Layout of the manipulator (a) front view (b) top view; (1) AC servo motor; (2) pneumatic cylinder; (3) step motor; (4) gripper; (5) cutting blade; (6) cylinder guide; (7) photoelectric sensor; (8) packing conveyor; (9) harvested pots

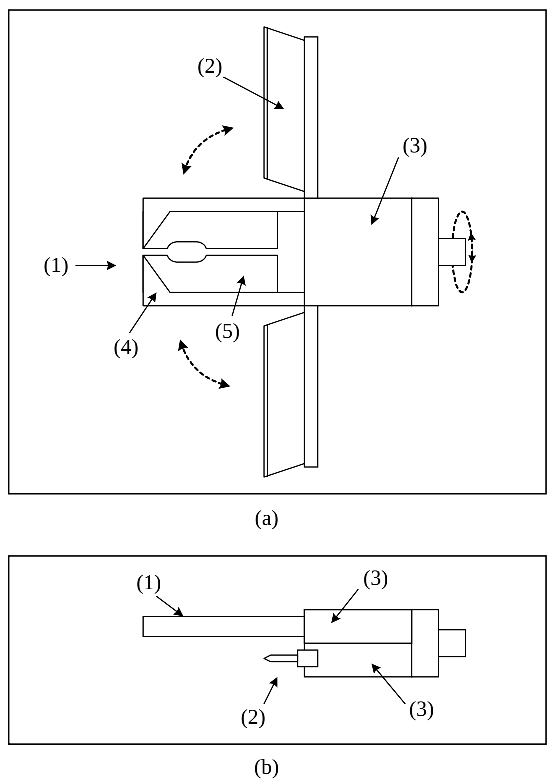

Fig. 4. Layout of the end-effecter (a) top view (b) side view; (1) gripper; (2) cutting blade; (3) air chuck; (4) monomer cast (MC), nylon; and (5) sponge

Table 1
Fuzzy rules applied to control plant gripper voltage

Fuzzy rule no.	*Leaf area index*	*Plant height index*	*Gripper voltage*
1.	Very narrow	Very small	Very low
2.		Small	Very low
3.		Medium	Very low
4.		Tall	Very low
5.		Very tall	Very low
6	Narrow	Very small	Very low
7.		Small	Low
8.		Medium	Low
9.		Tall	Low to medium
10.		Very tall	Medium
11.	Medium	Very small	Low
12.		Small	Low to medium
13.		Medium	Medium
14.		Tall	Medium to high
15.		Very tall	High
16.	Wide	Very small	Low to medium
17.		Small	Medium
18.		Medium	Medium to high
19.		Tall	High
20.		Very tall	Very high
21.	Very wide	Very small	Medium
22.		Small	Medium to high
23.		Medium	High
24.		Tall	Very high
25.		Very tall	Extra high

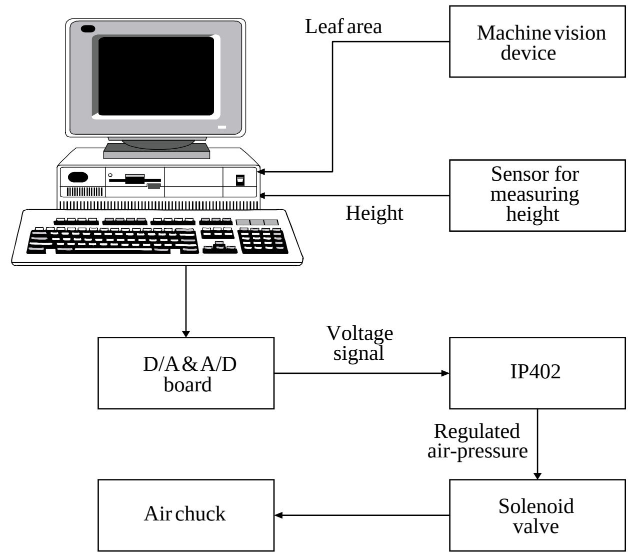

Fig. 5. Components of the fuzzy logic controller; D/A, digital to analogue; A/D, analogue to digital; IP402, pressure regulating valve proportional voltage

2.4. *Control device*

The manipulator was controlled by a one-chip microcontroller, PB-1S(Compile Technology, Korea) which was an improved version of 16C73A(PIC), programmed with BASIC. It was composed of 14 input/output ports and two other output ports for generating frequency. The pneumatic cylinder was controlled by a double-acting solenoid valve, which was driven by a relay.

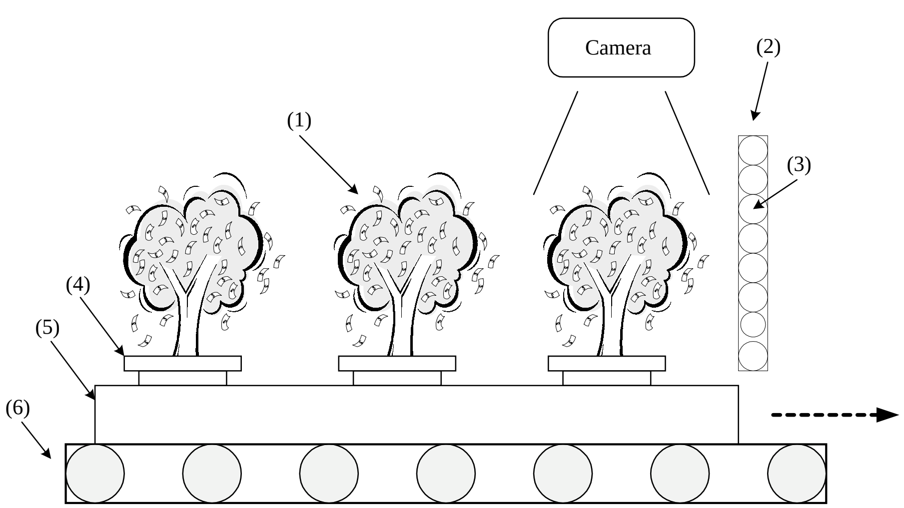

Fig. 6. Layout of the vision system and photoelectric sensors; (1) lettuce; (2) vertically placed photoelectric sensors; (3) a photoelectric sensor; (4) pot; (5) a pot tray; and (6) lettuce feeding conveyor

2.5. *End-effector*

The end-effector was composed of a cutting blade and a lettuce gripper. As shown in *Fig. 4,* the cutting blade was designed to cut the lettuce plant held in a pot with an open-type air chuck. The end-effector was driven by a solenoid valve and relay, and controlled with the PB-1S.

As the stem size of the lettuce is different, the appropriate grasping force on the stem should be considered. So, to harvest the lettuce plant successfully, the lettuce gripper must hold the base of the lettuce with proper force determined by the 25 fuzzy rules as shown in Table 1 depending on the size of the lettuce such as leaf area and height. Fuzzy logic control is more adequate to determine the grasping force than any other because of the non-linear properties of the plant.

As shown in *Figs 5* and *6*, leaf area and height detected with the machine vision system and photoelectric sensors, respectively, were used as input variables of the fuzzy controller, and the driving voltage of the air chuck as an output variable. Membership functions of the input variables are given in *Figs 7–9*. Relation between the gripping force, which is proper to grasp a lettuce plant, and pressure was measured by experiment. As shown in *Fig. 10,* the test result was dependent on grasping point from hinge of the gripper to the position for grasping a lettuce plant.

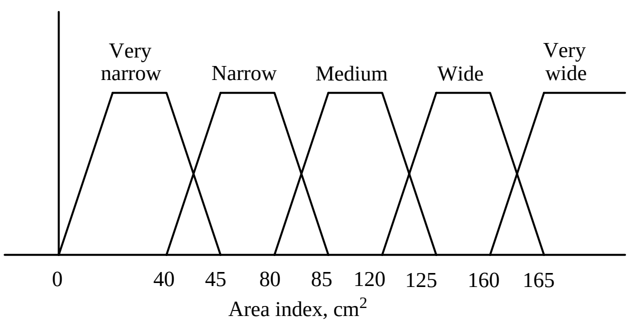

Fig. 7. Membership function of the leaf area index

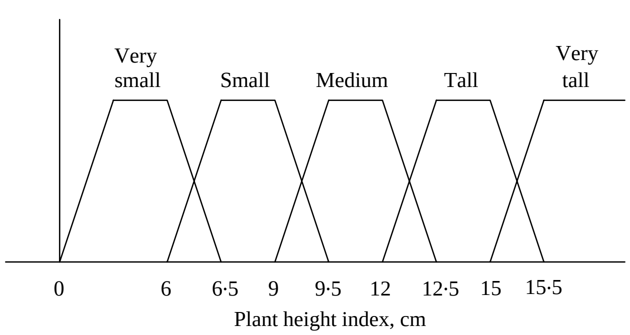

Fig. 8. Membership function of the plant height index

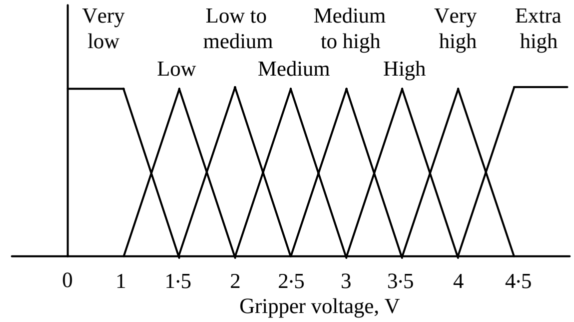

Fig. 9. Membership function of the gripper voltage

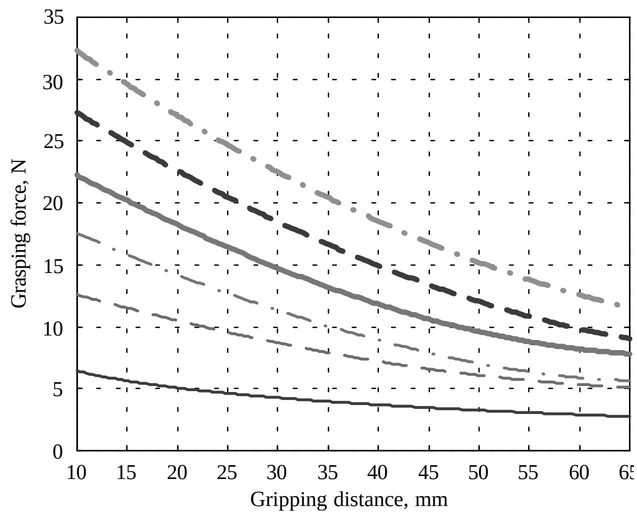

Fig. 10. Relation between gripping distance and grasping force for a range of air pressures; ——, 0·1Mpa; – – –, 0·2 Mpa; –·–·–, 0·3 Mpa; ▬▬, 0·4 Mpa; ▬ ▬ ▬ , 0·5Mpa; ▪·▪·▪, 0·6Mpa

Also, the maximum and minimum gripper sizes, the rigidity of grip surface, and the weight, size and geometrical shape of lettuce were necessary. The gripper was driven by an air chuck with an opening and closing interval of 0–180°, and the finger of the gripper was made of monomer cast (MC) nylon. To reduce the impact force on the lettuce plant during grasping, sponge was attached to inner part of the finger.

2.6. *Machine vision system*

A machine vision system was used to take the image of a lettuce plant and obtain such information as the leaf area and geometrical shape of lettuce plant. The system was composed of a colour charge-coupled-device (CCD) camera (PULLiX) and a frame grabber (Matrox corona-LC/8). Luminous intensity was kept between 2·3 and 3·0 klx on the entire field of view. A chain code method was used on the acquired image to detect its outline, and leaf area was calculated. Information on detected leaf area was used as an input variable of fuzzy controller to control the force of the lettuce gripper.

2.7. *Photoelectric sensors*

Six photoelectric sensors attached to a vertical bar at 3 cm intervals detected the height of the geometrical shapes of lettuce. The photoelectric sensor was a direct reflection type, and its control output was an NPN open collector.

2.8. *Leaf-lifting and lettuce-feeding devices*

Leaf-lifting device was fabricated to prevent damage to the lettuce by lifting drooping leaves when the end-effector approached a lettuce plant. It was operated by a solenoid valve and relay, and was controlled by control signal from the PB-1S. Lettuce-transfer device was fabricated to feed lettuce plants into proper position one by one and was driven by an AC motor, MC34C87(a chip for line driver) and relay.

3. Results and discussion

In order to evaluate harvesting performance of the end-effector, lettuces (*Lactuca sativa* var. *crispa*), which was appropriate for greenhouse cultivation and commonly found in Korea, were selected and cultivated. As shown in *Fig. 11,* the test result of fuzzy controller-controlled griping force of the lettuce gripper showed that as leaf area and height increased, griping force was also increased, maintaining stable grasp so as not to damage the lettuce.

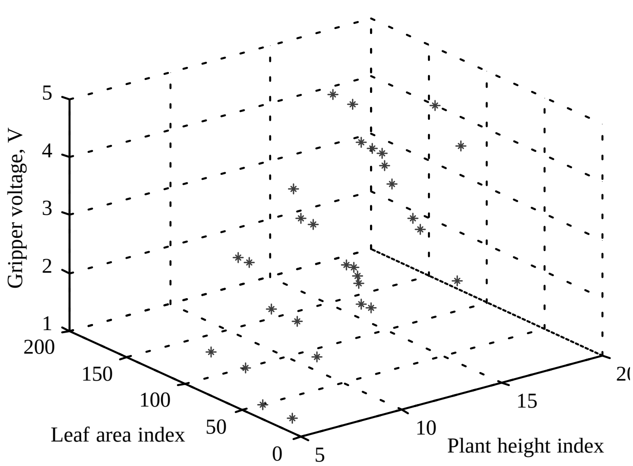

Fig. 11. Result of fuzzy logic control

Table 2
Performance of the robotic lettuce harvester

Handling condition	*No. of lettuces*	*Percentage*
Undamaged	80	94·12
Minor damage	5	5·88
Total	85	100·00

Harvesting test on 85 heads of lettuce was conducted. As shown in Table 2, 80 of a total of 85 heads were successfully harvested with an average harvesting time of 5 s. Five damaged heads still had commercial value because only the edges of its bottom leaves, which sometimes should be removed if discoloured yellow, was partly torn.

4. Conclusions

This study was conducted to develop a lettuce-harvesting robot to automate plant factories, which produce green vegetables on a large scale. The important results were as follows.

A lettuce-harvesting robot system composed of a three-degrees-of-freedom manipulator, an end-effector, a lettuce-feeding device, leaf-lifting device, machine vision device for taking the image, photoelectric sensors for detecting height, and a fuzzy controller was developed.

Twenty-five rules for the fuzzy controller were used to determine appropriate griping force of the gripper. Information on leaf area and height were used as input variables for the fuzzy controller, and the driving voltage of the air chuck was used as an output variable.

Success rate of the harvesting was 94·12%, and average harvesting time was about 5 s per lettuce.

Test results showed that the developed lettuce-harvesting robot system could be applied to the automation of the plant factory.

Acknowledgements

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