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学位論文全文に代わる要約
Extended Summary in Lieu of Dissertation

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学位論文題目：
Title of Dissertation　Development of a Multi-operation System for an Intelligent Greenhouse
(太陽光植物工場におけるマルチオペレーションシステムの開発)

学位論文要約：
Dissertation Summary

1. Introduction

Over the centuries, agriculture has morphed into the modern large-scale bio-industry as it is today. The major changes in agriculture have occurred through cultivation of crops. Despite commendable achievements, there have been some alarming issues and causes for concern regarding the world agriculture sector, such as declining productive land and water resources, challenges in providing sufficient food for an increasing world population, declining labor force engaged in agriculture, increasing labor cost, and the environmental impact of agricultural production. In the current situation, greenhouse production of agricultural crops is the most sustainable solution. Unlike open-field agriculture, greenhouses are structured and well-controlled environments. Greenhouse crop production is a highly repetitive and labor-intensive operation. For instance, in greenhouse crop production, labor is often tedious, non-ergonomic and sometimes carried out by unskilled personnel. Automation technology can be used to replace some traditional labor functions, and to improve productivity, health and job satisfaction of personnel, but there are serious technical challenges in automating operations, especially in agriculture (Kassler, 2001; Gay, 2008). In greenhouses, robotic solutions, particularly for guidance, harvesting and specific cultivation applications have been developed for guidance (Gonzalez et al., 2009; Longo et al., 2010; Mandow et al., 1996; Li et al., 2009), Harvesting (Peter et al., 2009; Hayashi et al., 2010, 2014; Han et al., 2012; Arima et al., 1996, 1999; Van Henten et al., 2003; Hayashi et al., 2002; Kitamura et al., 2009 and Bachche et al., 2013), Spraying (Subramanian et al., 2005 and Rafiq et al., 2014). Most present-day greenhouse robots can be used only for a single task for which they are being developed. These robots can only be used a few times a year because agricultural production depends on seasonality, which increases the time required for a return on investment and discourages farmers from using robots. Also, at the research level, there are few studies involving multi-functional robots (Monta et al., 1995; Van Henten et al., 2003, 2006; Belforte et al., 2006; Sanchez-Hermosilla et al., 2013; Shinde et. al., 2013). Robots can efficiently perform tedious tasks in harsh environments while ensuring fast and skillful operations. Moreover, a multi-operation system would be economical when considering seasonality. Hence, Multi-operation system which can perform different tasks for different crop systems or system which can work for whole crop cycle of single crop is essential.

2. Multi-operation system

By considering the need of multi-operation system for economical automation; we are developing a flexible multi-operation system that can perform different tasks for different crops (Fig. 1), such as growth diagnosis, pollination, pest monitoring, spraying and harvesting. To carry out these different tasks, a robust and efficient autonomous navigation unit that can support and control all the above-mentioned units becomes crucial.

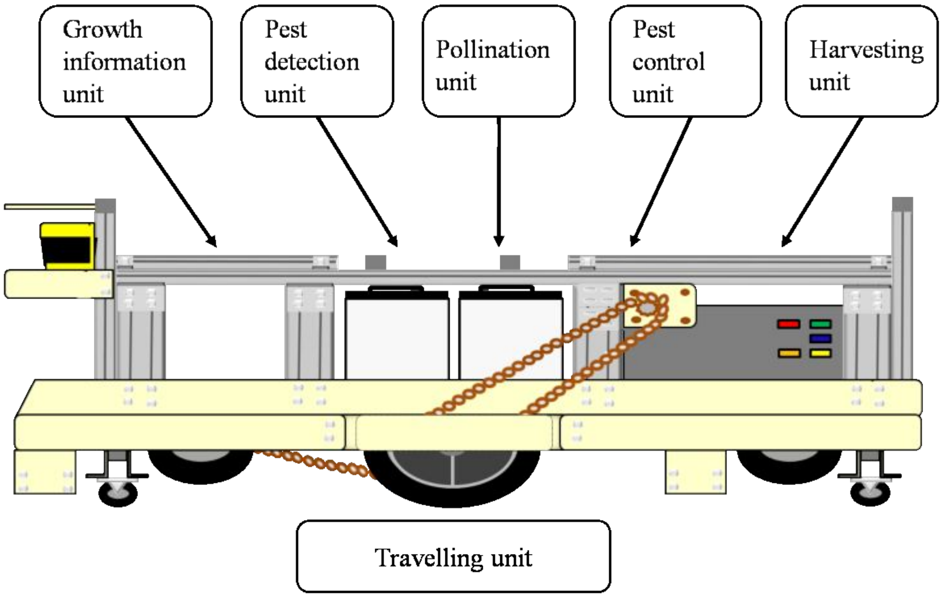


Fig.1. Overview of a multi-operation system

3. Auto- guided travelling unit

We have developed an Auto-guided travelling unit with laser scanner guidance, henceforth referred to as an AGTU-scanner (Fig. 2(a)). Operational control method of AGTU-scanner is shown in Fig . 2(b). Three zones A, B and C were configured in SZ-H1S software for external environment recognition (Fig. 3). Along with laser scanners absolute encoders were employed for relative position determination. For navigation testing was carried out. Straight movement test was carried out at operating speed of 0.2 m/s and at a gap setting of 20, 40, 60, 80 and 100 mm between zones B and greenhouse wall at ideal (with sheet on both side) and working (normal greenhouse) condition. Ten trials for each gap setting were carried out. To measure the error, reference motion path was marked with an equal interval of 200 mm. A measuring scale was fixed at the bottom of travelling unit and video camera was mounted at the top. Errors were calculated manually at a regular interval of 200 mm from video data obtained through a camera. The lateral error of the AGTU-scanner was calculated through video data obtained during the test by manually measuring the difference between distances from the reference motion path and trajectory followed. Error readings were taken from each trial as described above to calculate the average error, maximum error, standard deviation, and path root mean square error. Performance measures are illustrated in Table 1 and 2. From the results of physical experiments it is observed that a gap setting of 100 mm is best in ideal and working conditions with comparatively less maximum error, less average error, less rms, less time to cover a distance of 10 m, and minimum trajectory correction counts in present greenhouse condition. The PLC control is driving the error around zero. Schematic diagrams for pipe rail approach angle and maximum allowable offset angle are shown in Fig. 4. The AGTU-scanner enters the pipe rail safely for an offset distance of up to 220 mm. Maximum allowable offset angle was found to be 79° at a gap setting of 100 mm.

This compact travelling unit showed better performance with collision-free operation. The experiments undertaken during this study demonstrated the accuracy of the guidance system under ideal test conditions, and the developed travelling unit also exhibited successful guidance in working conditions too.

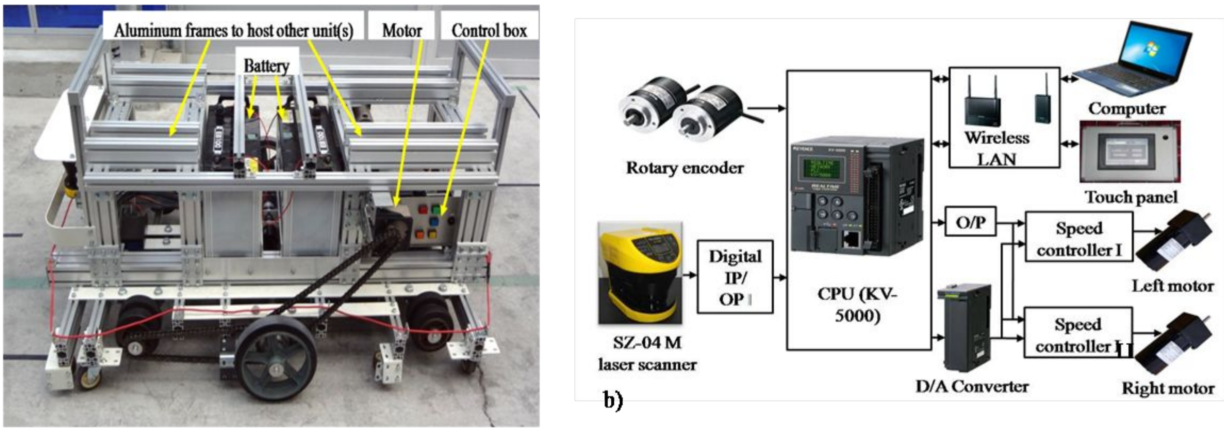


Fig. 2. a) AGTU-scanner b) Operational control method.

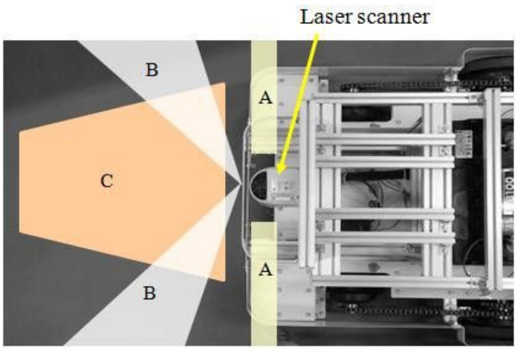


Fig. 3. Configured zones of SZ-04M laser scanner.

Table 1 Performance measures of the AGTU-scanner guidance system under an ideal condition. A negative sign indicates that the error is biased to the left

Setting (mm)	Maximum error (mm)	Average error (mm)	rms	Standard deviation	Time (s)	Motion correction count
20	56.50	-22.23	3.96	17.84	52.30	10.10
40	44.20	-13.22	2.78	15.15	51.40	6.00
60	36.10	0.08	2.12	14.70	51.30	4.80
80	47.50	-0.37	3.02	18.54	49.80	2.90
100	57.20	1.12	3.80	22.94	50.10	1.60

Table 2 Performance measures of the AGTU-scanner guidance system under working condition. A negative sign indicates that the error is biased to the left

Setting (mm)	Maximum error (mm)	Average error (mm)	rms	Standard deviation	Time (s)	Motion correction count
20	42.00	-7.15	2.58	16.94	56.70	48.70
40	39.70	-7.78	2.57	16.49	56.60	55.00
60	43.40	-12.25	2.57	13.61	54.80	40.40
80	30.00	-5.97	1.76	10.31	52.50	23.40
100	26.50	-6.14	1.91	11.76	50.60	7.40

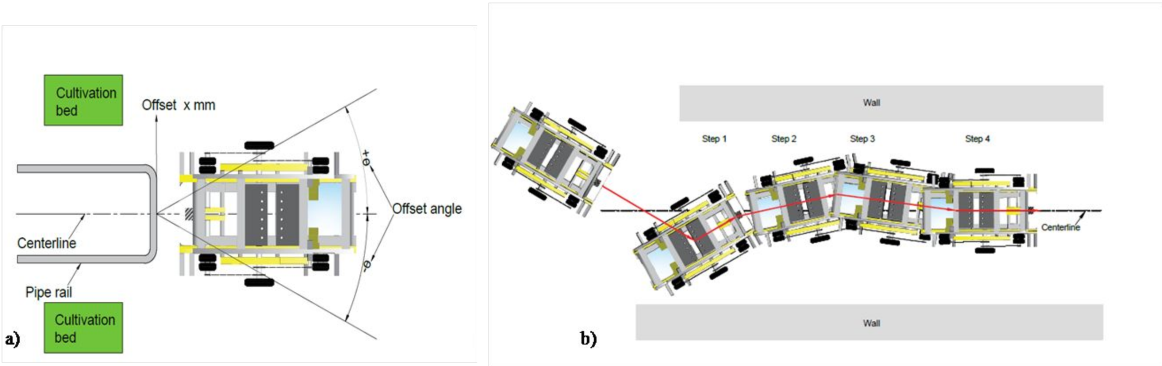


Fig. 4. Schematic diagram of experimental set-up for determining a) pipe rail approach angle b) maximum allowable offset angle

4. Artificial pollination unit

Due to alarming decline in the pollinator's population all over the world along with increasing food crisis it become necessary to find an efficient alternative for pollinating the flowers artificially. Hence, it was decided to check the feasibility of ultrasonic non-contact pollination device's acoustic radiation pressure for tomato pollination. Non-contact ultrasonic artificial pollination unit is shown in Fig. 5. Pollination of tomato is studied by - a) bumblebee, b) vibration with an artificial pollination unit, c) hormone (4-CPA), and d) control treatment. The experiment was carried between 26th January, 2015 to 23rd March, 2016 in fourth chamber of Ehime University's intelligent greenhouse B. The performance is compared by pollination efficiency and shape factor obtained during each treatment as shown in Fig. 6. All the harvested tomatoes from all the treatments were image analyzed in ImageJ software to calculate the shape factor as given below in equation 1.

$$Shapefactor = \frac{4\pi A}{P^2} \tag{1}$$

Where A is area in mm^2 and P is perimeter in mm. The results obtained from this study shows that all treatments were effective in increasing fruit set, although hormone treatment produced the best results. Bumblebee and pollination unit's performance was found almost similar. Shape factor analysis showed best results for bumblebee treatment and lowest for hormone treatment. The obtained results showed satisfactory results. Hence, this unit can be used in commercial greenhouses for pollination purpose.

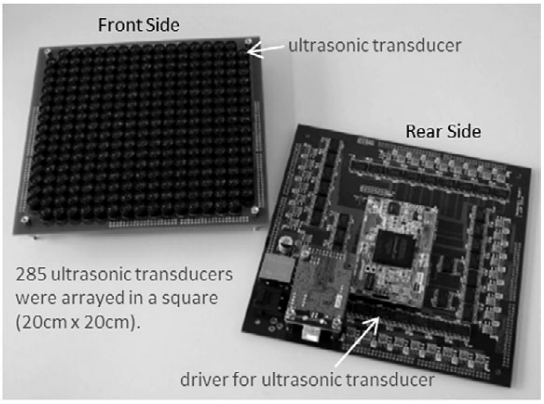


Fig. 5. Appearance of artificial pollination unit

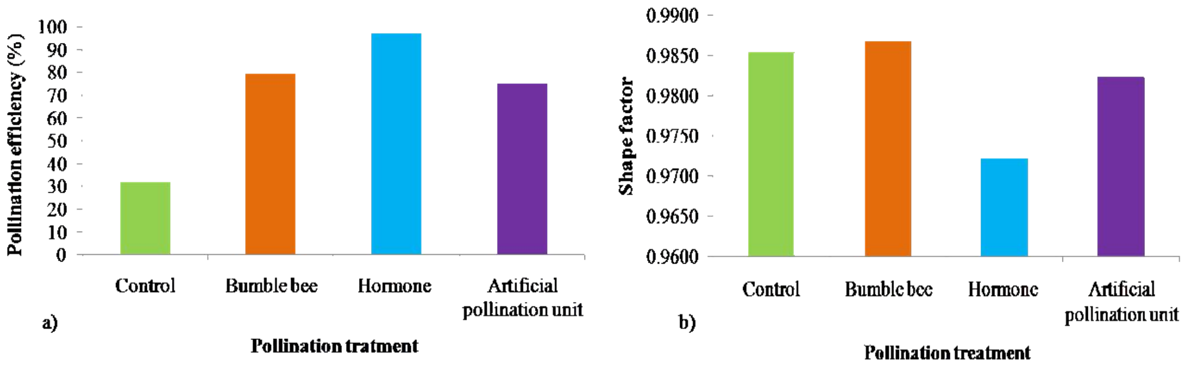


Fig. 6. Performance comparison of each pollination treatment on the basis of a) pollination efficiency b) shape factor.

5. Pest monitoring unit

While meeting the food requirement, safety and security of the food is also becoming equally important. Hence during practicing different measures for improved food production there is challenge to maintain the quality and at the same time keeping the environmental balance. Integrated pest management is vital to produce high quality food without disturbing environmental balance. We have developed a pest monitoring system as one of the unit of multi-operation system to have optimal control in accordance with the pest occurrence. Fig. 7. shows an overview of a pest monitoring generation system. We are introducing pest monitoring system at low cost and by promoting the site deployment to collect a broad and detailed pest occurrence data. There are a number of insect sheets already installed above plants in an intelligent greenhouse. In our approach we are targeting to take images of these already installed sheets while suppressing any new investment to generate the database. This data provides various information that contributes to the stable and high-quality of agricultural production. After analyzing this huge data precise pest management can be implemented. Insect trapping sheets are mounted above cultivation as shown in Fig 8 a). Images were taken by digital camera (DSC-HX10V, 1820 million pixels, SONY Corp.) fitted to the frame of the growth diagnostic unit. Image of the insect trapping sheet is shown in Fig. 8 b). Experiment was carried out between April 18, 2014 until January 27, 2015, twice a week. In this experiment, the image input was performed manually and then image data was transferred to the computer.

Manual counting of number of insects trapped by 100 trap sheets was performed to check the accuracy of image processing. Insect counting algorithm is shown in Fig. 9. Discriminant analysis was used for separating insect area as shown in Table 3.

The graphical representation of pest count result is shown in Fig. 10. The standard deviation of the difference between the correct answer data and image count result of the pest population was found to be 9.26. Though the result is less accurate it can be considered to be effective to show a relative trend of pest occurrence in greenhouse. It helps to do early detection of pest occurrence. Further by mapping pest occurrence it was found that entrance was source for entry of the pest inside greenhouse and preventive measures can be taken.

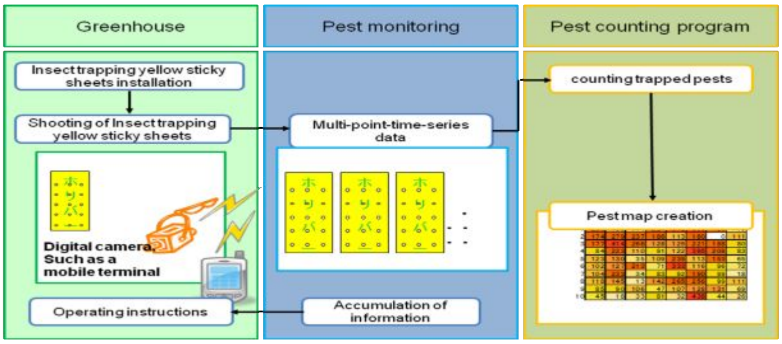
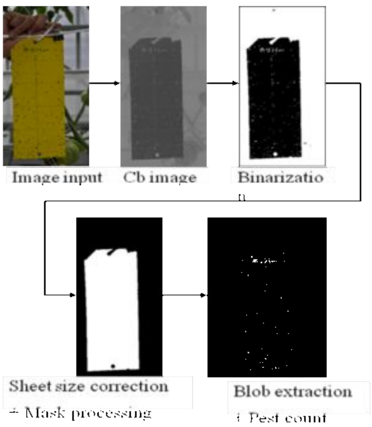


Fig. 7. Pest monitoring system

Fig. 8. a) Installation situation of trap sheet for pest control b) Trap sheet for pest control



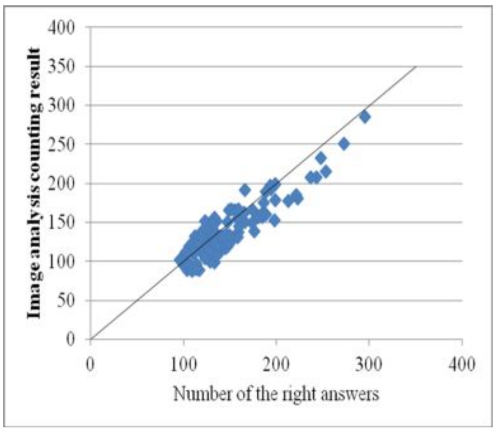


Fig. 9. Pest counting algorithm. **Fig 10.** Graphical representation of pest count result.

Table. 3 Classification of pixel sizes as per representation

Pixels	Representation
0-59	Dotted line on insect trap sheet
60-790	1 pest
791-1370	2 pests
1371-2000	3 pests
2001~	Characters on insect trap sheet

6. Cucumber harvesting unit

Cucumber is among one of the most popular commercial vegetables cultivated worldwide. Cucumber is third largest produced vegetable in Japan after tomato and onion with production of 5, 74, 000 tons. In case of cucumber total 1095 working hours are required for cultivation and harvesting of cucumber in 10 acre greenhouse. About half of these hours are required only for harvesting and post harvesting operations (MAFF, 2007). Due to the faster growth rate of cucumber, even a delay of one or two days may lower the market price (Arima, 1996). Therefore, automation of cucumber harvesting operation is very much essential. Thus, an autonomous robot for harvesting cucumbers grown in greenhouse with inclined trellis training system was developed (Fig. 11) as one of the unit of multi-operation system. Modular harvesting unit consists of auto-guided travelling unit, manipulator, fruit recognition system and an end-effector. Rectangular co-ordinate type of manipulator was used for this unit (Fig. 12).

The novel concept of cucumber harvesting using distance information obtained from ultrasonic and laser sensors to harvest cucumbers of length more than 180 mm is introduced. Arrangement of sensors in fruit detection unit is shown in Fig. 13. An end-effector is composed of a gripping portion with the opening and closing of the gripper and a peduncle cutting mechanism (Fig.14).

Three fruit recognition algorithms were designed and tested with an aim to improve fruit detection, gripping and harvesting efficiency in laboratory conditions with model fruits of different lengths. First algorithm detects cucumber based on its straightness, second algorithm detects cucumber based on difference in cucumber and peduncle diameter and third algorithm detects cucumber based on difference in cucumber and peduncle diameter and with acceptable straightness of cucumber.

The experiments were undertaken with wooden model fruits of length 170, 180, 200, 210, and 230 mm to test the performance of the fruit detection algorithms. A model fruit of length 170 mm was used to verify whether fruits shorter than the required length were being omitted or not. Fruit longer than 230 mm were not considered in this experiment because after daily harvesting there is a lower chance of having fruits exceeding 230 mm. General flow of harvesting is shown in Fig. 15. During experiments, the model fruit was hanged from the inclined trellis and for each fruit length ten attempts were made to determine the fruit detection rate, gripping position determination rate, and harvest success rate. Performance of algorithm-1,-2 and -3 for fruit detection rate, gripping position determination rate, and harvest success rate is illustrated in Fig. 16, 17 and 18 respectively.

For fruit detection using algorithm-1, the average fruit detection rate, gripping position determination rate, and harvest success rate were 77.5, 25, and 37.5%, respectively. By using this algorithm, mistaken harvests of 170 mm fruit was observed, because the laser sensors measure the distance of an object in its vicinity but are unable to differentiate between cucumber fruit and its peduncle. Therefore, the point where fruit ends and peduncle starts cannot be determined properly as shown in Fig. 19, and it results in lower gripping position determination rate as well as lower harvesting success rate.

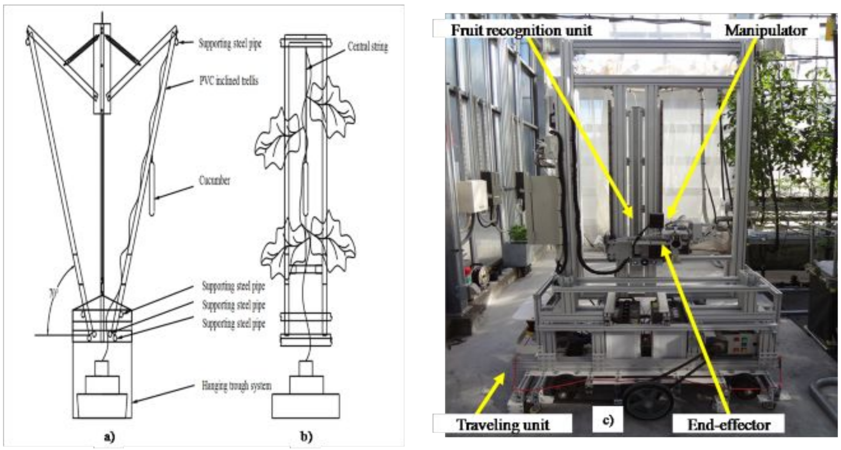
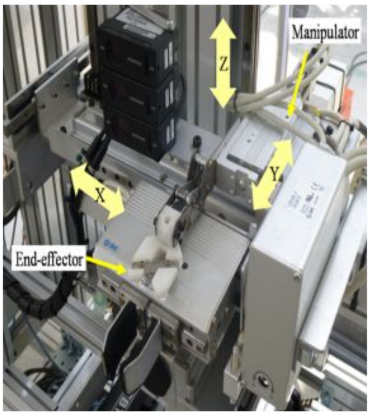
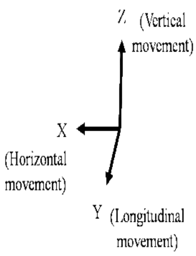


Fig. 11. Inclined trellis training system a) side view b) front view c) modular cucumber harvesting unit.





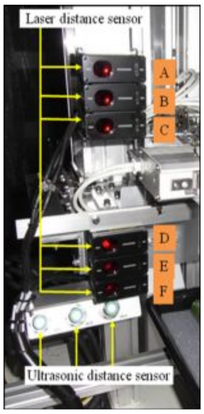


Fig. 12. Manipulator of cucumber harvesting unit. **Fig. 13.** Fruit detection unit sensor arrangement.

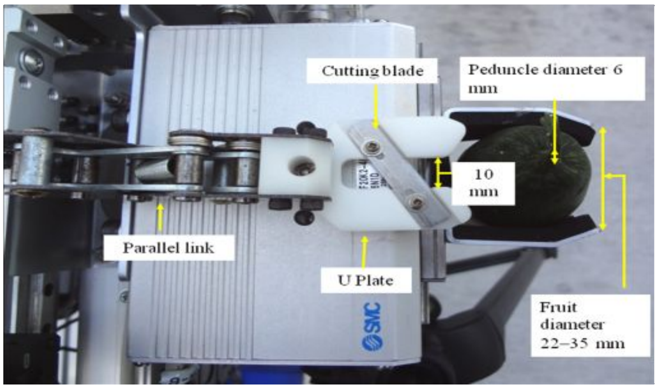


Fig. 14. Close-up of the end-effector

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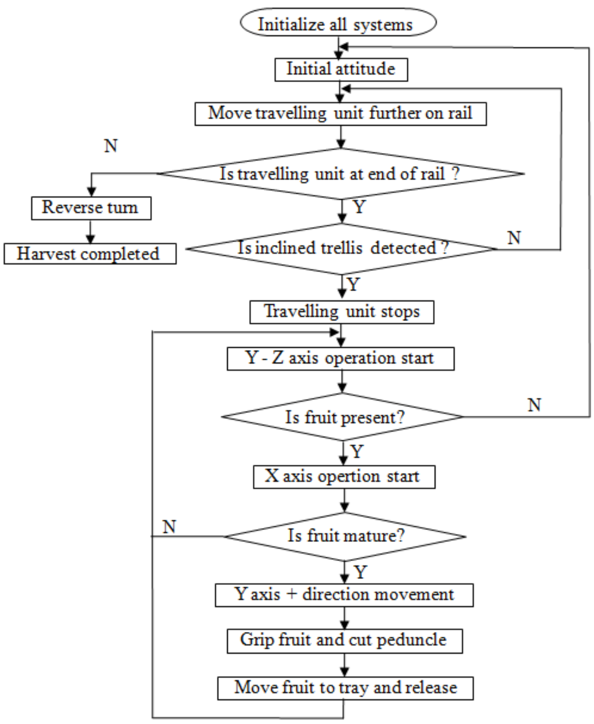

Fig. 15. General flow of harvesting

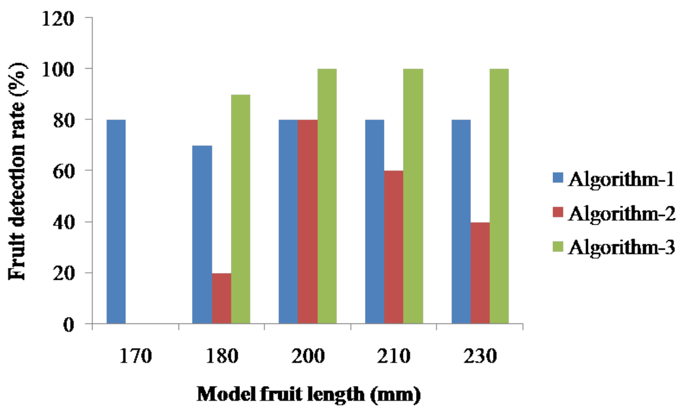

Fig. 16. Fruit detection rate for model fruit lengths using algorithm-1, -2 and -3.

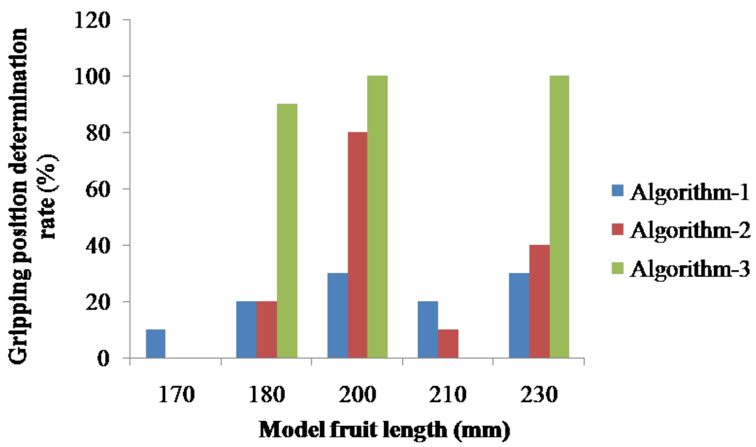

Fig. 17. Gripping position determination rate for model fruit lengths using algorithm-1, -2 and -3.

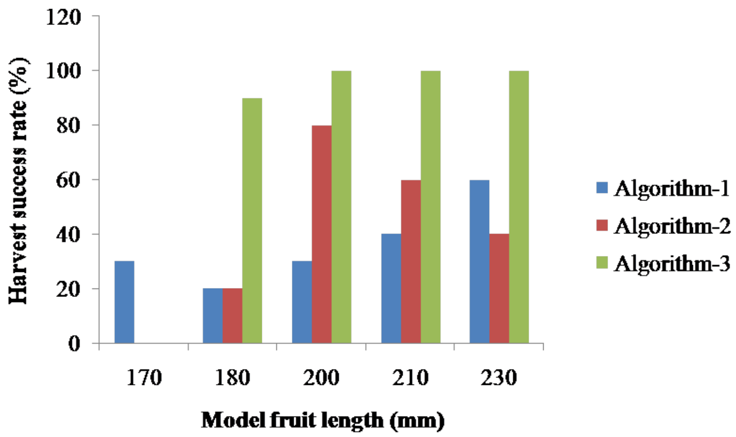

Fig. 18. Harvest success rate for model fruit lengths using algorithm-1, -2 and -3.

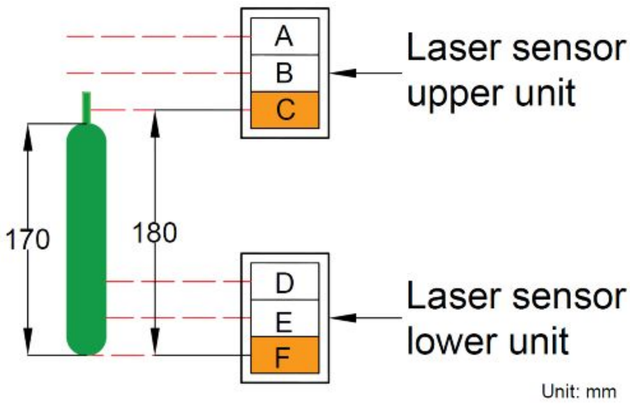

Fig. 19. Undesired detection of cucumbers shorter than 180 mm using algorithm-1

Therefore, the fruit detection algorithm-1 needed to be improved to differentiate between fruit and peduncle. Accordingly, algorithm-2 was developed to decide the gripping position based on the distance measured by sensors A, B, and C and fruit bottom detection by comparing the distance measured by sensors E and F. Undesired detection of cucumbers shorter than 180 mm is avoided by changing the gripping position and fruit bottom deciding conditions. By using this improved algorithm-2, the average fruit detection rate, gripping position detection rate, and harvest success rate were 50, 37.5, and 50%, respectively.

The reason for the low fruit detection efficiency in algorithm-2 may be due to variations in fruit detection signal timing of the cucumber bottom entry in the detection zone of an ultrasonic sensor. During the experiments, early fruit bottom detection by ultrasonic sensor results in positioning laser sensor F below the fruit bottom; on the other hand, late fruit bottom detection results in positioning laser sensor F above the fruit bottom. Therefore, the fruit bottom detection condition by comparing distances measured by sensors E and F cannot be satisfied. Moreover, the condition *d(sensor E) < d(sensor F)* can be satisfied only for straight cucumbers, but in field conditions it is not possible to always have straight cucumbers. Therefore, by considering this factor, the fruit bottom detection condition needed to be improved. Although the average fruit detection rate using algorithm-2 was lower, it successfully determined the appropriate gripping position for almost all detected fruits. For 210 mm cucumbers, the gripping position is determined at sensor B if *d(sensor A) > d(sensor B)*, and is determined at sensor C if *d(sensor B) > d(sensor C)*. For 210 mm, both these conditions are satisfied, which was not considered in the algorithm. Therefore, the 210 mm cucumber gripping position determination rate was comparatively lower. Hence, further improvement in the algorithm for appropriate gripping position determination and fruit bottom detection was necessary.

To further improve the algorithm, fruit recognition algorithm-3 was developed. For this, the condition *d(sensor A) > d(sensor B) > d(sensor C)* was considered; moreover, the difference between distances measured by sensors AB and BC was considered for gripping position determination. Taking into account the practical situation of slight bending of cucumbers and variation in ultrasonic sensor detection time, in this algorithm fruit bottom detection is done by either sensor F or E, which resulted in significant improvement in the fruit detection rate compared with algorithm-1 and -2 as shown in Fig. 16. The average fruit detection rate, gripping position determination rate, and harvest success rate were 97.5, 72.5, and 97.5%, respectively. For 210 mm fruit, the unit failed to grip the fruit, which might be due to the late detection of the fruit bottom by the ultrasonic sensor resulting in positioning sensor B at the peduncle rather than the fruit top. Therefore, the gripping position of almost all fruit was determined at the position of sensor C, resulting in the failure of gripping position determination. In all other cases, the harvestable cucumbers were flawlessly detected and gripped. Also, a harvest success rate higher than the gripping position determination rate was observed with all three algorithms, because the blade cutting device has a movable range up to 35 mm (therefore, slight variation in gripping position does not affect the harvesting success rate). A cucumber harvesting unit has been developed to use information obtained from laser and ultrasonic sensors for successful cucumber harvesting.

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(Note)　The Summary should be about 10% of the entire dissertation and may include illustrations