

Development of Small Automatic Guided Vehicle by Contact Detection to Hydroponics Cultivation System

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Abstract

A small autonomous vehicle is required for automatic spraying, carrying, harvesting etc in greenhouse production areas and small open vegetable fields. This study uses simple structural guidance using horticultural cultivating materials to develop an automatic guided vehicle. The developed vehicle has four wheels: two front steering wheels and two rear driven wheels. The vehicle has a detection unit, a steering unit and a control unit. The detection unit has two extension rollers and a potentiometer, whose function is to detect the distance from the vehicle to the guided material. The control method is used for adjusting the ON/OFF control of the front wheel steer by detecting the distance between the object material and the vehicle. The driving tests were conducted on a plastic film covered soil surface of a greenhouse isle, the concrete surface of a greenhouse central road, and in the open field. The results of the straight driving control displayed absolute maximum errors of 35 mm, 23 mm, and 29 mm on the covered soil path, concrete path, and in the open field, respectively. The test results proved that the straight driving control of the developed system was sufficiently accurate to be used for spraying and carrying operations.

Discipline: Agricultural machinery

Additional key words: greenhouse, horticulture, orchard, tomato, vegetable

Introduction

In Japan, the development of a small sized, autonomous vehicle for spraying, harvesting, carrying, and other work is in demand from vegetable and orchard cultivators due to aging laborers and labor shortage. The vehicle should be able to operate on the narrow paths of a greenhouse, on small areas in open vegetable fields, and on hillside orchards. In Japan, the rail system is generally used in greenhouses greater than 10,000 m² since they do not require any other guidance system other than the rail in Japan. However, in greenhouses smaller than 5,000 m², the rail system is usually not preferred due to the expensive operation of the technique and the significantly high initial cost to set up the rail network. Therefore, a vehicle with a tire system is generally used in Japanese

greenhouses smaller than 5,000 m². Similarly, a small agricultural vehicle with tire guidance is also preferred in small vegetable fields and in small orchards. Therefore, there is a demand for the development of an automatic guided vehicle.

Many researches on the autonomous guidance system of a tractor tire system have been conducted for rice production (Yukumoto et al. 1998). A few tire system autonomous vehicles were developed for horticultural fields. It was proved that an autonomous tractor with a differential GPS cannot be used in a greenhouse (Bell 2000). An autonomous vehicle using RTK-GPS (Barawid 2010) was developed for an orchard. However, RTK-GPS cannot be used inside a greenhouse. To be suitable for a small-scale cultivator, an autonomous vehicle system for a greenhouse and a small open horticultural field should

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be of low cost. Currently, it is considered difficult to drive an autonomous vehicle using a non-touch sensor or image processing sensor on a narrow greenhouse path; therefore, an autonomously driven vehicle using the guidance mechanism of a touch sensor and simple horticultural cultivating material is preferred for the greenhouse and for small open horticultural field related operations.

Autonomous vehicles equipped with an ultrasonic sensor, as a no-rail system, were developed for the greenhouse (Gonzales et al. 2008, Lee et al. 2015). A type of autonomous vehicle was driven straight by a crawler steering with a PID (proportional-integral-derivative) control system on a detected distance from the bed-side end to the mobile robot. The steering was controlled automatically, with an error range of -0.4 m to 0.8 m, by sensing the outward part of the canopy. A different autonomous vehicle utilized an ultrasonic sensor and a detection rail of 60 mm as guidance for the vehicle. The guidance rail technique for the ultrasonic sensor was considered a suitable option; however, the installation of the guidance system was an additional cost. Moreover, weeds around the open field pipe could not be detected by the ultrasonic sensor.

The autonomous greenhouse sprayers using image processing sensors were developed by Dar (2011). The developed sprayers could detect a path between the canopies in the greenhouse by detecting the visually clear border of the canopy and the path. However, when a leaf covers the camera and when the path is partly concealed by the leaf, it is not possible to detect the path. In Japanese greenhouses and horticultural fields, there is a high probability of leaves covering the path, thereby making the border of the canopy and the path unclear. A camera navigation system of an autonomous vehicle was researched in an artificially drawn line-path for a greenhouse (Younse & Burks 2005). The wall detection and fuzzy control system using an ultrasonic sensor was developed and manufactured (Singh et al. 2004, 2005) for the same. However, experiments of the system using the ultrasonic sensor was conducted on the path and comprised of parallel wooden beams supported by steel stands. In the case of an actual path and an actual leaf in the canopy, the ultrasonic sensor and image processing sensor could not detect the no-leaf area and the long-leaf area in the canopy. Therefore, the method requires a higher reliability technique for detecting the path in a greenhouse and in an open field. The autonomous greenhouse sprayers that use machine vision and a rider with steering fuzzy control were developed by Subranmanian et al. (2005). The sprayer could detect an artificial wall made from a plate covered in plastic film only.

Currently, several types of autonomous sprayers for

the narrow path in a greenhouse and a horticultural field are available in the market. One of these autonomous sprayers is a non-controlled sprayer that only follows a high soil ridge using a tire. Another type of autonomous sprayer is a guided autonomous sprayer that uses an electromagnetic line for guidance. The former type of autonomous sprayer requires a hard, high, and wide ridge for guiding the tire. This type of vehicle cannot travel straight without a high ridge on the soil. The latter type of autonomous sprayer requires a significant initial cost for installation of an electromagnetic line and requires considerable maintenance of the long electromagnetic line.

It is considered difficult to guide an autonomous sprayer with a contactless sensor such as image processing, range finder, and ultrasonic sensor on a narrow path when the plants are tall, and the conditions and circumstances are varied. A contactless sensing method is not reliable for the crowded canopy since the actual path is not visually clear between the border of the crop and the path due to the presence of leaf and stems on the path. In case a hydroponics cultivation bed with crop has abundant bush, leaf, and stem protruding out of the bed, then, a contactless sensor would be unable to detect the precise distance between the bed and the vehicle. Therefore, a touch sensor is considered as having a higher reliability with lower cost than a contactless sensor.

The purpose of this study is to use a touch sensor and simple horticultural cultivating materials to develop a model of an automatic guided vehicle for multi-purpose operations such as spraying, harvesting, and carrying in various horticultural fields like a greenhouse and small open horticultural field. We have developed an automatic guided vehicle on the basis of the aforementioned design requirements. The vehicle can be driven straight automatically with the guidance of conventional horticultural materials used by ordinary cultivators. The guidance system is connected to the detection unit of the vehicle.

Materials and methods

1. Vehicle platform

Figure 1 shows a complete schematic drawing of the automatic guided vehicle system. Figure 2 shows the two types of vehicles manufactured. The authors manufactured an autonomous vehicle by adding a detection unit, a steering unit, and a control unit by modifying a commercially available electrically powered vehicle (HC-670, Yazaki Kako Corporation). The vehicle has two steering wheels in the front and two driven wheels in the rear; the driven wheels of the vehicle are operated

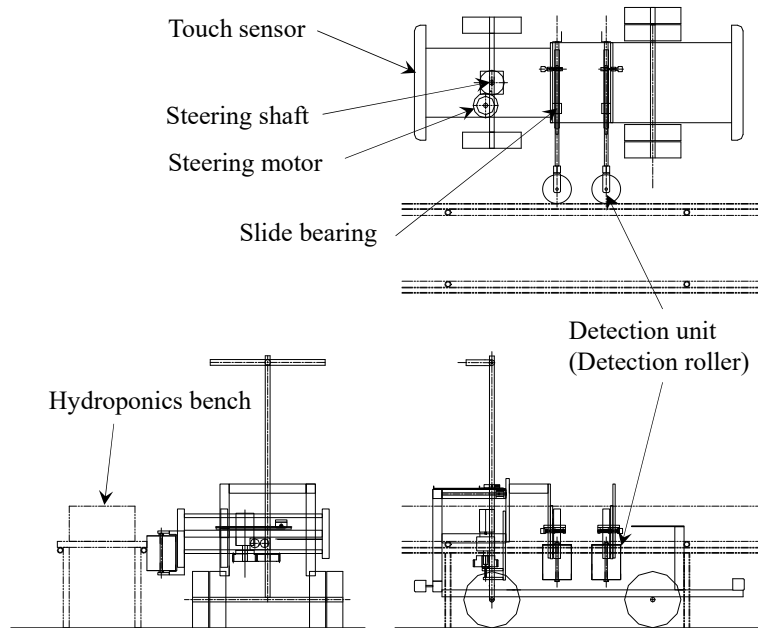


Fig. 1. Schematic drawing of total system of automatic guided vehicle



Fig. 2. Two types of manufactured vehicle

Upper photo: Horizontal detection type for hydroponic cultivation system, Lower photo: detection unit for plastic pipe

by the rotation of a stepper motor. The vehicle dimensions are 1472 cm, 896 cm, and 1191 cm in length, width, and height respectively, and its weight is 118 kg. The operator can select an automatic or manual steering control mode using the control panel. Two 12 V (21 Ah) batteries were wired in series to supply 24 V power to the system. The vehicle is equipped with a programmable controller (KV-3000, Keyence) for the vehicle steering control. The detection unit detects the distance between the vehicle and the guidance material. The two front wheels are steered in the central position of the axis that connects the left and right wheels. The wheel axis is rotated for steering by a stepper motor (QS-M60, Keyence).

2. Two types of guidance materials for autonomous vehicle control

Figure 3 shows the structure of a hydroponic cultivation system for the manufactured automatic guided vehicle. The hydroponics cultivating materials consist of the steel construction pipes and a cultivation bed (Tokai Trading Co., Ltd). The dimensions of the cultivation bed are 286 mm in width, 153 mm in height, and 1200 mm in length for a single unit. Pipe frames (diameter ϕ 26 mm) support the cultivation bed. The cultivation bed, made from rockwool, is used for hydroponic tomato greenhouse production. The authors manufactured the autonomous vehicle with two options in the detecting unit for two types of the guidance techniques. In this study, the authors developed the guidance method by using a plastic pipe. There are 2 reasons: One reason is, the autonomous vehicle should be able to drive in the central

aisle in a greenhouse without a cultivation bed. The other reason is, the author tried to research a utilization of the autonomous vehicle in an open field for a generalization of the autonomous vehicle. The plastic pipe (diameter $\phi 32$ mm, Yazaki Kako Corporation) was used as guidance for the autonomous vehicle.

3. Detection unit

Figure 4 shows a schematic drawing of the detection unit of the manufactured autonomous vehicle. The detection unit is primarily a set of horizontally extended rollers with constant force springs supported at the front and rear positions on the manufactured vehicle. The

constant force spring has a constant pulling force of 5 N. The detection rollers can slide from left to right on the vehicle. Each roller moves and contracts laterally to support the frame of the cultivation bed. The frame support of the rollers is pulled by the constant spring fixed on the vehicle body. The frame support of the rollers is connected to a pinion gear and an encoder to measure the distance between the vehicle and the guide.

Figure 5 shows the dimensions of the detection roller. The diameter of the detection roller is 125 mm and has a width of 115 mm for lateral wall detection. The roller with groove width 45 mm and diameter 77 mm follows and detects the pipe on the ground.

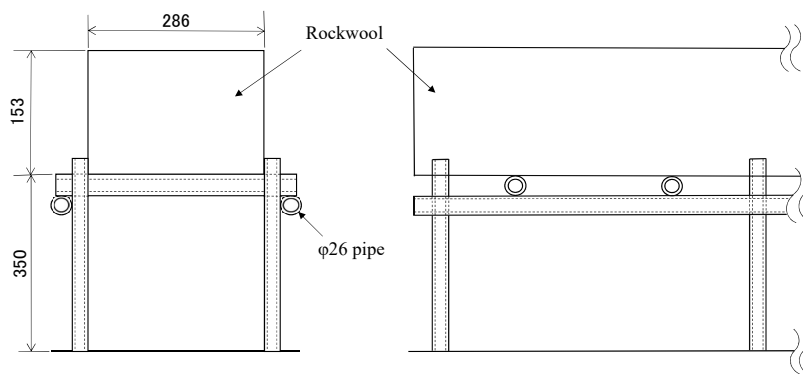


Fig. 3. Structure of hydroponic cultivation system for manufactured automatic guided vehicle

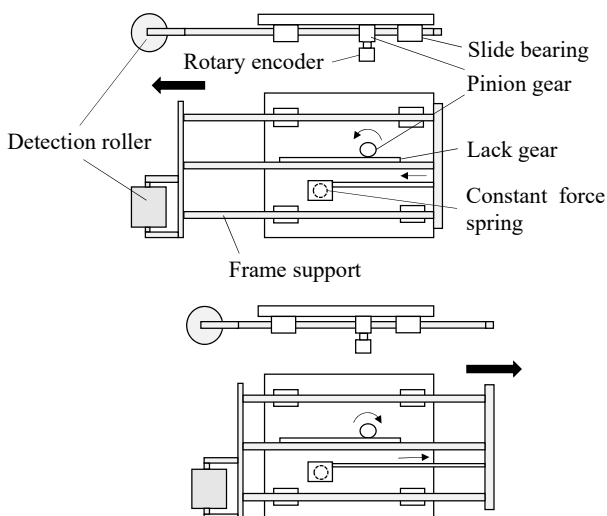


Fig. 4. Schematic drawing of detection unit
 Top: detection roller on left position
 Bottom: detection roller on right position

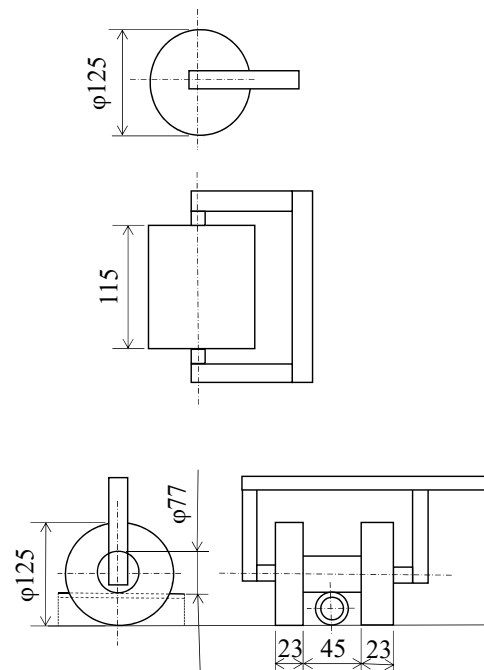


Fig. 5. Dimensions of detection roller
 Top: lateral detection
 Bottom: pipe detection

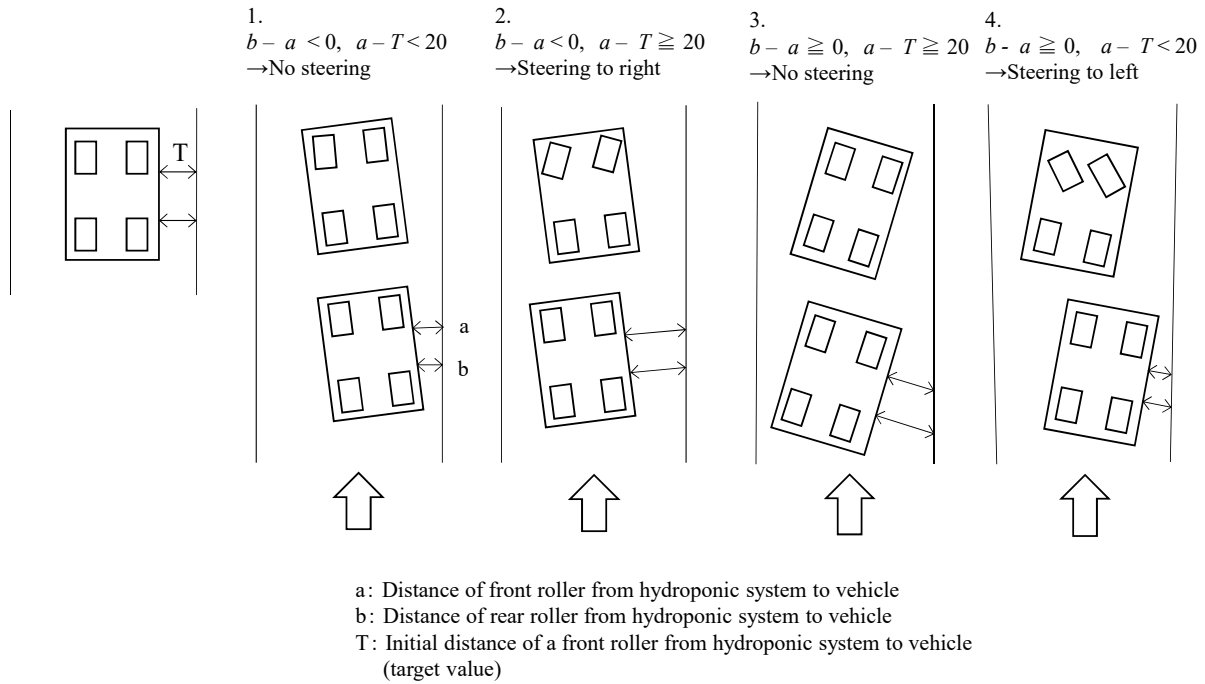


Fig. 6. Control method for vehicle straight driving

Upon detection of the plastic pipe on the ground for an open horticultural field, the rollers in the horizontal direction are directed to function in the vertical direction. The vertical front and rear rollers are positioned on the pipe for straight driving control.

4. Steering unit

The steering shaft is connected to a stepper motor through spar gears. The vehicle is steered automatically by the rotation angle control of the stepper motor, which is controlled by a signal from the programmable controller. The steering shaft is rotated with respect to the deviation of the vehicle from the center line of the cultivation bed. A steering of the tire rotation speed gap is used frequently for an autonomous vehicle in a greenhouse (Singh et al. 2005). A speed gap of the tire rotation causes the plastic film to be pulled, thereby damaging the Japanese greenhouse. Almost all Japanese greenhouses have plastic films on the ground. The steering method of turning of the tire direction does not cause film pulling or significant damage. The vehicle with a steering tire can be used to steer heavier loads than the vehicle with the speed gap technique in both the tires.

5. Vehicle control

Figure 6 shows the control method for a straight driving vehicle. Figure 7 shows the flowchart for the straight driving control. A simple “ON/OFF” control

method was adopted to investigate the fundamental performance of the developed detection system. The steering is categorized into four driving phases by a combination of the detected position of the front and rear tires from the hydroponics cultivation system. Essentially, the vehicle was controlled to drive straight within ± 20 mm from the initial position of the vehicle. On measuring

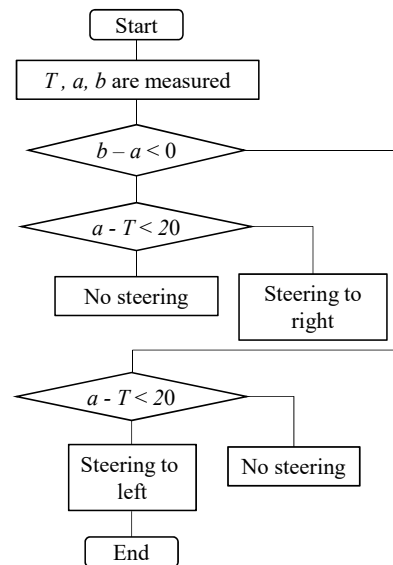


Fig. 7. Flowchart for straight driving control

the displacement of the front and rear rollers, the direction of the vehicle and the distance from the vehicle to the hydroponics cultivating material can be calculated.

First, T , a , and b are measured and calculated by the rotary encoders, where T is the initial distance of a , which is the distance between the touching point of the front roller and wall of the hydroponic material to the base point of the front roller, and b is the distance between the touching point of the rear roller and wall of the hydroponic material to the base point of the rear roller.

Thereafter, $b - a$ and $a - T$ are calculated, and the front wheel is steered by the calculated values at each sampling time. The resultant steer is defined by the following conditions: 1) If $b - a$ is less than 0 mm and $a - T$ is less than 20 mm, then, the vehicle is steered right. 2) If $b - a$ is less than 0 mm and $T - a$ is more than or equal to 20 mm, then, the vehicle is not steered. 3) If $b - a$ is more than or equal to 0 mm and $a - T$ is less than 0 mm, then the vehicle is steered left. 4) If $b - a$ is more than or equal to 0 mm and $a - T$ is more than or equal to 0 mm, then, the vehicle is not controlled.

When vertical rollers are utilized, a plastic pipe is used as a guide on the ground and the vehicle is controlled by an ON/OFF control method, same as by detecting the hydroponic cultivation bed using lateral rollers as mentioned in Section 4. In case either of the detection rollers are positioned at 85% of the maximum or minimum length of the detection bars, the steering will be controlled such that the vehicle moves in the opposite direction to prevent the vehicle from colliding with the hydroponic cultivation bed.

6. Experimental procedure

(1) Profile of experimental path

Experimental runs were conducted to investigate the performance of the developed control system while the manufactured autonomous vehicle was observed in control on three different ground surfaces: the concrete surface in the greenhouse central path, the hard soil surface between the hydroponics cultivation beds in the greenhouse, and the hard soil in an open field path covered with very short cut grass of the horticultural field. The height of the cut grass was less than approximately 50 mm. The concrete surface was smooth and flat.

Figure 8 shows the profiles of the experimental path's surfaces. the hard soil in the greenhouse and the hard soil in an open field. The ground heights were measured at the central point and both sides in the path cross-sectional direction, and at every 1 m distance in the longitudinal direction of the 10 m test run by a laser surveying instrument. The central position of the starting point of the test path course was set at a ground height of 0 cm.

The surface heights of the hard soil in the greenhouse and in the open field were -3 to 21 cm and -19 to 6 cm, respectively.

(2) Combination of guiding material and experimental ground

In the hard soil surface of the greenhouse path between the cultivation beds, the frame of the cultivation bed was adapted as the guidance material for the test runs. In the concrete surface of the central path in the greenhouse and in the open field, the plastic pipe was adapted as the guidance mechanism for the autonomous control on the ground.

(3) Test procedure

Test runs were conducted for the evaluation of the straight driving control of the automatic guided run. In addition to the three series of test runs at each ground type, the authors conducted a test run by manual steering on the same course of the greenhouse path as that of the autonomous controlled run. The length of the test run was 10 m. The speed of the vehicle was set at 0.35 m/s.

7. Data acquisition

The steering angle and the positions of the front and rear rollers were measured and were saved in an electronic file for analysis by using a programmable controller with a sampling speed of 0.05 s. The lateral errors (Yukumoto et al. 1998) in the positions of the rollers were evaluated. The root mean square value (Singh et al. 2005) of error was also calculated from the measured data for the performance evaluation of the guidance system. Range of lateral error and average errors were also calculated and

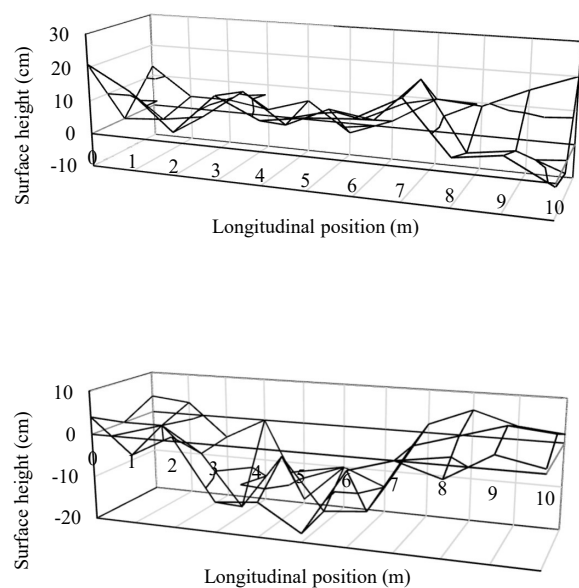


Fig. 8. Profiles of experimental path's surface
 Top: hard soil in greenhouse
 Bottom: hard soil in open field

were evaluated based on the three repetitions.

Results and discussion

1. Experimental run on concrete path in greenhouse

Figure 9 shows the result of the test run by using pipe detection roller on the concrete path of the greenhouse. The vehicle ran smoothly with a significantly low error for both the rollers, approximately ± 20 mm at the beginning till approximately 17 s. In this study, the adaptation of the ON/OFF control for the vehicle control resulted in an overshoot, and the vehicle demonstrated hunching after the overshoot. In the central path of the greenhouse, because the floor was flat with no rough surface, there was no external disturbance in test run while the vehicle was in straight driving control. The range of the error was considered as small for the practical use of spraying and carrying.

The errors of ± 20 -40 mm were similar to the results of the earlier research on the subject (Singh et al. 2005). The steering angle varied periodically within $\pm 1.6^\circ$ of the steering angle against hunching; this variation was insignificant in terms of the steering.

Since the primary purpose of this research was the development of a fundamental autonomous system mechanism guided on a horticulture construction material,

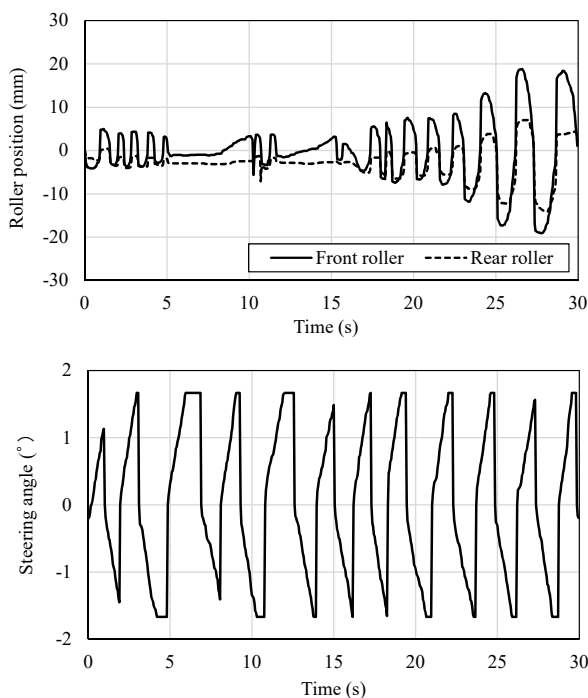


Fig. 9. Result of test run using pipe detection roller on concrete path of greenhouse
Top: position of detection roller
Bottom: steering angle

the above-stated developed system was a modified simple steering controlling system. The error presented by the developed method was larger than that of progressed control. It is considered possible to decrease the error further by adopting a PID control to the test model.

2. Experimental run on hard soil path in greenhouse

Figure 10 shows the result of the test run using lateral detection roller on the hard soil path in the greenhouse. The hunching, with an approximate error of ± 30 mm, occurred soon after starting the test run and continued until the end of the test run. The range of hunching on the hard soil path was larger than that of the concrete path in the greenhouse. It can be concluded that the disturbance of the ground height in the hard soil path was larger than that of the concrete path in the greenhouse. The steering angle was periodically varied at $\pm 1.6^\circ$. However, the range of error was considered within the permissible range for carrying harvested fruit and cultivation material on the furrow path in the greenhouse.

While the previous developed vehicles using the image processing sensor could detect and drive straight autonomously in a visible condition of the border of canopy and path (Dar et al. 2011) or in a visible tape line on flat floor (Younse & Burks 2005), the author's developed vehicle could drive straight autonomously in

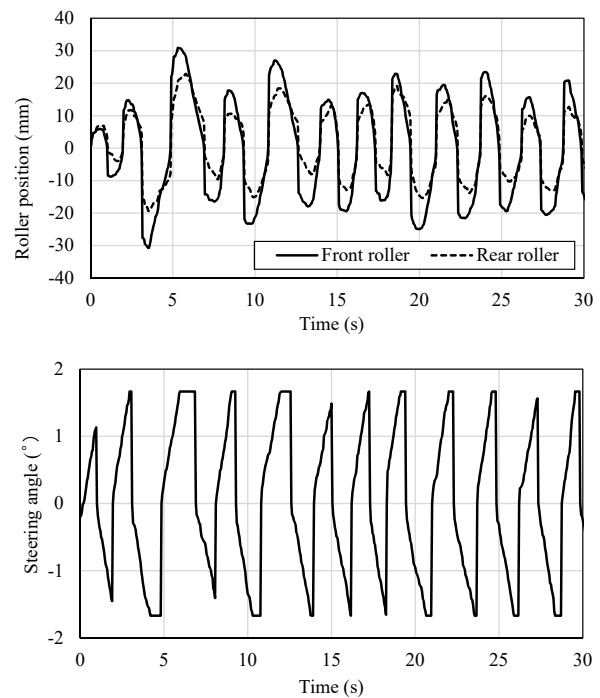


Fig. 10. Result of test run using lateral detection roller on hard soil path in greenhouse
Top: position of detection roller
Bottom: steering angle

a non-visible condition of the border of canopy and path or no guidance line on floor. This is an advantage of the author's developed vehicle using the detection roller.

A distance of more than 20 cm should be maintained for the ultrasonic sensor to detect a canopy, and the shape of the canopy should be like a wall based on the previously developed vehicle (Gonzalez et al. 2009). In the case of fruit vegetables (e.g., tomato), leaves extend to a path closely since a vehicle touched the leaves. Therefore, the previously developed vehicle using ultrasonic sensor was not successful since autonomous straight driving in actual plant with leaves extending to the path and the spaces between leaves are less than 20 cm. The developed vehicle is expected to be able to drive straight autonomously between actual plants with leaves extended to the path and with spaces larger than 20 cm between leaves grown from both sides of cultivation bed to the developed vehicle. This is also an advantage of the developed vehicle using the detection roller over the one that uses the ultrasonic sensor.

When the rail system is compared to the developed system, an initial cost for the rail can be decreased. Workers in the greenhouse path can walk on the path

between the benches comfortably because there is no rail on the ground. These are also advantages of the developed vehicle.

3. Experimental run on hard soil path in open field

Figure 11 shows the result of the test runs using vertical detection roller on the hard soil path in the open field. In the initial three seconds of the test run, there was no hunching. Four seconds after starting the run, a small hunching was produced, which gradually increased more than ± 25 cm; moreover, periodically, a hunching of less than ± 20 cm was also produced. The steering angle was periodically varied $\pm 1.6^\circ$. Furthermore, the error was within ± 25 cm in the open field test. The aforementioned error is considered insignificant for automatic guided driving, spraying, and carrying operations. The error was similar to that of the hard soil path of the greenhouse. Because it is confirmed that the developed vehicle can be used for open field, it can be adapted to open vegetable field and orchard field too. The usage of the developed vehicle in more different types of fields will result in lower manufacturing cost because of the mass production of the vehicle.

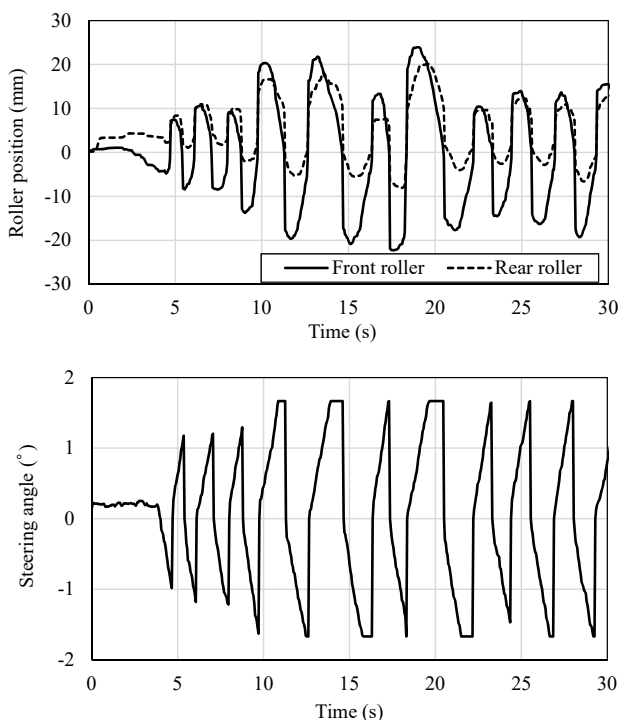


Fig. 11. Result of test run using pipe detection roller on hard soil path in open field
 Top: position of detection roller
 Bottom: steering angle

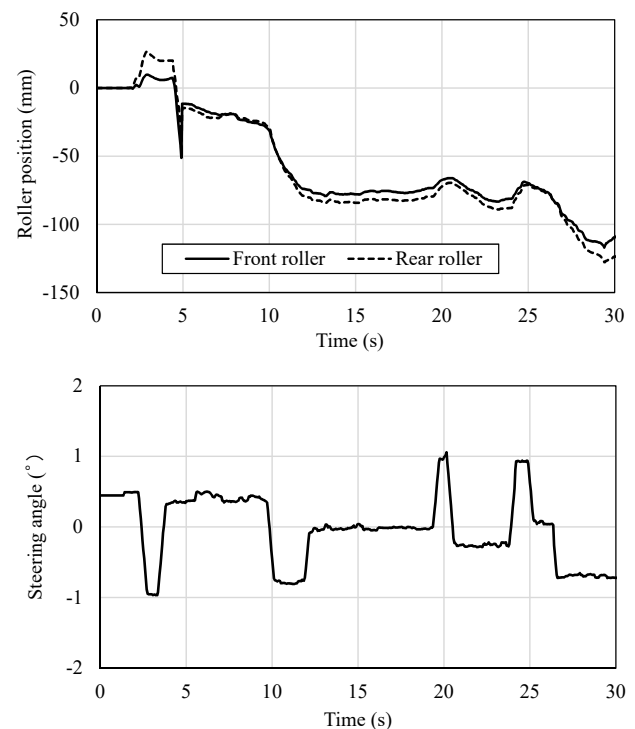


Fig. 12. Result of test run of manual steering
 Top: position of detection roller
 Bottom: steering angle

4. Experimental run by manual steering

Figure 12 shows the results of manual steering. It can be observed that contrary to the automatic guided steering, there is no hunching in the manually guided steering. The error of each roller ranges from -120 to $+30$. A noticeable trend can be observed that the error continues to decrease; however, it cannot attain a value close to zero. This denotes that the operator cannot steer the vehicle to maintain the distance from the side of the vehicle to the horticultural structure. The operator was able to steer the vehicle to drive within the sides of the horticultural structure and was able to prevent the vehicle from colliding with the wall; however, the operator was unable to maintain the distance from the horticultural structure to the side of the vehicle.

5. Comparison of Errors

Table 1 shows an error comparison in the experimental runs. The ranges of the lateral errors in automatic guided driving are significantly larger than those of manual steering. In addition, the table indicates that manual steering displays a trend that the operator tends to steer the vehicle to one side and is unable to precisely maintain the initial position with respect to the hydroponics structures. The average error of the automatic guided driving on the concrete path in the greenhouse was the lowest in comparison to the three automatic guided test sets. The average, the root mean square, and the range of the lateral errors of the test run in the furrow path in the greenhouse were lower than those in the open vegetable field. This can be because the cross-direction profile of the surface of the open vegetable field is smoother than that of the furrow path in the greenhouse. Since the path is approximately 1150 mm wide and the width of the vehicle without the detection unit is 654 mm, there is sufficient space for the automatic guided vehicle to drive straight with an approximate error of ± 30 mm in the test runs of this study. The error of manual steering also ranged from -64 to 9 mm. Therefore, there were no space constraints for the functioning of the automatic guided straight driving.

Conclusions

We have successfully developed an automatic steering vehicle that can be guided by the hydroponics cultivating structure and the agricultural tubes in a greenhouse and in a horticultural open field. The average errors were -2.0 mm using the guiding mechanism of the hydroponics cultivating structure at a greenhouse on a furrow path, -0.2 mm using a guiding mechanism of a tube on a concrete path, and 1.8 mm using a guiding mechanism of a tube in the open field. These values of error were considered acceptable for practical use in a horticultural field. We aim to further study the development of improved control for turning at the end of the path for automatic spraying in the future. The developed automatic guided system can be adapted successfully for greenhouse spraying, including newly static electro-spraying system (Yoshinaga et al. 2016). The system can also be effectively adapted for carrying harvested fruits in the greenhouse.

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Table 1. Error comparison in experimental runs

Control	Test path	Range of lateral error (mm)	Average error (mm)	RMSE (mm)
Automatic control	Hard soil path in greenhouse	$-35.3 \sim 30.5$	-2.0	0.7
	Concrete path in greenhouse	$-22.5 \sim 20.3$	-0.2	0.4
	Hard soil path in open vegetable field	$-16.9 \sim 28.8$	1.8	0.4
Manual	Hard soil path in greenhouse	$-64.2 \sim 8.8$	-29.6	0.8

RMSE: Root mean square error

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