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Autonomous Guidance Using Ultrasonic Sensors for a Small Orchard Sprayer

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Abstract: Chemical application is very hazardous in confined spaces under the canopy ceiling in Korean vineyard. For a small orchard sprayer adaptable to such a working condition, a low-cost autonomous steering control system was developed using two ultrasonic sensors, two electrically-operated cylinders and 80196kc microprocessor. A distance ranging system timed the round-trip for each ultrasonic wave to travel against parallel targets, placed every 1.5m spacing along both sides of a desired path. A steering control algorithm of the autonomous operation began with ranging left and right targets and the heading was decided using difference between the distances. Electrically-operated cylinders actuated steering clutches to guide the sprayer.

Evaluation tests showed that the orchard sprayer could travel within RMS value of 5 cm along the desired path. Ground speed did not affect the performance of the autonomous guidance system at the speed ranges of 0.29~0.52m/sec.

Keywords: Autonomous travel, Ultrasonic ranging, Orchard sprayer, Steering control.

Introduction

Chemical application is an essential process for agricultural production; however, it is one of the most avoidant agricultural operations. In Korean vineyards, grapevines are grown over tension-wired structures, allowing more sunlight but resulting in confined spaces under the canopy ceiling. Agro-chemicals are more hazardous to orchard sprayer operators when they are working in such a confined environment, closely exposed to the chemicals. Protective gear or cab has been a mean to protect the operators from the contact with agro-chemicals. However, spraying, nonetheless, is a hazardous job. An autonomous guidance technology would be the ultimate safety answer by removing the operators from spray vehicles (Cho and Ki, 1999).

Many research works on the autonomous guidance have been done in agricultural engineering as well as robotics (Kehtarnavaz and Griswold, 1991). Contrary to the autonomous operations of many industrial guided vehicles or robots, applying the technology to agricultural machinery was realized to be more difficult due to the irregular and unpredictable environment conditions. Thus, agricultural machines should be equipped with the local sensing capabilities for finding their relative positions (Hague and Tillett, 1996).

Jang et al. (1995) developed an inductive cable guidance system with a remote controller for guiding an orchard sprayer along a buried cable. Five low impedance coils were used to detect the induction voltage differential to determine the path of sprayer. However, the burying cable could be an obstacle to the feasibility of this system due to its inconvenience and limitation.

In some studies, machine vision systems and acoustic sensors were used to determine the travel path by recognizing lead-marks along the row (Cho et al., 1996; Ki et al., 1996; Jang et al., 1998; Cho and Ki, 1999). A camera for the machine vision system was necessary to be located at a certain height in front of the vehicles for receiving clear images of the path, so that it may hit low profile canopy. Various algorithms were adopted in the developments to determine their desired paths; however, these methods experienced some difficulties for turning at the end of row. A DGPS was also used to inform the position of a guidance system (Cho et al., 1997; Lee et al., 1998), increasing the reliability during end-turn. Those

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developments were relatively successful; however, the machine vision or GPS were expensive and might be useless in the area where GPS signal could not reach or penetrate.

Therefore, a study developing a low cost guidance system was necessitated. The autonomous travel system should be also adaptable to a low profile orchard sprayer, small-scaled enough to be maneuvering in such narrow and low ceiling vineyards. Such an orchard sprayer would be feasible by measuring distances to existing targets with two ultrasonic sensors and determining the desired steering angle by a microprocessor. The targets could be columns or poles of tension structures. The operating principle of this autonomous travel system was to move the sprayer between those targets, placed on a certain interval along both sides of desired path of an orchard sprayer. This research was intended to investigate the feasibility of using ultrasonic sensors for the autonomous guidance system. The specific objectives of this research were to develop: a distance measuring system with ultrasonic sensors and steering control algorithm using a microprocessor, steering actuators of the autonomous orchard sprayer with interface circuits, and to evaluate system performance in the field.

Materials and Methods

1. Experimental Sprayer

The sprayer used in the experiment was a small-scaled vineyard sprayer (SS180-CT, Hanseo Co., Korea), 1985 × 720 × 1030 mm (length × width × height), with crawler treads. Steering of the unmodified sprayer can be done by pulling left and right levers connected with cables to crawler clutches, working at two stages. Driving power to a crawler would be disengaged at the first stage and braked at the second stage, so that the clutches could be used for a quick skid-turn at a minimum radius.

The experimental guidance system consisted of two ultrasonic ranging modules, two electrically operated power cylinders, a hydrostatic transmission (HST) and 80196kc microprocessor for steering control, and was applied into the commercial orchard sprayer. For the autonomous operation of steering, the clutch activating cables were replaced by the two power cylinders to pull or release clutches steering the sprayer to a desired path. In addition, the original mechanical transmission was fixed to the 3rd shift and the HST was plugged into the power train, so that the sprayer could go and stop autonomously by controlling the angle of swash plate of the HST. Fig. 1 shows the modified orchard sprayer with the guidance control system.

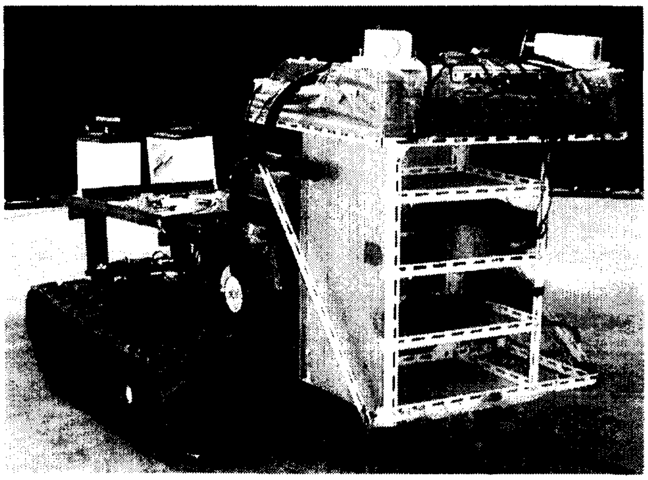


Fig. 1 Experimental orchard sprayer with the guidance system.

2. Guidance Control System

(1) Distance Ranging System

A distance ranging system used in this study was consisted of a ultrasonic sensor (Electrostatic Transducer and 6500 Ranging Module, Polaroid, U.S.A.) and an interface circuit, driven by the 80196kc microprocessor. Initiated by High Speed Output (HSO) signal from the microprocessor, the ultrasonic sensor transmitted the ultrasonic wave into atmosphere and received an echo signal reflected from the target. A pulse activated by the echo interrupted to stop the timer of microprocessor triggered by the init HSO signal. The time difference between the init and the echo signals represented the elapsed time during which ultrasonic wave travels to and from the target. The distance was calculated by multiplying the half time of the round-trip by the propagation speed of ultrasonic wave in the air. The operating time of one ultrasonic sensor was set to 30 ms so that the maximum distance to be measured was approximately 5 m. The minimum distance of 0.4m was determined by the internal blanking time of ultrasonic sensor not to detect transducer ring after transmit and give a false distance measurement.

The two ultrasonic sensors were mounted at the front end of the sprayer 45 cm apart and each sensor aimed at 30 right and left from the direction of travel, so that distances to right and left targets located ahead of experimental orchard sprayer were sequentially obtained. While two HSO ports were used to initiate the two ultrasonic sensors one by one, two echo signals from the ranging modules were OR-gated to be input to the external interrupt pin of the micro-processor (fig. 2). Each distance data was read every other 30 ms, so that the guidance control system could update the distances to right and left targets every 60 ms.

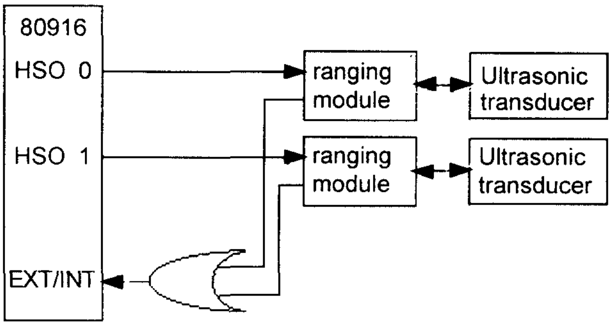


Fig. 2 Interfacing schematic of two ultrasonic sensors with the microprocessor.

For the evaluation of performance, the distance ranging system was calibrated at the ranges of 0.5 to 5.0 m. The numbers of raw digital counts from the timer were regressed with the distances to a flat surface target, resulting as in eq.(1) with 1.0 of R^2.

$$Y = 0.4965\ X + 1.66589 \quad \cdots\cdots\cdots\cdots \quad (1)$$

where X : digital counts in decimal and
Y : range in cm.

(2) Power Cylinders for Steering Clutches

Two power cylinders with the maximum stroke of 50 mm were used for actuating steering clutches. The control circuit of the cylinder was designed as shown in fig. 3. The low level output from the I/O in the microprocessor activated a relay to maintain the retracted position. The power cylinder had an internal protection circuit to stop excessive current flow in case that the piston reached at both ends of its stroke. When the output signal goes high, the piston moves forward to disengage the steering clutch at the speed of 50 mm/s. At the end of stroke, the protection circuit is activated by a limit switch of which location can be adjusted by the operating range of steering clutch lever.

Since it takes at least 350 ms to disengage the clutch completely, the high level signal should be maintained for 6 cycles of reading distances to target. The same amount of time was required for re-engaging.

(3) Control of Hydraulic Transmission(HST)

A step motor was used to control of swash plate angle of HST as shown in fig. 4, where the proximity sensor was for locating the swash plate at zero angle (stop state of running HST). From this position the step motor controlled the angular position of swash plate, so that the desired ground speeds were consistently achieved.

3. Steering Control Algorithm

Steering control of the autonomous operation began with ranging left and right targets along a desired path. Although the targets on both sides were located apart, the distance ranging system kept acquiring distance data to one target for a moment traveling along the path. It is because the ultrasonic sensor

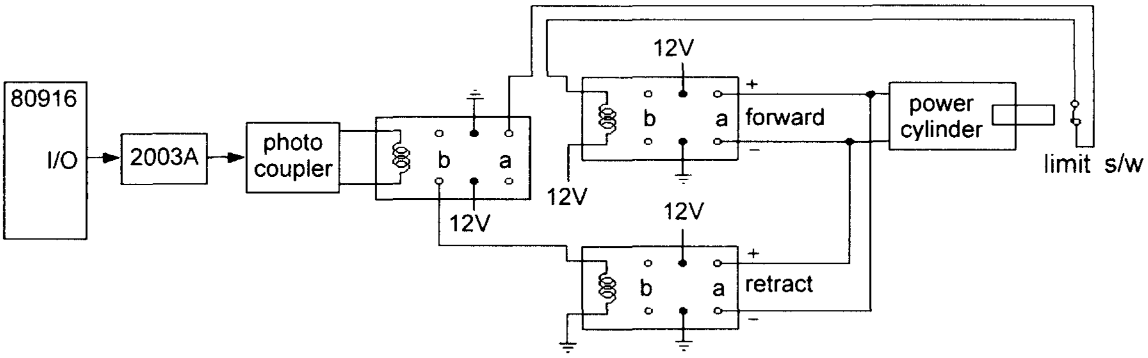


Fig. 3 Circuit diagram for the control of the power cylinder.

detects only nearest target within its beamwidth, a cone-shaped propagating pattern with the angle of ± 9°.

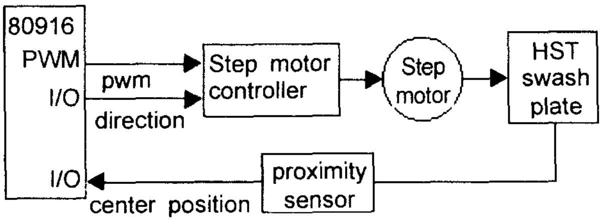


Fig. 4 Schematic of the hydrostatic transmission (HST) control with a step motor and proximity sensor.

As shown in fig. 5, the distance to target #2 would be maximal when the one end of beamwidth of ultrasonic sensor passed by target #1. As the orchard sprayer moved forward, the distance to target #2 decreased until the other end of beamwidth passed by that target, and then the ultrasonic sensor started to detect the next target. Repeating this procedure, the autonomous guidance system continuously acquired its position data relative to targets on both sides when the proper interval of targets was maintained. Proper arrangement of targets could be determined by the aiming angle of ultrasonic sensor, its beamwidth and the width of desired path of orchard sprayer. Under given environment as shown in fig. 5, the allowable maximum spacing between targets, D_t, could be calculated as follows:

$$D_t = W_c\{\tan(90° - \alpha + 9°) - \tan(90° - \alpha - 9°)\} \;\cdots\cdots\cdots \quad (2)$$

where α is the aiming angle (30°) of the ultrasonic transducer having the beamwidth of ±9°, and W_c is the side clearance between the sensor and imaginary target line, determined by the target row spacing.

On the other hand, the maximum and the minimum distances that could be read by the distance ranging system were as follows:

$$L_{max} = W_c / \cos(90° - \alpha + 9°) \;\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (3)$$

$$L_{min} = W_c / \cos(90° - \alpha - 9°). \;\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (4)$$

Also L_{max} and L_{min} should be limited within the range the distance ranging system could detect.

The steering action of sprayer was decided using the difference between distances to left and right targets along the desired path as defined in eq. (5).

$$E = D_R - D_L \;\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (5)$$

where D_R and D_L are the distances to targets on the right- and left-side of path, respectively. If the orchard sprayer moved along the center line, then the value of E would be zero. If $E > 0$, the orchard sprayer should be steered to right side. Otherwise, it should move to left. That is, the sign of E determined the direction of steering and the absolute value of E indicated the amount of necessary steering angle, in turn determining the duration of clutch disengagement. Infinite value or false distance data occasionally showed up due to the system noise and the last six finite data were averaged for calculating E value to increase the reliability of distance data.

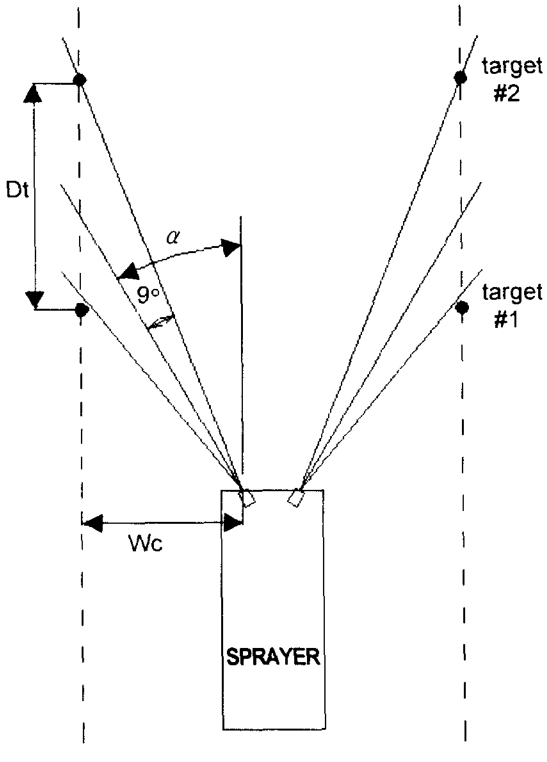


Fig. 5 Arrangement of targets and ultrasonic sensors. (Dt: allowable maximum spacing of targets, Wc: clearance between the sensor and imaginary target line, α: aiming angle at 30° left from the direction of travel)

Four levels of the proper duration time as related to the distance difference, E value for the steering control were tabulated in table 1. Total duration time assigned for the clutch operation was the multiples of 60 ms because the ultrasonic distance ranging system updated the distance every 60 ms, as mentioned above. A large duration time for the large value of |E| completely disengaged the clutch for 350 ms and maintained the state of disengagement for the remaining time, which resulted in the sprayer being steered a lot. There was no steering operation for |E| < 1m.

Table 1 Duration time levels of clutch operation as related to the difference of right and left distances to targets

Difference |E|	Duration time for clutch operation (ms)	
	Disengagement	Re-engagement
< 1m	0	0
1~2m	360	360
2~3m	1080	360
> 3m	1700	360

4. System Evaluation

The performance of the developed autonomous system was evaluated at a straight path with the row spacing of 3m on a flat surface, where the steel pipe targets were placed every 1.5m on both sides. Tests were conducted at the three levels of initial positions, heading angles, and ground speeds with two replications along the total travel distance of 10m. The initial position of the sprayer was offset by 0.0, 0.25 and 0.5 m from the middle of the desired path. Three different heading angles of 0°, +10° and +20° to the left and three different ground speeds of 0.29, 0.41, 0.52 m/s were selected as the levels of test variables. The trajectory of rear end of the sprayer was recorded every 10cm by manually measuring the deviations from the center of path. The deviation was represented with the root mean square (RMS) value as in eq.(6) (Cho and Ki, 1999).

$$RMS = \sqrt{\frac{\sum (deviation)^2}{(No.of\ data\ collected)}} \quad \cdots\cdots\cdots\cdots\cdots (6)$$

Results and Discussion

Fig. 6 shows typical ranging raw data to parallel target rows along the straight path. The measured distance to a target decreased as the sprayer moved forward until the sensor passed by the target and then detected the next target. Repeating this procedure, the ranging system was able to continuously read the distances to the target rows with a few false data points. There was no target between 8 to 10 m at the right-hand side. The distance ranging system was programmed to output the distance data as 5 m when no echo signal came out from the ranging module. Most of infinite distance data were fell on the line of 5m, but false data was more frequently observed than on the interval where a target existed.

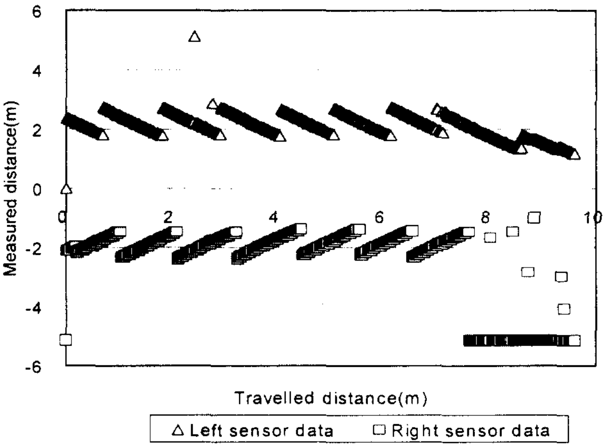
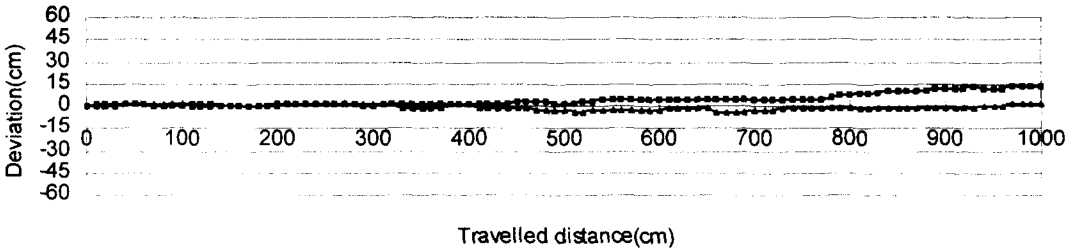


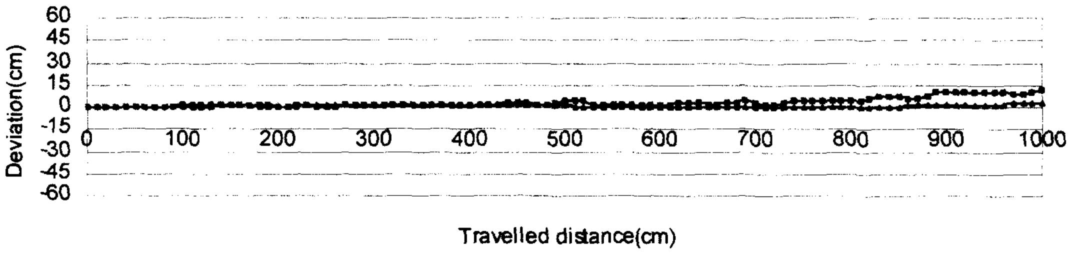
Fig. 6 Typical ultrasonic ranging data along the parallel target rows.

The test results for the three different ground speeds in the straight path without any initial offset or heading angle were presented in Fig. 7. The effect of ground speed on the RMS was not significant (table 2); however, the RMS was somewhat different between the replications. For the first replication, the deviation seemed to be increased as the orchard sprayer moved forward. This inconsistency was caused by the irregularity of initial conditions when the orchard sprayer started each trial. That was why the orchard sprayer would not start to be steered until the distance difference became greater than 1m. The different ground speeds did not affect the system performance at the speed ranges of 0.29~0.52m/sec.

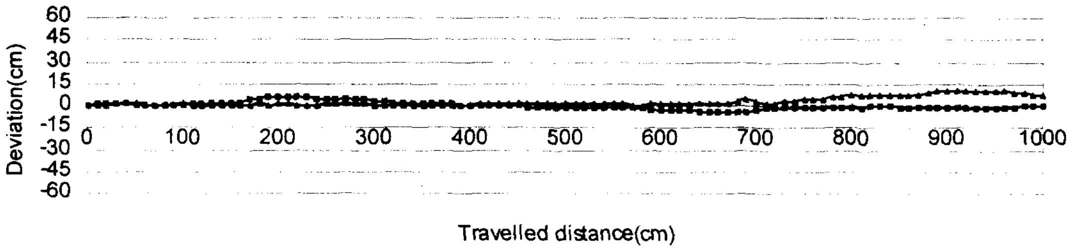
Fig. 8 shows the travel paths began from the locations with lateral offsets of 0.0, 0.25 and 0.5 m, respectively. The lateral offset did not affect the system performance. It took 1.5~3m for the speed sprayer to be steered within the acceptable range from the desired path. When the more lateral offset was applied, the longer distance was required. All trials



(a) at the ground speed of 0.29 m/s (Low)



(b) at the ground speed of 0.41 m/s (Mid)



(c) at the ground speed of 0.52 m/s (High)

Fig. 7 Guidance system performance at the three different ground speeds of (a) 0.29, (b) 0.41 and (c) 0.52 m/s without any initial offset or heading angle.

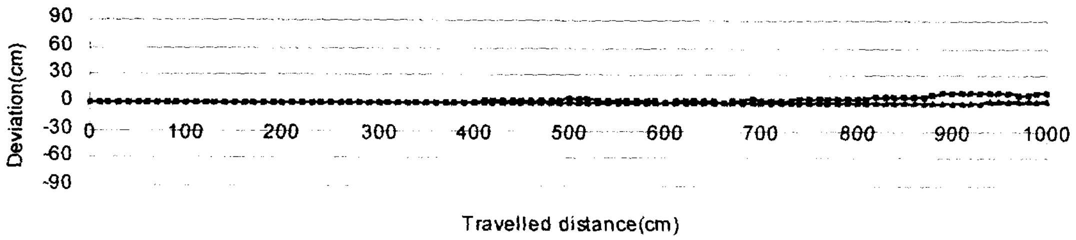
Table 2 RMS values for the effect of ground speed on the guidance system performance

Replication	RMS (cm)		
	At the ground speed (m/sec)		
	0.29	0.41	0.52
1	5.66	4.33	4.31
2	1.86	0.93	2.48

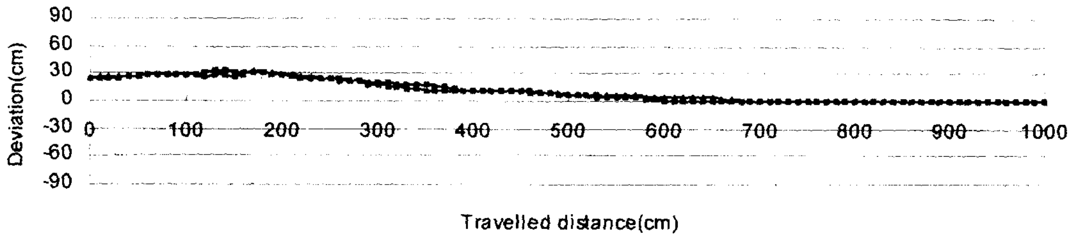
with various offsets showed that the final destinations were sincerely close to the center of path. However, as discussed above, a trial without any offset seemed to be off from the center as the sprayer moved forward. A small initial deviation within the control criterion (E<1m) could cause the diverging performance until the error becomes greater than the assigned criterion. This undesired performance can be adjusted by finding a proper range of the control criterion.

Fig. 9 shows the travel paths with initial heading angles of 0°, +10° and +20° to the left, respectively. An Initial heading angle without lateral offset caused the immediate skid-turn to the right, resulting in the left deviation measured at the rear end of the orchard sprayer (fig. 9-b). In case of excessive heading angle as in fig. 9-c, the sprayer may overshoot the intended center line before steered back to the desired path. Both cases needed 5~7m to steer the orchard sprayer within the acceptable range from the desired path. All trials with various heading angles showed sincere control performance to the destination. However, the heading angle could affect the stability of sprayer control system.

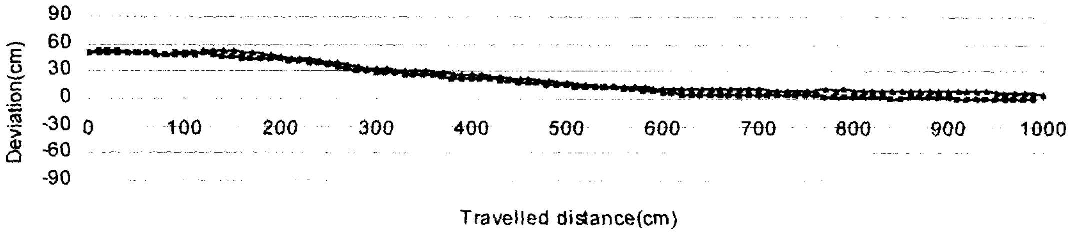
Further research should be conducted to turn the



(a) at the initial offset of 0.0 m



(b) at the initial offset of 0.25 m



(c) at the initial offset of 0.50 m

Fig. 8 Guidance system performance at the different lateral offsets of (a) 0.0, (b) 0.25 and (c) 0.50 m with the initial heading of 0° and a ground speed of 0.41 m/s (Mid).

orchard sprayer at the end of tree row. It is recommended that an additional control algorithm for turning mode be developed. After the ultrasonic ranging systems are passed by the last target in the row, it will keep reading infinite distance data. A certain amount of consecutive infinite distance data confirms the orchard sprayer to pass through the tree row. Then the control mode is needed to be changed into the turning mode, which turns the orchard sprayer by 90° , keeps moving straight for 3m and turns it again by 90° . A gyro-sensor is recommended for the feedback control.

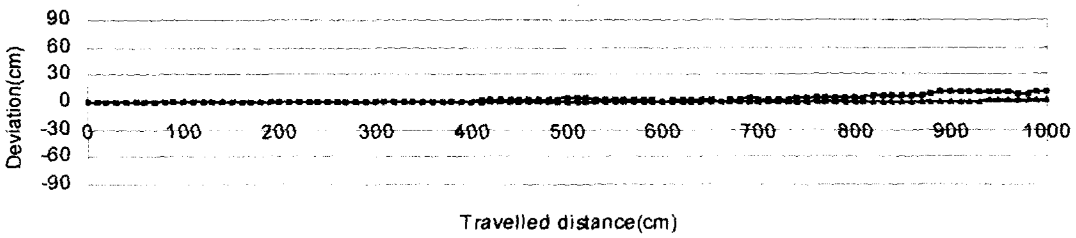
Conclusions

For the chemical application in a confined working space such as Korean vineyard, the autonomous steering controller was developed and its system performance was evaluated with a small-scaled crawler type orchard sprayer. The developed guidance system consisted of two ultrasonic ranging modules, two power cylinders, a hydrostatic transmission, a 80196kc microprocessor and steering control algorithm. The research results were summarized as follows:

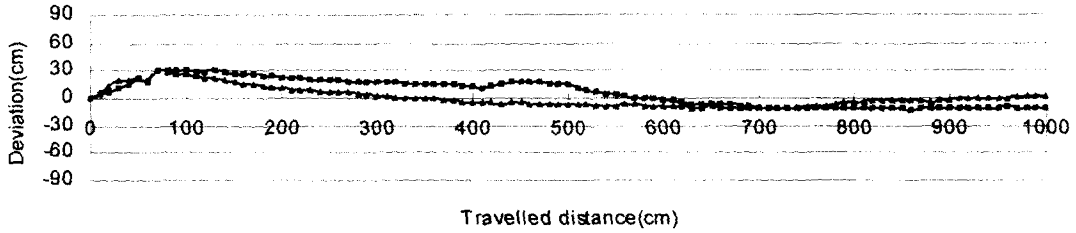
The distance ranging system was developed using two ultrasonic sensors. The system was controlled by the 80196kc microprocessor and reliably performed by timing the round-trip for the ultrasonic wave to travel between the ultrasonic sensor and the target.

Two power cylinders were used for actuating steering clutches with an internal protection circuit to stop excessive current flow in case that the piston reached at both ends of its stroke. The HST was adapted to control the ground speed, go and stop of the autonomous orchard sprayer. Interface circuits to operate the power cylinders and the stepping motor for HST were developed.

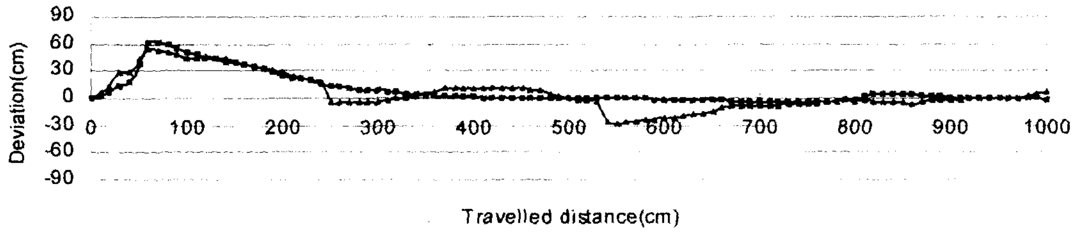
The steering control algorithm of the autonomous operation began with ranging left and right targets and



(a) for the heading of 0°



(b) for the heading of +10°



(c) for the heading of +20°

Fig. 9 Guidance system performance for the different heading angles of (a) 0°, (b) +10° and (c) +20° without initial lateral offset at a ground speed of 0.41 m/s (Mid).

the heading was decided using the difference between distances to left and right targets along the desired path.

The evaluation tests showed that the orchard sprayer could travel within RMS value of 5cm along the straight path. It did not take much time to track the desired path even if the orchard sprayer started with a lateral offset and tilt heading angle. Up to the speed range of 0.52m/sec, the different ground speeds did not affect the performance of the autonomous guidance system.

Further research was needed to turn the orchard sprayer at the end of tree row. It was recommended that the guidance control system use an additional algorithm for the turning mode.

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