AUTONOMOUS SPEED SPRAYER GUIDANCE USING MACHINE VISION AND FUZZY LOGIC

S. I. Cho, N. H. Ki

ABSTRACT. *A Fuzzy Logic Controller (FLC) was developed for autonomous operation of a speed sprayer in an orchard. The operation of the FLC was graphically simulated under the real condition of the orchard. Machine vision was used to determine vehicle heading and four ultrasonic sensors were used to detect obstacles during the operation. Operation time duration of the hydraulic cylinders was inferred as output of the FLC. The results of simulation showed that the speed sprayer could be operated autonomously by the FLC that used sensor inputs from machine vision and ultrasonic sensors. After the graphic simulation, autonomous speed sprayer operation in a real orchard was conducted using the developed FLC. Orchard image analysis and signals of ultrasonic sensors were processed in real time. The speed sprayer was modified to be steered by two hydraulic cylinders. The results of field test showed that the speed sprayer could be operated by the FLC. The ultrasonic sensors didn't contribute to the improvement of guidance performance; however, they assisted the speed sprayer to avoid trees or obstacles in emergent situations.*
Keywords. *Speed sprayer, Simulation, Fuzzy logic control, Machine vision, Ultrasonic sensor.*

Fruit trees are treated to minimize harvest losses and increase quality and productivity of fruits in orchards. Fruit trees are pruned, fruits are wrapped to minimize the losses due to birds, and they are sprayed with agri-chemicals to reduce the losses due to insects and disease. Spraying is the most dominant among these three operations and plays an important role in reducing the harvest losses and improving productivity. Between 30 to 35% of losses can be saved when harmful insects and diseases are eliminated by spraying.

The problem with most agri-chemicals is that they are hazardous to human beings. When a speed sprayer operator is exposed to agri-chemicals during spraying, toxicity of agri-chemicals can cause critical human health threat. Conventional spraying methods include a manually operated self-propelled vehicle, called a speed sprayer. A second method is used in small-scale orchards when the operator has to walk through an orchard with a portable sprayer on his/her back. Operators in both of these operations can be affected by agri-chemicals. To prevent the health threat, protective gear has been the only means to protect the machine operator and may protect the operators from contact with agri-chemicals. Spraying itself, nonetheless, is a dangerous job and operators are always in danger of exposure to agri-chemicals. Designing an autonomous spray vehicle and removing the operator from the vehicle would be the ultimate safety solution.

Article has been reviewed and approved for publication by the Information & Electrical Technologies Division of ASAE.

The authors are **Seong In Cho**, Associate Professor, Department of Agricultural Engineering, College of Agriculture and Life Sciences, Seoul National University, South Korea; and **No Hoon Ki**, Graduate Research Assistant, Department of Agricultural & Biological Engineering, Purdue University, West Lafayette, Indiana. **Corresponding author:** No Hoon Ki, Purdue University, Department of Agricultural & Biological Engineering, West Lafayette, IN 47907; voice: (765) 494-1210; fax: (765) 494-1210; e-mail: nohoon@ecn.purdue.edu.

Blackmore and Steinhauser (1993) steered a mechanical weeder using intelligent sensing and a self-organizing fuzzy logic technique. Kamada and Yoshida (1992) tested the operation of a low speed vehicle using color image processing and fuzzy logic. Toda et al. (1993) used fuzzy logic in a mechanical weeder and an agricultural vehicle, respectively. In these studies, fuzzy logic was used because agricultural environments include ambiguous information. Especially, images obtained from an orchard include noises, and it is hard to find vehicle headings from these images. Collision with trees can cause damage to both the machine and the tree.

The objectives of this study were to:

- Develop image processing algorithms to detect the vehicle heading.
- Install ultrasonic sensors to measure the distance between speed sprayer and obstacles.
- Modify the speed sprayer for self-steering.
- Design a Fuzzy Logic Controller (FLC) to steer the autonomous operation.

METHOD AND MATERIALS

STRUCTURE OF MACHINE GUIDANCE SYSTEM

The autonomous guidance system consisted of a machine vision system, a hydraulic steering system, ultrasonic sensors, and a FLC. Information from both machine vision and ultrasonic sensors was used as the inputs to the FLC. The vehicle heading was decided from the machine vision images and the distance between the obstacle and speed sprayer was determined from ultrasonic sensor data. The test model was a speed sprayer (Hansung, Korea), 3180 × 1255 × 1275 mm (length × width × height), with three pairs of wheels (fig. 1).

MACHINE VISION SYSTEM

The machine vision system consisted of a PC Vision Plus Frame Grabber (Imaging Tech. Inc., Bedford, Mass.)

Figure 1–A typical compressed orchard image that was used to determine steering heading direction.

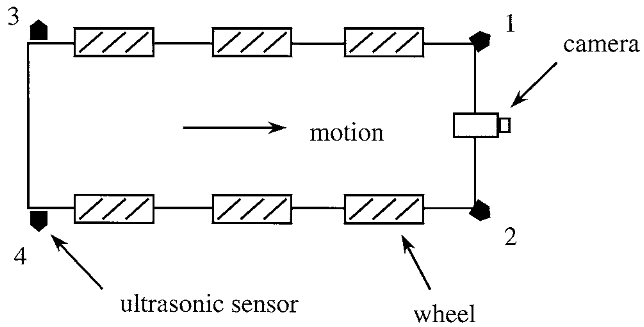


Figure 2–Installation of camera and ultrasonic sensors.

Figure 3–Autonomous operation of the speed sprayer in an orchard.

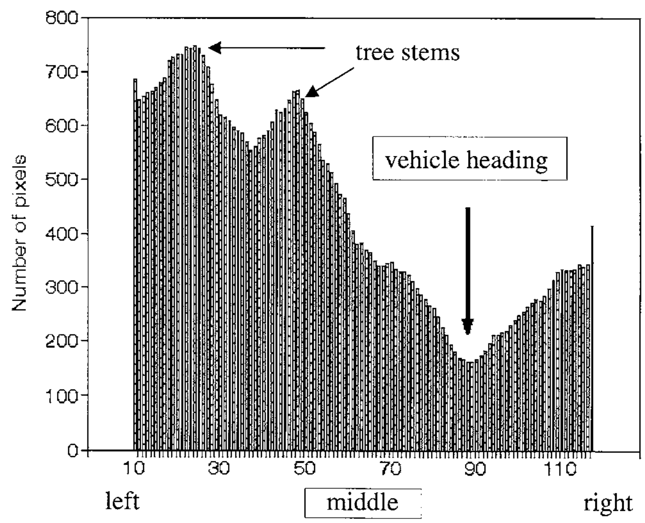


Figure 4–Vertical histogram and vehicle heading.

and a black and white CCD camera. The frame grabber had a resolution of 512 × 512 × 8 pixels. The camera was installed in the upper middle of the frontal area of the speed sprayer (figs. 1 and 2).

Images acquired by the CCD camera were compressed to 128 × 128 pixels. Vertical components (tree stems and branches which stand vertically) in the compressed image were enhanced using the Prewitt mask and the vertical edges were detected using the Sobel mask. The vertical edge detected image was binarized with the magnitude and direction by the Sobel operation (fig. 3). A vertical direction histogram which is the number of pixels whose value is one along the vertical line of binarized image was used to detect the direction of running. In the histogram, the lowest valley implied the vehicle heading (fig. 4). Trees stems and branches which were far away from the speed sprayer looked smaller than the ones closer to the speed sprayer. Consequently, the vertical components (vertical edges) near the vehicle heading were rare due to the perspective. To evaluate the robustness of the machine vision algorithm, images were acquired in various seasons, times of day, and lighting conditions. The machine vision algorithm could find the direction of the running in all cases. The time to process one whole image was 1.2 s using an IBM PC 486.

Hydraulic Steering System

The speed sprayer was steered by two hand levers that control hydraulic brake and clutch. Once one lever was pulled, the three wheels on this lever were fully braked and skidded. Torque from the engine was applied only to the other three wheels on the other lever. The hydraulic system is shown in figure 5. It was composed of two bi-directional hydraulic cylinders, two three-port-four-way direction control valves, one relief valve, and a hydraulic pump. Solenoid valves (direction control valves) were used to control hydraulic cylinders with the FLC signals. Table 1 gives the specification of the hydraulic cylinder. The FLC output signals were interfaced with solenoid valves through an Intel 8255 and relays were used as an I/O interface.

Ultrasonic Sensors

A circuit was designed to drive four ultrasonic sensors and to measure obstacle distances. Table 2 shows the specification of the ultrasonic sensors. Distance measurement range of the ultrasonic sensor in an orchard

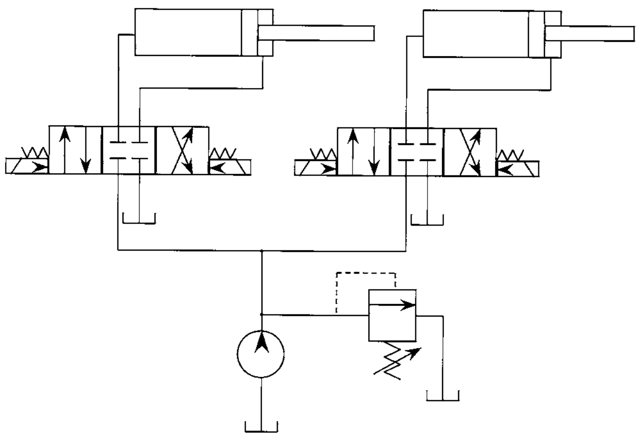


Figure 5–A schematic diagram of the hydraulic system for the steering system.

was about 4 ~ 5 m. To simplify the circuit, an Intel 8255 for counting units and relays for hydraulic cylinders were arranged on one printed circuit board (PCB). Figure 2 depicts the position and mounting of the ultrasonic sensors. Two ultrasonic sensors were installed at two rear upper corners of the speed sprayer and the other two ultrasonic sensors at two front upper corners of the speed sprayer to detect obstacles. The rear ones transmitted and received signals perpendicular to the sides of the speed sprayer . The angle between the speed sprayer and the signal emitted by front ultrasonic sensors was 30°.

FUZZY LOGIC CONTROLLER

The vehicle heading and distances to obstacles were the inputs of the FLC. The FLC inferred the operation time duration of two hydraulic cylinders. The left and right hydraulic cylinders were operated separately and had different linguistic variables.

Determination of linguistic variables is to divide the fuzzy input variable into a number of discrete units. For example, linguistic variables used for the vehicle heading were LT (LefT), MD (MiDdle), and RT (RighT). Each of them has the meaning of "the vehicle heading is to its left, middle, and right". Instead of using these three linguistic variables, five variables may be used as LT (LefT), LM (between Left and Middle), MD (MiDdle), RM (between Right and Middle), and RT (RighT). A fuzzy rule is a combination of these linguistic variables for each fuzzy variable. For the autonomous speed sprayer guidance, three

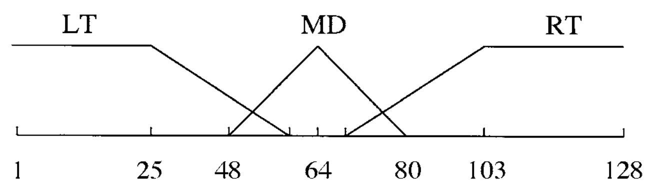
Table 1. Specification of the hydraulic cylinder for the hydraulic steering system

Diameter	40 mm
Rod diameter	15 mm
Displacement	35 mm
Rod velocity	35 mm/s
Applied force	107 kgf

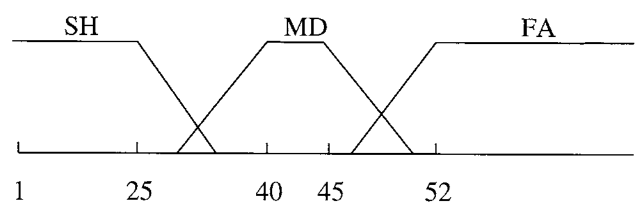
Table 2. Specification of the ultrasonic sensor to detect obstacle distances

Name	Polaroid Ultrasonic Ranging Unit
Range	15-1050 cm
Type	Transmitter and receiver on one body
Frequency	50 kHz
Resolution	1.8 cm

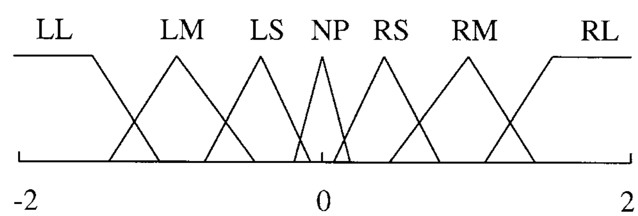
linguistic variables were enough. Too many variables can cause high complexity of fuzzy rule base. Similarly, the linguistic variables for the ultrasonic inputs were SH (SHort), MD (MiDdle), and FA (FAr). The linguistic variables for the operating time duration of hydraulic cylinder were LL (Left Long), LM (Left Medium), LS (Left Short), NP (No oPeration), RS (Right Short), RM (Right Medium), and RL (Right Long). Membership functions for these variables were shown in figures 6a-c. The negative values in figure 6c were the operation time duration of the left hydraulic cylinder and the positive values were the operation time duration of the right hydraulic cylinder. The shapes of membership functions were determined considering longitudinal tree interval, lateral tree interval, and tree height. Thirteen fuzzy rules were developed for the fuzzy control. An example of the fuzzy rule is given in table 3. The condition statement in if-clause [Direction = RT] says that the vehicle heading is located in the right side of the speed sprayer. The first ultrasonic sensor detects an obstacle close to speed sprayer (statement [US_INPUT_1 = MD]). DC (Don't Care) means that the input doesn't matter, and, consequently, the rest of



(a)



(b)



(c)

Figure 6–Membership functions of the fuzzy logic controller for (a) vehicle heading, (b) ultrasonic signal, and (c) operation time duration of hydraulic cylinder.

Table 3. An example of the fuzzy rule

If
  [Direction = RT] and
  [US_Input_1 = MD] and
  [US_Input_2 = DC] and
  [US_Input_3 = DC] and
  [US_Input_4 = DC],
Then
  [Cylinder_Time = RS]

the inputs don't matter (statement [US_INPUT_* = DC]). Then, the FLC infers "Pull the right hydraulic cylinder for the short period of time and release it" as the statement [CYLINDER_TIME = RS] and the speedsprayer turns a little to its right as a result. Operation time duration of the hydraulic cylinders was calculated (inferred) by FLC.

Modeling of Speed Sprayer and Orchard

The speed sprayer was tested in a chestnut orchard, in College of Agriculture and Life Sciences, Seoul National University. The width of the speed sprayer running (lateral tree interval) was 5 m. The distance between the trees (longitudinal tree interval) was 6 m, and the total length of speed sprayer running was 35 m.

The simulation conditions of the autonomous speed sprayer guidance were the same as in a real orchard. The speed sprayer was modeled with equations 1, 2, and 3 as shown in figure 7.

$$x(t+1) = x(t) - r \times \cos[\theta(t) + \phi(t+1)] \tag{1}$$

$$y(t+1) = y(t) - r \times \sin[\theta(t) + \phi(t+1)] \tag{2}$$

$$\theta(t+1) = \theta(t) + \phi(t+1) \tag{3}$$

where

- θ = angle between centerline of speed sprayer and x axis (radian)
- ϕ = steering angle (radian)
- r = moving distance in one time step (m)
- x = x position of speed sprayer (m)
- y = y position of speed sprayer (m)
- t = time (s)

To simulate the speed sprayer operation, the elapsed time (t) was calculated during each speed sprayer control action and was multiplied by the velocity to obtain the moving distance (r). The ground condition was considered to be flat and no slip between the wheels and the ground was assumed.

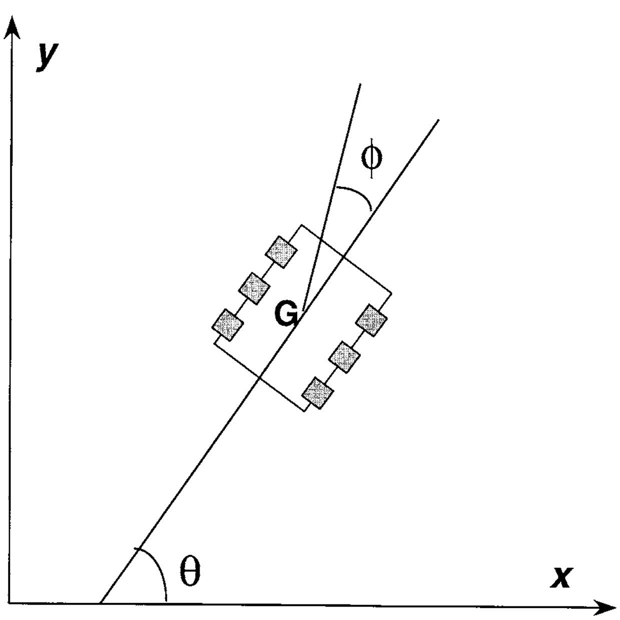
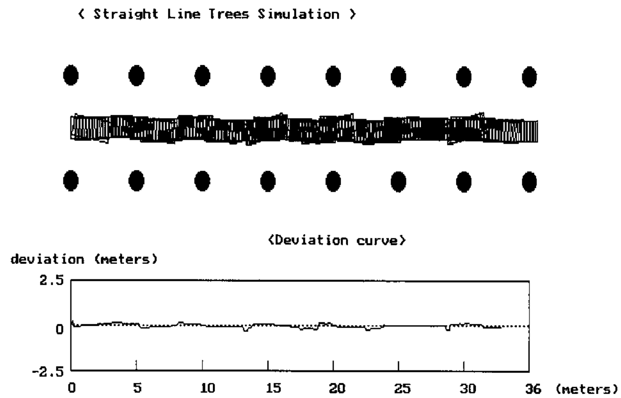
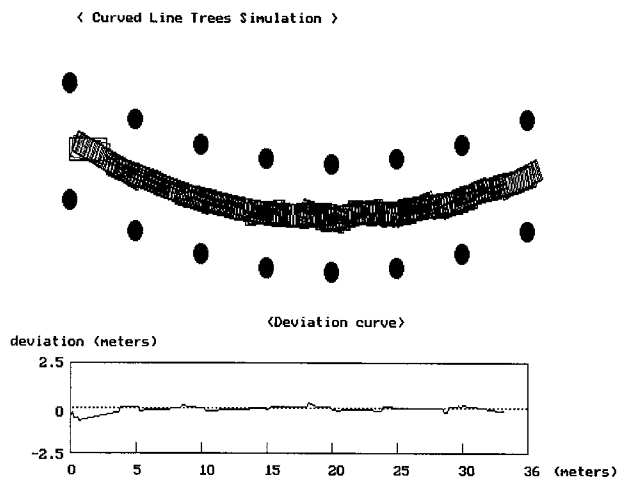


Figure 7–Modeling of the speed sprayer steering, where θ is the angle between centerline of speed sprayer and x-axis, ϕ is the steering angle, and G is the center of gravity.



(a)



(b)

Figure 8–Simulation of the autonomous speed sprayer operations: (a) along a straight path, and (b) along a curved line.

The simulation speed was consistent with a real speed sprayer operation speed (1.6 km/h). The speed sprayer was initially set to the same direction and location as in a real test. The images were obtained from the orchard in advance. The image which the speed sprayer could obtain at its position of the real operation was given to the speed sprayer model. Figures 8a and 8b show the simulations along a straight path and along a curved path, respectively. The curved path was not tested in a real operation because curved path image couldn't be obtained. Assuming that the curvature of the path is very large as in figure 8b, the images obtained from straight path were used for the simulation.

Evaluation of Guidance Performance

To evaluate the guidance performance, an ideal path was compared with the path produced by FLC (Kehtarnavaz and Griswold, 1991; Li and Wilson, 1994a,b) and Root

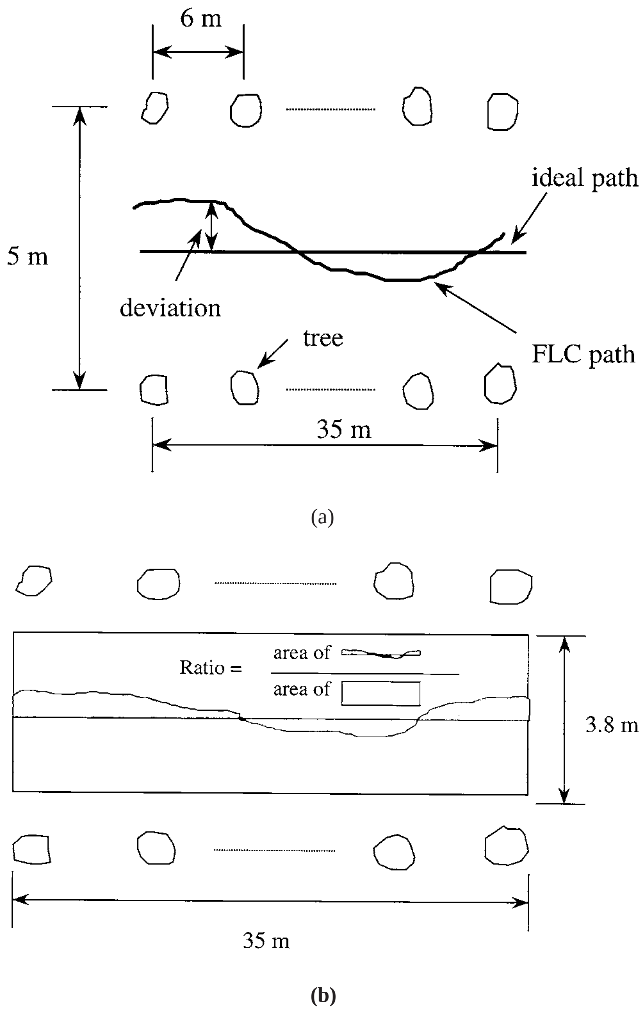


Figure 9–Examples of the guidance performance evaluation: (a) deviation measurement, and (b) ratio of areas calculation.

Mean Square value (RMS) was calculated to represent the error (fig. 9a). The RMS was calculated using equation 4:

$$\text{RMS} = \sqrt{\frac{\Sigma\,(\text{deviation})^2}{(\text{number of data})}} \qquad (4)$$

where deviation represents the difference between an ideal path and the FLC-predicted path, and number of data is the number of data collected.

The other performance evaluation method of the FLC was the ratio of areas. The area between ideal path and FLC-predicted path was compared with the area in which the speed sprayer can run (fig. 9b). The area in which the speed sprayer can run was 133 m^2 (3.8 m × 35 m). To evaluate the RMS values and the ratio of areas, 36 data points were marked along the ideal path and the deviations were measured at each data point.

Results and Discussions

Graphic Simulation of the Autonomous Guidance

Two control intervals, 4.0 s and 1.5 s, were evaluated. Control interval is the time duration for one control cycle, that is, the time consumed from the beginning of control (obtaining image) to the end of control (hydraulic cylinder operation). Table 4 shows the RMS values and the ratio of areas. These values were smaller with the shorter control interval. The maximum deviation was 53 cm with a 1.5 s control interval.

Table 4. Performance evaluation of the graphical simulation*

		Machine Vision		Machine Vision and Ultrasonic Sensors	
Cycling Time	Trial Number	RMS (cm)	Ratio of Area (%)	RMS (cm)	Ratio of Area (%)
4.0 s	1	38.07	7.81	26.64	6.21
	2	24.52	5.78	25.61	6.03
1.5 s	1	22.93	4.95	23.14	5.19
	2	20.90	4.61	19.48	4.39

* Root Mean Square (RMS) and ratio of area of steering error were used as evaluation criteria.

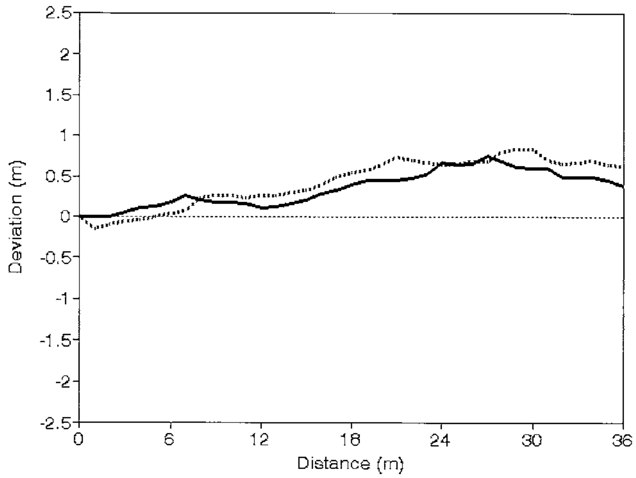
In the simulation, the speed sprayer could be autonomously operated with the image processing algorithm and ultrasonic sensors. The guidance performance with the machine vision only was worse than that with both the machine vision and the ultrasonic sensors in the control interval of 4.0 s. There was no obvious performance difference at the 1.5 s control interval.

Autonomous Guidance Field Test

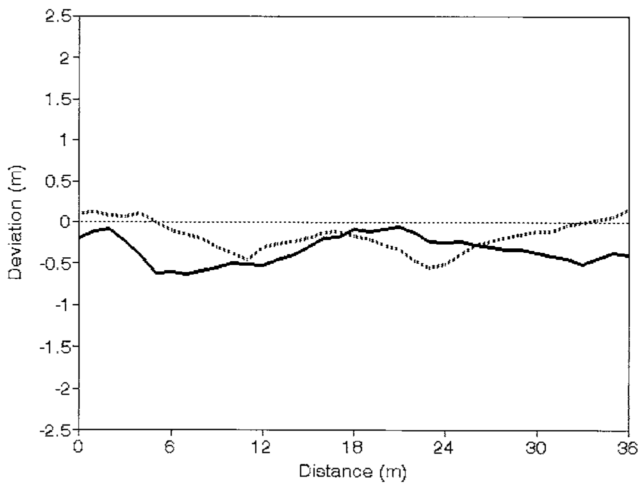
At first, only the vehicle heading was used as an input to the FLC. This could be done by setting the ultrasonic signal input infinite and pretending that there were no obstacles. Figures 10a and 10b show the real operation paths with the control intervals of 4.0 s and 1.5 s, respectively. Table 5 shows the RMS values and the ratio of areas. The RMS values and ratio of areas were smaller with shorter control interval as shown in the simulation. The maximum deviation was the 64 cm with the control interval of 1.5 s. The shorter the control interval, the better the guidance performance.

Second, both vehicle heading and ultrasonic sensor signals were used as the inputs. Figure 11a is the path with the 4.0-s control interval, and figure 11b is the path with the 1.5-s control interval. The RMS values and the ratio of areas are given in table 5. The maximum deviation was 72 cm with 1.5 s of control interval; this was worse than the one with the results of machine vision only. This result was due to the erroneous recognition of ultrasonic signals due to long tree branches or leaves. RMS values and the ratio of areas, on the other hand, are not quite different from those of machine vision only. The ultrasonic sensors didn't contribute to the improvement of guidance performance of the speed sprayer. However, they could be used to avoid trees or obstacles in emergency situations such as the unexpected appearance of either a human or an animal.

In the field operation, shorter control interval also gave better guidance performance as shown in the simulation. The weather condition and the number of leaves in the field of view affected image quality and thus the effectiveness of the image processing operation. The machine vision alone couldn't find the direction of running exactly as a human did. But this ambiguity could be eliminated with the FLC and ultrasonic sensors. Fuzzy reasoning is not based on one rule only, inference is the combination of several rules. One



(a)



(b)

Figure 10–The effect of control interval on steering deviation using the machine vision only (field test): (a) 4.0 s of control interval, and (b) 1.5 s of control interval.

input did not dominate the inference. Even though the machine vision produced wrong vehicle heading data, outputs of the FLC with ultrasonic sensors were not dramatically affected.

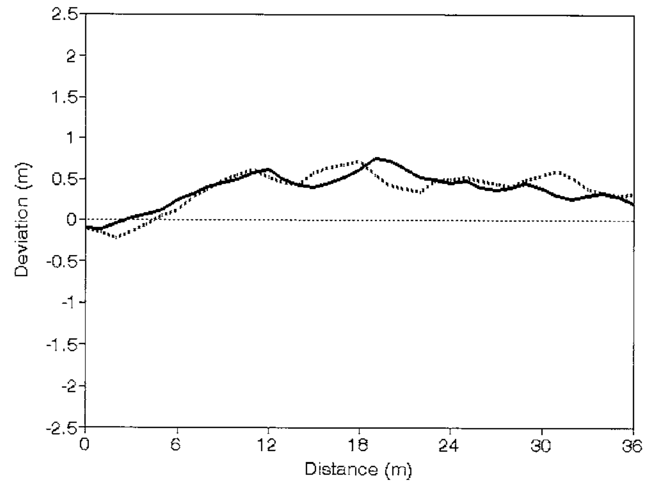
CONCLUSIONS

In this study, a Fuzzy logic control system (FLCS) was developed for the autonomous operation of speed sprayer. The FLCS had five inputs; one vehicle heading, and four distances from obstacles. The duration of the hydraulic cylinder operation time was inferred as an output of the FLCS to steer the speed sprayer. To perform the autonomous operation, a machine vision unit, a hydraulic system, and four ultrasonic sensors were used. A black and white CCD camera with a frame grabber was used for the machine vision system. The speed sprayer was modified to be steered by two hydraulic cylinders. Four ultrasonic sensors were installed; two of them on the front of speed sprayer, and the other two on the back of it.

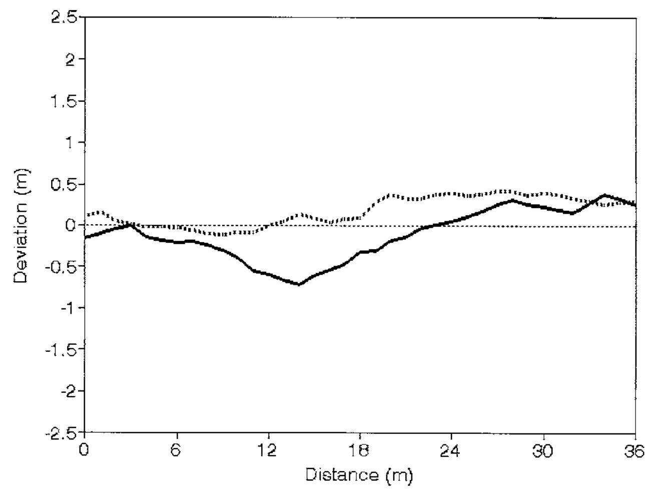
Table 5. Performance evaluation of the real operation*

		Machine Vision		Machine Vision and Ultrasonic Sensors	
Cycling Time	Trial Number	RMS (cm)	Ratio of Area (%)	RMS (cm)	Ratio of Area (%)
4.0 s	1	42.17	9.67	42.82	10.52
	2	52.62	12.34	44.76	11.30
1.5 s	1	38.39	9.34	33.26	7.97
	2	25.29	5.72	25.45	5.68

* Root Mean Square (RMS) and ratio of area of steering error were used as evaluation criteria.



(a)



(b)

Figure 11–The effect of control interval on steering deviation using both the machine vision and the ultrasonic sensors (field test): (a) 4.0 s of control interval, and (b) 1.5 s of control interval.

To demonstrate the autonomous guidance of speed sprayer, it was simulated graphically under the same conditions of a real orchard. The simulation proved that the speed sprayer could be operated autonomously with the machine vision and ultrasonic sensors. After the graphic simulation, the speed sprayer was tested in a real orchard. Field test results showed that the speed sprayer could be operated autonomously by the FLCS along with the machine vision and ultrasonic sensors. The ultrasonic sensors did not contribute to the improvement of autonomous guidance operation. However, the ultrasonic sensor signals could be used to avoid an unexpected appearance by either a human or animals.

REFERENCES

Blackmore, B. S., and T. Steinhauser. 1993. Intelligent sensing and self-organizing fuzzy logic techniques used in agricultural automation. ASAE Paper No. 93-1048. St. Joseph, Mich.: ASAE.

Kamada, H., and M. Yoshida. 1992. *A Visual Control System Using Image Processing and Fuzzy Theory,* 111-128. New York, N.Y.: Springer-Verlag.

Kehtarnavaz, N., and N. C. Griswold. 1991. Visual control of an autonomous vehicle (BART)—The vehicle—Following problem. *IEEE Trans. Vehicular Tech.* 40(3): 654-661.

Li, Y., and J. N. Wilson. 1994a. Development of an intelligent steering control algorithm for vision-based agricultural vehicle guidance. ASAE Paper No. 94-3513. St. Joseph, Mich.: ASAE.

_____. 1994b. Simulation study of a vision-based agricultural vehicle guidance system. ASAE Paper No. 94-3608. St. Joseph, Mich.: ASAE.

Toda, M., O. Kitani, T. Okamoto, and T. Tori. 1993. Studies on autonomous vehicles for agricultural robotics. ASAE Paper No. 93-3091. St. Joseph, Mich.: ASAE.