

초음파센서를 이용한 변량제어 스프레이어

전홍영 주허핑

Ultrasonic Sensor Controlled Sprayer for Variable Rate Liner Applications

H. Y. Jeon H. Zhu

Abstract

An experimental variable rate nursery sprayer was developed to adjust application rates for canopy volume in real time. The sprayer consisted of two vertical booms integrated with ultrasonic sensors, and variable rate nozzles coupled with pulse width modulation (PMW) based solenoid valves. A custom-designed microcontroller instructed the sensors to detect canopy size and occurrence and then controlled nozzles to achieve variable application rates. A spray delivery system, which consisted of diaphragm pump, pressure regulator and 4-cycle gasoline engine, offered the spray discharge function. Spray delay time, time adjustment in spray trigger for the leading distance of the sensor, was measured with a high-speed camera, and it was from 50 to 140 ms earlier than the desired time (398 ms) at 3.2 km/h under indoor conditions. Consequently, the sprayer triggered 4.5 to 12.5 cm prior to detected targets. Duty cycles of the sprayer were from 20 to 34 ms for sensor-to-canopy (STC) distance from 0.30 to 0.76 m. Outdoor test confirmed that the nozzles were triggered from 290 to 380 ms after detecting tree canopy at 3.2 km/h. The spray rate of the new sprayer was 58.4 to 85.2% of the constant application rate (935 L/ha). Spray coverage was collected at four areas of evergreen canopy by water sensitive papers (WSP), and ranged from 1.9 to 41.1% and 1.8 to 34.7% for variable and constant rate applications, respectively. One WSP area had significant ($P < 0.05$) difference in mean spray coverage between two application conditions.

Keywords : Variable rate applications, Ultrasonic sensor, Tree liners, Sprayers, Real-time sensing

1. INTRODUCTION

Nursery and floriculture crop growers in the USA used 31 tons of active ingredients (AI) for tree liner production in 2006 (USDA, 2007). Tree liners typically refer to young trees being transplanted to fields or containers to become market-ready trees. Applying chemicals is an important process to protect liner from biological harms. Broadcast application is one of the common application technologies due to its convenience. However, broadcast application rates were typically determined by the largest liner group to prevent under-application. Thus, the broadcast application may frequently create over-application issues for relatively

smaller liner groups. Thus, the sprayer that autonomously adjusts spray output with tree canopy size would be beneficial to the growers in terms of reducing chemical use.

A major obstacle to develop automated liner sprayers is to sense tree liners under narrow row space (1.2 to 1.5 m). One of detection technologies is ultrasonic sensors, and their potentials in detecting trees have been well documented (Giles et al., 1988; Tumbo et al., 2002; Zaman and Salyani, 2004; Jeon et al., 2011). Their results showed that the ultrasonic sensors had sufficient performance in detecting tree canopy.

Furthermore, ultrasonic sensors have been used for automated orchard sprayers to detect tree presence and control

spray application (Giles et al, 1987; Moltó et al., 2000, Solanelles et al., 2006; Gil et al., 2007; Balsari et al., 2008). For example, Giles et al. (1987) developed an orchard sprayer equipped with three ultrasonic sensors. A microcomputer controlled spray manifolds by canopy detection results.

Another air-assisted orchard sprayer (Gil et al., 2007) was equipped with three ultrasonic sensors. Application rates were determined by canopy detection results. Canopy volume was estimated with the distance to canopy, row spacing and ground speed, and the flow rates of the sprayer were accordingly adjusted with a rate of 0.095 L/m^3 .

Although ultrasonic sensor-equipped orchard sprayers have been well documented, potential issues in nursery liner applications have not been addressed. Thus, the objective of this study was to develop an experimental ultrasonic sensor-controlled sprayer for tree liner applications with following specific goals:

- 1) to develop an experimental ultrasonic sensor-controlled sprayer for variable rate liner application,
- 2) to examine the performance of the sprayer in triggering and modulating spray against detected target, and
- 3) to investigate effects of variable rate application in spray coverage.

2. MATERIALS AND METHODS

A. Spray Boom and Spray Delivery System

The developed ultrasonic sensor-controlled sprayer (fig. 1) had a pair of vertical booms. Five 0.36 m long, horizontal bars were mounted on each boom at spacing of 0.41 m to support nozzles and sensors. A spray nozzle (XR11006,

Teejet Co., Wheaton, IL, USA) coupled with a PMW solenoid valve (Capstan Ag Systems, Inc., Topeka, KS, USA) was mounted at the rear end of the bar. The width (W) and height (H) of the sprayer were 1.5 m and 2.1 m, respectively. The booms were connected with a custom-manufactured spray delivery system that consisted of a diaphragm pump (9910-D30, Hypro Co., New Brighton, MN, USA), four-cycle gasoline engine (GX160, Honda Co., Ltd, Minato, Japan) and pressure regulator (GS40GI, Hypro Co., New Brighton, MN, USA). The pump was driven by the engine, and the system pressure was adjusted by the regulator. The system was carried by a 3-point hitch of a tractor (John Deere 2640A, Deere & Compnay, Moline, IL, USA) in the field.

B. Ultrasonic Sensing Unit

Five ultrasonic sensors (LV-MaxSonar-WR1, Baxter, MN, USA) with a divergence angle of 9 degree were installed at the front end of the horizontal bars on one of the booms (fig. 1). The sensor had a detection range from 0.3 to 6.5 m, and its resolution was 3.82 mV/cm. The sensor operation required 5 VDC which provided from a custom-designed microcontroller board. IP (Ingress Protection) 67 rated enclosure protected internal circuits, and the enclosure was modified to attach a 6.8-cm length pipe (inner diameter: 6.0 cm) with sound absorbing foam (thickness: 1.3 cm). The foam was adhered to the inside of the pipe to prevent potential crosstalk between adjacent sensors. In addition, the spatial resolution was increased by limiting the ultrasonic wave pathway (Jeon et al., 2011). Five sensors were simultaneously triggered for 40 μs to discharge ultrasonic wave, and canopy detection signals were acquired after 49 ms. Thus, the sensor-to-canopy (STC) distances of all sensors were detected on an identical canopy plane.

C. Spray Modulation Unit

Spray output was adjusted by modulating solenoid valves which were controlled by a solid-state relay (SSR) based on an N-channel Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET, RFP12N10L, Fairchild Semiconductor International, Inc., South Portland, ME, USA) to increase control speed and lifetime of valve control switches. The valves were modulated at 10 Hz with duty cycles (DC) from 0 (no spray) to 100 ms (continuous spray) at the resolution of 5

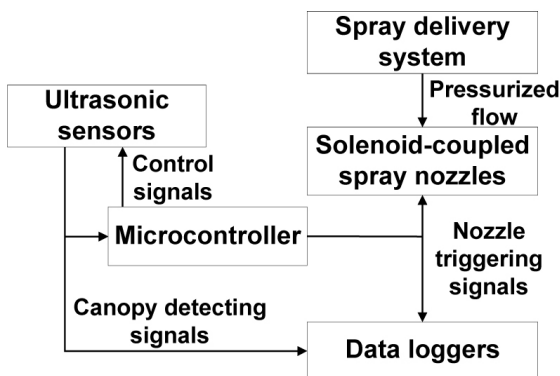


Fig. 1 A schematic diagram of ultrasonic sensor controlled sprayer for liner applications.

ms. The minimum DC was determined at 20 ms to prevent nonlinear flow rate changes which occurred with DC less than 20 ms. The valve power (12 VDC) was provided by a custom-designed microcontroller board. A general-purpose diode (1N4007, Vishay Intertechnology, Inc, Malvern, PA, USA) and transient voltage suppressor (SA20CA, Fairchild, South Portland, ME, USA) were used to protect SSR from EMI (Electromagnetic interference) and semiconductor breakdown by transient voltages (Tyco Electronics, 2009).

D. Microcontroller

A custom designed microcontroller board (fig. 2) was used to control the sensing and spray modulation units. The board power was provided by a wet-cell battery (12 VDC) of the tractor. The power was adjusted with a voltage regulator (KA78T05, Fairchild Semiconductor International, Inc., South Portland, ME, USA) to 5 VDC for the sensors and Peripheral Interface Controller (PIC) (18F4523, Microchip technology Inc., Chandler, AZ, USA). In addition, each detection signal was connected with a first order passive low pass filter with a cutoff frequency of 21 Hz to eliminate high frequency signal noise.

A control signal from the PIC triggered the sensors, and an embedded 12-bit analog-to-digital (AD) converter converted analog canopy detection signal to digit data. The PIC executed two processes every 50 ms. Canopy detection data between adjacent sensors was examined to eliminate the noise as a post processing.

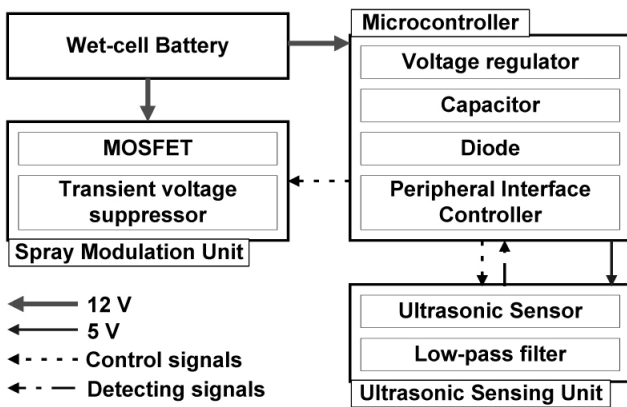


Fig. 2 Microcontroller board for controlling sensors and modulating solenoid valves.

A spray delay time against detected tree canopy was set to 300 ms (desired time: 398 ms) at 3.2 km/h to compensate

leading distance of the sensors and synchronize detection and modulation timing. Thus, the PIC sent control signals to MOSFET, and the solenoid valve powered approximately 8.7 cm (98 ms) ahead of detected canopy to trigger the nozzles at 3.2 km/h.

The maximum rate of 935 L/ha, a typical application rate for liner applications, was used for variable rate applications. Flow rates of nozzles were estimated with detected canopy volume, and application ratio of 0.08 L/m³. Flow rates were controlled by adjusting modulation DCs.

The control program was written in MicroCode Studio (Version 3.0.0.5, Mecanique, Saltburn by the Sea, UK). A PICBASIC PRO compiler (MicroEngineering Labs, Inc., Colorado Spring, CO, USA) compiled the program into a hex file. The hex file was programmed into PIC by a programmer (a melabs USB programmer 4.31, MicroEngineering Labs, Inc., Colorado Spring, CO, USA).

E. Spray Trigger Timing Accuracy

Accuracy of spray trigger timing for detected targets was examined. While two targets (132 cm (H) × 9 cm (W)) were moving along a custom-designed linear track at 3.2 km/h, the sensors detected targets and triggered the solenoid valves to spray targets. Two targets were separated by 105 cm, and the target speed was measured by a radar gun (Railmaster-VP, Decatur Electronics Inc., Decatur, IL, USA).

Spray triggering scene was captured by a high-speed camera (Silicon Video 642, EPIC Inc., Buffalo Grove, IL, USA) at 200 fps (frames per a second). A laser pointer above the nozzle aimed at the spray axis to display a laser point on targets when they arrived on the spray axis. The spray timing accuracy was manually measured by timing between spray nozzle trigger and target arrival on spray axis. An air-pressurized tank (approximately 620.5 kPa) was used to supply pressurized tap water to the spray nozzles.

F. Spray Modulation Accuracy

The spray modulation accuracy was evaluated to identify potential variations in application rates. A flat wood panel (185.4 cm (H) × 24.8 cm (W)) was placed on the line-of-sight of the sensors, and the distances between the sensors and panel were from 0.30 to 0.76 m. At different distances, the microcontroller controlled the sensors to detect the panel, and modulated solenoid valves. Modulation DCs were

measured by an oscilloscope (Fluke 199, Fluke Co., Everett, WA, USA) at a 5-ms time division while the microcontroller was triggering solenoid valves.

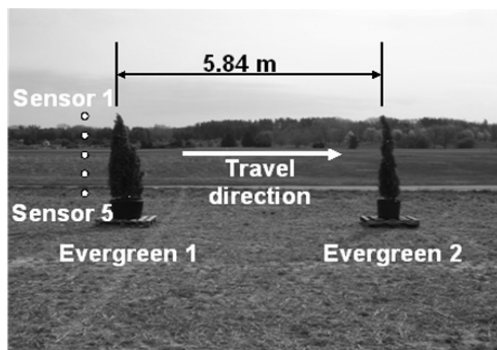
G. Outdoor Test

Spray timing and application rates

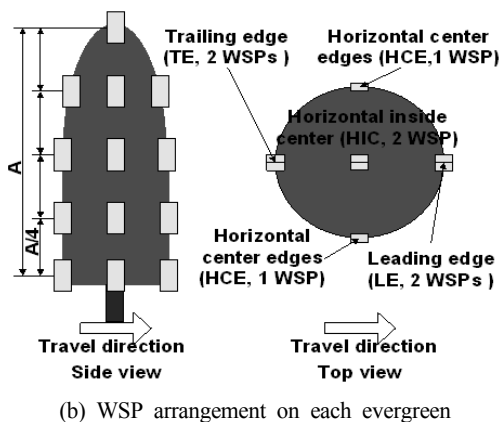
Spray timing against detected canopy was examined under outdoor condition. Two microloggers (CR3000, Campbell Scientific Inc, Logan, UT, USA) were connected to the microcontroller to acquire canopy detecting and solenoid triggering signals for variable rate applications at 100 Hz during the test. The boom center was aligned with canopy centers of two trees during the test. Ground speed of the sprayer maintained at 3.2 km/h. In addition, actual application rates were estimated with triggering signals for solenoid valves.

Spray coverage

Spray coverage on two evergreen trees (fig. 3(a)) was collected with 34 water sensitive papers (WSP, 52 × 76 mm, Spraying system Co. Wheaton, IL, USA) per evergreen canopy.



(a) Evergreen arrangement for outdoor test



(b) WSP arrangement on each evergreen

Fig. 3 Isolated evergreen and WSP mounting arrangement for outdoor test.

Space between two trees was 5.84 m to test spray control performance of the sprayer. Vertical distance between WSPs (A/4) was about 0.41 m, and tree canopy was divided into four sections, horizontal inside center (HIC), and horizontal center edges (HCE), leading edge (LE), and trailing edges (TE). Detail WSP arrangement is in fig. 3(b).

Two application conditions were tested: variable and constant rate applications. The microcontroller controlled the sensors to detect canopy and modulated the solenoid valves for variable rate applications, and the application rates were from 0 (no spray) to 935 L/ha. The microcontroller was disabled for the constant rate (935 L/ha) application. For each spray condition, three replications were made, and tap water was used as spray liquid.

WSPs were collected at 10 minutes after each spray and then stored in labeled bags. Dried WSPs were scanned by a 600-dpi (dots per inch) scanner (SCX-4828FN, Samsung Electronics Co. Ltd, Suwon, Korea), and scanned images were processed by DepositScan program (Zhu et al., 2010) to compute spray coverage (%) on WSPs.

Differences in mean spray coverage between constant and variable rate applications were examined by analysis of variance (ANOVA) assuming completely randomized design (CRD) and mean separation using Tukey-Kramer (SAS, 2008). Least significant difference (LSD) values were calculated for spray coverage data from each application condition.

3. RESULTS AND DISCUSSION

A. Spray Trigger Timing Accuracy

Identified spray delay time was from 258 to 348 ms: solenoid valves were triggered from 50 to 140 ms ahead of targets. Mean delay time was 296 ms (Standard Deviation (SD): ± 29 ms). The range resulted in spray trigger from 4.5 to 12.5 cm ahead of detected targets at 3.2 km/h travel speed. Fig. 4 shows an example response of the sprayer to a moving target.

The sprayer was supposed to trigger the spray approximately 98 ms ahead of the targets. However, our results indicated that the mean spray timing was approximately 4 ms slower than the desired time. The outcome might result in triggering nozzles approximately 0.4 cm prior to the designated area. A range of spray timing inaccuracy was expected because of variations in target detection timing. For example, leading edge arrival timing of the target on

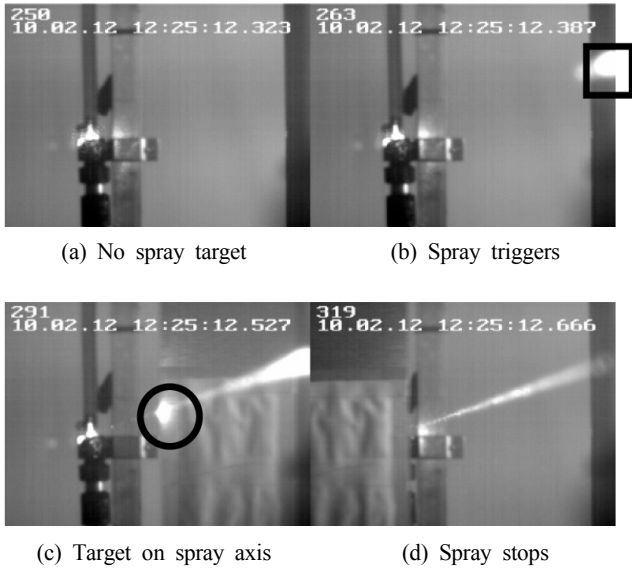


Fig. 4 Sprayer response against moving targets: a square on (b) and circle on (c) represents spray trigger and laser spot, respectively, on a target.

detecting area was not synchronized with trigger timing of the sensor. Thus, it was possible that the sensors might detect the target when the leading edge passed the detecting area, resulting in a varied trigger timing.

B. Spray Modulation Accuracy

DC range was from 20 to 34 ms for detected distances from 0.31 to 0.76 m (fig. 5). Actual DCs for modulating spray were generally longer than desired DCs. Therefore, typical application results were expected to be over-applications, and the additional volume was from 0 to 1.5 mL per modulation cycle (two XR11006 nozzles at 275.8 kPa). The potential increase in application rates by the additional volume was 108.3 L/ha.

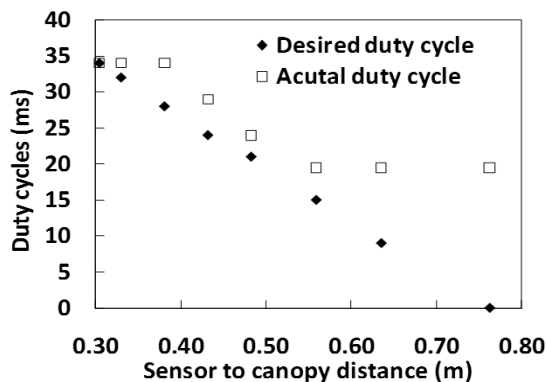


Fig. 5 Modulation DUC time of the sprayer and ideal modulation for canopy distance.

The level of application rate increase was raised with STC distances due to predetermined minimum DC (20 ms). The additional volume over-application volume can be reduced by improving DC resolution: the resolution ($9.26 \times 10^{-3} \text{ m}^3$) for canopy detection required a smaller modulation resolution (2 ms) to match with detected canopy. Mean of additional DCs was 6 ms which resulted in the additional spray volume of 0.48 mL per modulation.

C. Spray Timing and Application Rates

The sprayer showed reasonable performance in detecting canopy and triggering spray nozzles under outdoor conditions (fig. 6). The spray delay time was from 290 to 380 ms, and the mean was 318 ms (SD: ± 32 ms). Delay time measured might trigger spray approximately 1.8 to 9.8 cm (mean: 7.3 cm) ahead of detected canopy.

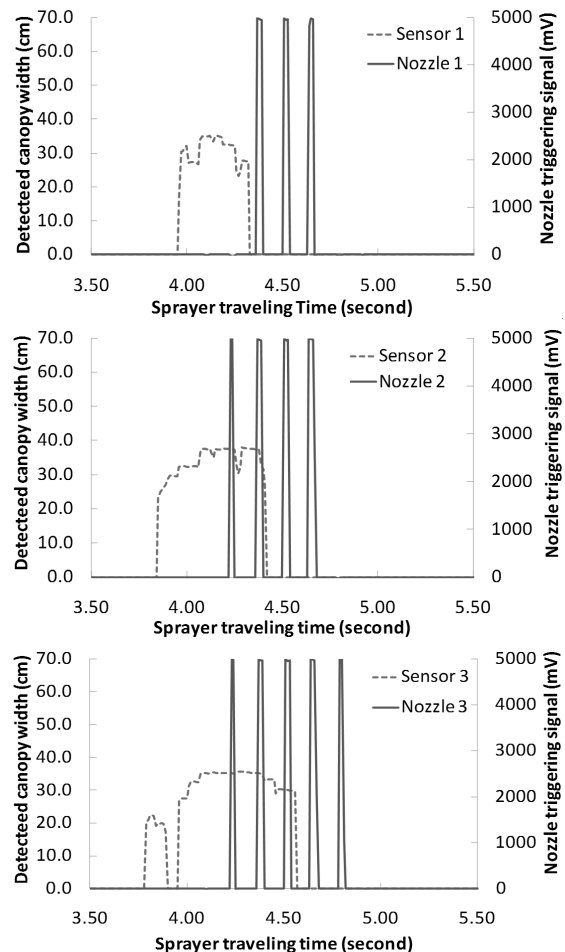


Fig. 6 Canopy detection and triggering spray from sensor 1 (Top of the boom) to sensor 5 (Bottom of the boom); dashed green and solid blue line represents detection results and nozzle trigger (at 5000 mV).

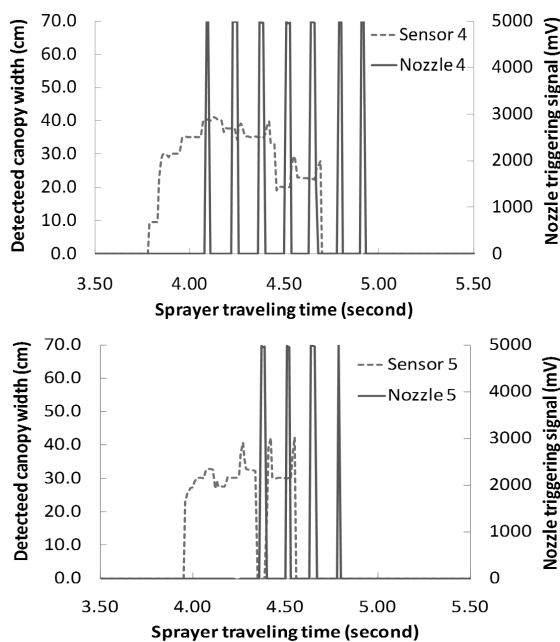


Fig. 6 Continued.

Estimated application rates were from 166.7 to 222.3 L/ha for each sensor-associated area, and the maximum rate was 1111.5 L/ha. Application rate reduction for two trees was from 14.8 to 41.6% compared to the constant application rate. Further reduction in application rates was expected under practical liner field conditions because presented reduction was estimated exclusively within tree canopy area, and relatively homogenous canopy size. However, typical liner fields have spacing between trees, and higher variations in canopy sizes and heights.

D. Spray Coverage

Mean spray coverage was from 1.8 to 34.7% for the constant application rate, and 1.9 to 41.1 % for the variable application rates (table 1). Relatively large CVs (72.4–73.1% and 55.0–64.6% for constant and variable rate application, respectively) at the horizontal inside center (HIC) were

Table 1 Mean spray coverage (%) from constant and variable rate applications

WPS positions	WSP height (m)	Evergreen 1		Evergreen 2	
		CRA*	VRA	CRA	VRA
HIC***	0	12.7	8.9	19.9	12.4
	0.75	4.9	3.0	4.6	5.1
	1.50	1.8	1.9	3.3	3.8
	2.25	4.4	5.4	6.9	2.4
	3.00	14.6	5.2	14.6	6.2
	Mean	7.7(A)**	4.9(A)	9.8(a)	6.0(a)
	CV****	73.1	55.0	72.4	64.6
HCE	0	25.5	20.2	29.4	24.8
	0.75	30.1	28.1	34.7	41.1
	1.50	24.6	34.2	32.3	31.8
	2.25	22.0	27.0	25.2	21.2
	Mean	25.6(A)	27.4(A)	30.4(a)	29.7(a)
	CV	13.2	21.0	13.4	29.4
LE	0	18.1	2.4	22.7	4.7
	0.75	24.0	3.4	23.6	2.9
	1.50	29.9	6.8	29.4	7.1
	2.25	25.2	6.5	28.0	6.3
	Mean	24.3(A)	4.8(B)	25.9(a)	5.3(b)
	CV	20.0	46.3	12.6	35.9
TE	0	7.4	6.1	8.3	4.5
	0.75	7.9	7.5	12.3	7.0
	1.50	17.8	9.8	19.0	14.3
	2.25	10.8	12.1	11.1	8.6
	Mean	11.0(A)	8.9(A)	12.7(a)	8.6(a)
	CV	43.7	29.4	35.9	48.0

* CRA and VRA refer constant and variable rate application, respectively.

** Letters in parenthesis indicate the row-wise mean comparison for WSP positions of each tree under variable and constant rate applications.

Statistically different ($P < 0.05$) means have different letters.

*** HIC, HCE, LE and TE refer horizontal inside center, horizontal center edges, leading edge and trailing edge.

****CV refers coefficient of variation in %.

observed in both applications simply because the sprayer lacked the penetration into dense evergreen canopy.

A significant ($P < 0.05$) coverage difference was identified at leading edge (LE). The significant ($P < 0.05$) difference might be due to lack of spray control for the constant rate application in the area without trees i.e. between or after trees. For example, variable rate sprayer stopped spraying when they passed LE of each canopy, however, the constant rate sprayer continued discharging spray, and a portion of discharged spray might drift to the LE. As a result, relatively higher coverage was observed at the LE for constant rate application. However, the rest of WSP positions (HIC, HCE and TE) had insignificant ($P > 0.05$) differences in mean spray coverage between two applications. The insignificant coverage difference between variable (VRA) and constant rate applications (CRA) implied that the application performance of VRA may be comparable with CRA. LSD values for evergreen #1 were 4.12, 8.00, 8.53 and 6.08% for HIC, HCE, LE and TE, respectively. Evergreen #2 has LSD values of 4.71, 9.12, 8.68 and 5.77 % for HIC, HCE, LE and TE, respectively.

4. CONCLUSION

An experimental variable rate liner sprayer was developed and tested. The sprayer used ultrasonic sensors to detect tree canopy, and PMW solenoid valve-coupled nozzles to control application rates. The sensors and nozzles were controlled by the custom-designed microcontroller.

Spray delay time, which compensates the leading distance of the sensor, was from 258 to 348 ms (mean: 296 ms) at 3.2 km/h. As a result, the sprayer triggered spray approximately 4.5 to 12.5 cm ahead of detected targets. Modulation DCs changed from 20 to 34 ms for the STC distances from 0.30 to 0.76 m. Over-application was generally observed during spray modulation, and thinner canopy liners might have the maximum over-application potential.

During the outdoor test, the sprayer triggered its nozzles approximately 1.8 to 9.8 cm ahead from detected canopy at 3.2 km/h. However, with the same spray coverage, the sprayer applied 58.4 to 85.2% spray volume of a constant rate application (937 L/ha). Mean spray coverage which measured with WSPs at four locations inside evergreen canopy ranged from 1.8 to 34.7% and 1.9 to 41.1% for the constant and variable rate applications, respectively. A significant ($P < 0.05$) difference in mean spray coverage was identified from

one of the four WPS locations between two applications.

ACKNOWLEDGEMENTS

Authors acknowledge A. Clark, K. Williams, and B. Nudd for their assistance through the research. Mention of proprietary product or company is included for the convenience of the readers and does not imply any endorsement or preferential treatment by USDA-ARS. This research was supported by USDA NIAR SCRI.

REFERENCES

- Balsari, P., G. Doruchowski, P. Marucco, M. Tamagnone, J. Van de Zonde, and M. Wencker. 2008. A system adjusting the spray application to the target characteristics. *Agricultural Engineering International: the CIGA Ejournal*. Manuscript ALNARP 08 002 Vol. X. May, 2008.
- Gil, E., A. Escolà, J. R. Rosell, S. Planas, and L. Val. 2007. Variable rate application of plant protection products in vineyard using ultrasonic sensors. *Crop Protection* 26:1287-1297.
- Giles, D. K., M. J. Delwiche, and R. B. Dodd. 1987. Control of orchard spraying based on electronic sensing of target characteristics. *Transactions of the ASAE* 30(6):1624-1630.
- Giles, D. K., M. J. Delwiche, and R. B. Dodd. 1988. Electronic measurement of tree canopy volume. *Transactions of the ASAE* 31(6):264-273.
- Jeon, H. Y., H. Zhu, R. C. Derksen, H. E. Ozkan, and C. R. Krause. 2011. Evaluation of ultrasonic sensor for variable-rate spray applications. *Computer and Electronics in Agriculture* 75(1):213-221.
- Moltó, E., B. Martín, and A. Gutiérrez. 2000. Design and testing of an automatic machine for spraying at a constant distance from the tree canopy. *Journal of Agricultural Engineering Research* 77(4):379-384.
- SAS. 2008. *SAS/STAT 9.2 User's Guide*. Cary, NC: SAS Institute Inc.
- Solanelles, F., A. Escolà, S. Planas, J. R. Rosell, H. Camp, and F. Gràcia. 2006. An electronic control system for pesticide application proportional to the canopy width of tree crops. *Biosystems Engineering* 95(4):473-481.
- Tumbo, S. D., M. Salyani, J. D. White, T. A. Wheaton and W. M. Miller. 2002. Investigation of laser and ultrasonic ranging sensors for measurement of citrus canopy volume. *Applied Engineering in Agriculture* 18(3):367-372.
- Tyco Electronics. 2009. The application of relay coil suppres-

- sion with DC relays. Application Notes 13C3311. Available at: http://relays.tycoelectronics.com/appnotes/app_pdfs/13c3311.pdf. Accessed 23 December 2009.
11. USDA. 2007. Agricultural Chemical Usage 2006 Nursery and Floriculture Summary. Washington, D.C.: USDA National Agricultural Statistics Service.
 12. Zaman, Q. U. and M. Salyani. 2004. Effects of foliage density and ground speed on ultrasonic measurement of citrus tree volume. *Applied Engineering in Agriculture* 20(2):173-178.
 13. Zhu, H., M. Salyani and R.D. Fox. 2010. A portable pixel recognition system for evaluating the distribution of spray deposits. ASABE paper No. 1008502. St. Joseph, Mich.: ASABE.