

Evaluation of novel ultrasonic sensor actuated nozzle in center pivot irrigation systems

Hadi A. Al-agele^{a,b,*}, Hisham Jashami^c, Chad W. Higgins^a

^a Department of Biological and Ecological Engineering and Water Resource Engineering, School of Engineering, Oregon State University, Corvallis 97331-3906, OR, USA

^b Department of Soil and Water Resource, College of Agriculture, Al-Qasim Green University, Al-Qasim District 964, Babylon, Iraq

^c Department of Civil Engineering, School of Engineering, Oregon State University, Corvallis 97331-3906, OR, USA

ARTICLE INFO

Handling Editor - J.E. Fernández

Keywords:

Angle of measurement
Arduino
Canopy height
Center pivots
HC-SR04 ultrasonic sensor
Sprinkler irrigation

ABSTRACT

Center pivot irrigation systems are used globally to irrigate large fields. They have higher water application efficiency than other sprinkler or surface irrigation approaches, but this water application efficiency may be further improved by dynamically adjusting the nozzle height in response to plant growth and canopy heterogeneities; this approach is referred to as dynamic elevation spray application (DESA). The key data input required to achieve DESA is the plant canopy height; however, this measurement is challenging to acquire in real-time due to canopy heterogeneity and potential interference from active water spray. An ultrasonic sensor was evaluated for this purpose. Both lab and field evaluations were conducted. Lab evaluations used view angles ranging from 0° to 35° at increments of 5°, and heights ranging from 0.5 m to 1.75 m for corn, clover, and potato. Field evaluations used view angles of 0° and 5°, and heights from 0.5 m to 1.25 m for green beans, green peppers, eggplants, grass, and ground. Regardless of plant type and height, results from the lab suggest that DESA sensor accuracy decreases about 0.5% with one unit increase in angle's degree. When corn was used, the sensor accuracy dropped almost 9%. Results for the field showed that the lowest accuracy (92%) was observed at the green beans with 1.25 height. Field tests with active water spray yielded significantly different measurements from without water spray, but still had accuracies > 97%. These findings demonstrate the feasibility of using ultrasonic sensors for DESA.

1. Introduction

Evaporative losses and wind drift contribute to reductions in water application efficiency in center pivot systems. Lower nozzle elevations reduce wind drift and evaporation losses (Rajan et al., 2015), but also reduce the sprinkler pattern overlap, either reducing uniformity or requiring more emitters. This also risks that the plant growth exceeding the nozzle elevation. Droplet size is inversely correlated with evaporation losses. Small droplets evaporate more readily than larger droplets. For example, 2% of 1.5-mm droplets were lost to wind drift and evaporation, while only 1% of 2.5-mm droplets were lost (Molle et al., 2012). This study was performed on the SupAgro farm in the region of Salon de Provence (south of the Rhone valley, France, Mediterranean climate). Molle et al. also attributed 30–50% of total losses to evaporation and 50–70% of losses to wind drift that pushed the droplets outside of the

target zone. When this happens, the uniformity of water application is reduced. Sadeghi et al. (2015) presents statistical relationships between water application efficiency and wind speed. Another advantage of DESA is that it has the potential to actually reduce consumptive use (i.e., ET). This form of efficiency gain can result in more water available for downstream water users in the watershed. This is in contrast to other approaches that exclusively reduce deep percolation (Perry et al., 2009). This paper investigates a new approach to reduce losses, Dynamic Elevation Spray Application (DESA), where the nozzle elevation is automatically adjusted with a microcontroller in response to changes in canopy height. These findings could help growers reduce water losses by using Dynamic Elevation Spray Application (DESA), where the nozzle elevation is automatically adjusted with a microcontroller in response to changes in canopy height. This approach requires that the canopy heights be monitored continuously with a sensor. In this paper, we

* Corresponding author at: Department of Soil Science and Water Resource, College of Agriculture, Al-Qasim Green University, Al-Qasim District 964, Babylon, Iraq.

E-mail addresses: alageleh@oregonstate.edu, Hadi.Abdulameer@agre.uoqasim.edu.iq (H.A. Al-agele), jashamih@oregonstate.edu (H. Jashami), chad.higgins@oregonstate.edu (C.W. Higgins).

<https://doi.org/10.1016/j.agwat.2021.107436>

Received 5 July 2020; Received in revised form 13 November 2021; Accepted 23 December 2021

Available online 31 December 2021

0378-3774/© 2021 Elsevier B.V. All rights reserved.

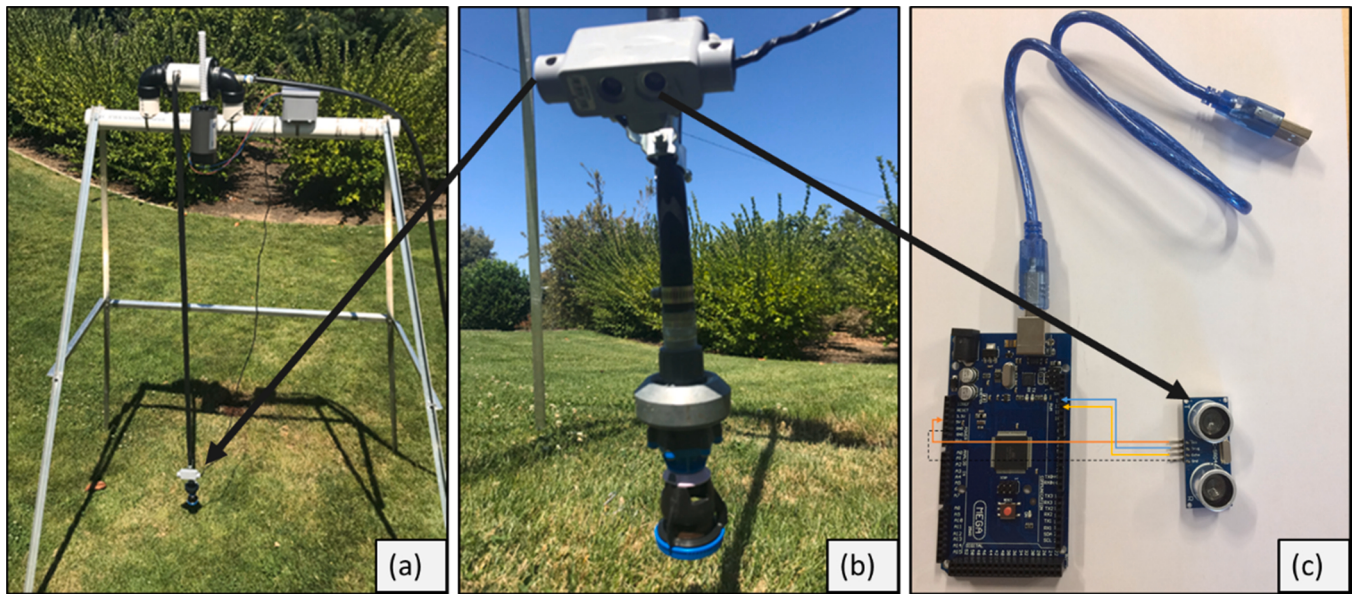


Fig. 1. a) A snapshot of the entire design assembly used for the sensor testing. b) The electronic sensor placed above the nozzle. c) Sensor and board assembly with circuit.

evaluate an acoustic distance sensor to measure canopy height. These sensors have been used to actuate pesticide and herbicide spray booms to improve application efficiency and uniformity. DESA should provide similar benefits for chemigation in overhead irrigation systems; however, actuation if the irrigation system represents a new challenge. The sensor must work while the nozzle is active, potentially contaminating the distance measurement.

2. Background

Ultrasonic distance sensors (model HC-SR04) have an established work history in agricultural and environmental applications (Arduino, 2015). Ultrasonic and laser measurements were used to measure citrus canopy volume compared to manual measurement methods (Tumbo et al., 2002), and had an $R^2 > 0.85$. Ultrasonic and LIDAR sensors were compared with the traditional manual and destructive canopy measurement procedure (Llorens et al., 2011). They found correlations between crop volume (CVU) values measured with ultrasonic sensors and leaf area index, LAI ($R^2 = 0.51$), and canopy volume measured with ultrasonic and LIDAR sensors ($R^2 = 0.52$). Balsari et al. (2008) used ultrasonic sensors to identify canopy target characteristics in terms of size and density to test a sprayer prototype. Guo et al. (2002) used ultrasonic sensors to detect any moving object in front of the vicinity of agricultural machinery in real-time to increase the safety sensing system. Ultrasonic distance sensors have been used to improve the efficiency of herbicide applications. When coupled with an RGB camera, a targeted and automated spray system used 20.2% less herbicide (Jejčić et al., 2011). Such sensors have been used for detection of water level (96.25% accuracy) in surface waters (Sarawati et al., 2012); early flood warning (Kuantama et al., 2013, 2012; Mohamed and Wei, 2014), and to detect the seed level in a seed tank (Sabanci et al., 2017). Additionally, these sensors have been used to safeguard pump sets by stopping pumps when water levels fall below the minimal operational levels (RANE, 2016). These ultrasonic distance sensors have also been used to provide input into robotics systems for miscellaneous agricultural operations (seeding, irrigation, weeding, fertilizing, etc.) (Agarwal and Thakur, 2016). Ultrasonic sensors have a vigorous design and a history of operation in an unfavorable working environment (humidity, vibration, dirt, temperature, fog) and have low costs when compared to other electronic circuits (Berntsen et al., 2006).

The center pivot has a history of continuous improvement to increase efficiency by reducing water evaporation, water loss, and energy usage. These improvements are achieved by increasing water application uniformity, reducing the system pressure, altering the drop-size distribution, or lowering the nozzle heights. Recently, Parod et al. (2018) patented a system that would adjust drop hose heights dynamically in response to canopy growth to reduce wind drift and evaporation losses, representing a next phase in the evolution of precision irrigation: dynamic elevation spray elevation application (DESA). The claim in the patent filing is that such systems would decrease water losses due to wind drift and evaporation. Al-agele et al. (2020) built a dynamic elevation spray application (DESA) prototype and demonstrated how pressure, flow rate, strike plate, and nozzle height impact the sprinkler pattern in the lab and field and compared these measurements to simulation. They found that wet diameter, overlap, and uniformity coefficient increased with heights and pressures; and that sprinkler pattern changes with increased pressures; the field measured CUs were lower than simulated but not significantly different.

The ultrasonic sensor is likely a good fit with DESA because of its history of canopy assessment and agricultural applications. The principle difference is that, in DESA, ultrasonic sensor measurements and irrigation are concurrent. The sensor must look through the spray. The objective of the present study is to evaluate the technical feasibility of DESA. This was achieved by performing a series of tests (lab, field, without the water spray, with spray) on canopy height measurements to determine the most accurate. Although there have been numerous studies on the environmental and agricultural application of the HC-SR04, the targeted application of canopy height measurements meant for dynamic nozzle height adjustment have not yet been studied. We seek to 1) evaluate the appropriateness of the sensor for a variety of canopy height measurements with different view angles and 2) quantify the error in the height measurement due to the water spray effect. We evaluate the technical feasibility by assessing the key data input into the feedback-control cycle for dynamic nozzle height.

3. Methodology

3.1. DESA components

DESA-enabled pivots would require that each nozzle (or bank of

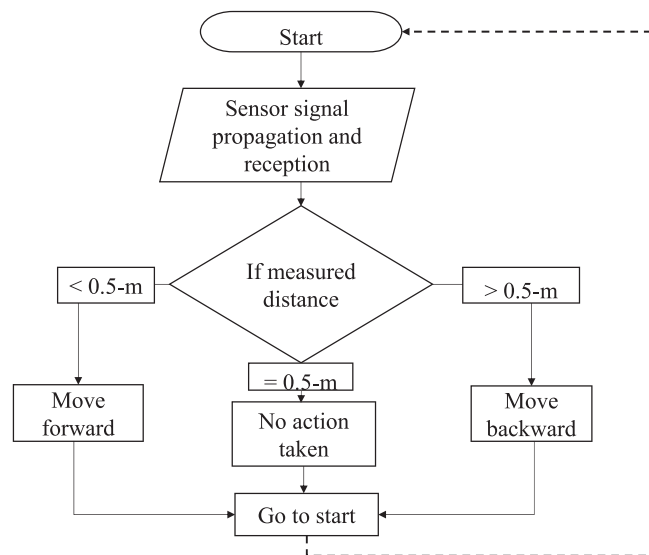


Fig. 2. Flowchart of the HC-SR04 ultrasonic sensor procedure.

Table 1

Descriptive statistics of mean sensor accuracy (%) for the lab experiment.

Variables	Descriptive statistics	Angle (°)			
		0.5-m	0.75-m	1.25-m	1.75-m
Ground	M	96.8	97.7	98.5	99.0
	(SD)	3.3	1.9	1.2	0.9
Corn	M	66.5	91.8	94.0	85.9
	(SD)	23.2	5.8	8.1	11.8
Clover	M	93.1	96.4	93.6	94.9
	(SD)	8.6	4.2	6.5	4.2
Potato	M	89.3	94.1	98.5	97.3
	(SD)	7.4	4.7	2.3	5.3

Table 2

Descriptive statistics of mean sensor accuracy (%) for the field experiment.

Variables	Descriptive statistics	0°			5°		
		0.50-m	0.75-m	1.25-m	0.50-m	0.75-m	1.25-m
Ground	M	98.6	98.6	99.7	97.9	98.8	96.2
	(SD)	1.9	1.4	0.4	1.8	0.9	5.0
Grass	M	98.5	98.9	99.1	98.9	97.8	99.4
	(SD)	1.6	1.5	1.1	1.1	2.1	0.6
Green Peppers	M	98.9	96.6	97.0	98.7	99.1	95.9
	(SD)	1.0	3.8	3.3	1.0	1.5	1.5
Eggplant	M	98.5	98.0	98.9	93.9	94.6	94.6
	(SD)	1.9	5.4	1.2	16.4	7.0	3.6
Green Beans	M	92.9	90.4	97.9	89.1	97.2	90.5
	(SD)	13.4	0.8	1.0	14.9	3.3	11.5

Table 3

Descriptive statistics of mean sensor accuracy (%) during irrigation.

Variables	Descriptive statistics	W/O Water spray			W/ Water spray		
		0°	5°	10°	0°	5°	10°
0.50-m	M	100	99.8	98.9	98.1	96.6	95.3
	(SD)	0	0.6	1.0	0.5	0.9	1.0
0.75-m	M	99.9	99.8	99.3	97.6	96.1	95.9
	(SD)	0.3	0.5	0.7	0.6	0.5	0.4
1.25-m	M	99.9	99.9	99.7	99.3	99.0	98.2
	(SD)	0.2	0.3	0.4	0.4	0.4	0.4
1.75-m	M	99.8	99.7	99.6	99.7	99.5	97.7
	(SD)	0.3	0.3	0.3	0.3	0.4	3.3

Table 4

Summary of GLM for the lab testing experiment.

Variables	Levels	A parameter estimate	P
Constant	–	101.5	< 0.001*
Angle	–	-0.3	< 0.001*
Height	0.50	Base	–
	0.75	-1.0	0.59
	1.25	-1.2	0.51
	1.75	-1.2	0.50
	Ground	Base	–
Plant Type	Corn	-17.2	< 0.001*
	Clover	0.4	0.84
	Potato	-2.2	0.22
Summary Statistics			
R-sq. (adj)	68%		
AIC	8377		
BIC	8545		

* Significant at the 95% confidence level.

associates nozzles) be associated with a sensor, microprocessor, and a motorized means to adjust the position of the nozzle head. The timescale of change is related to the length over which the change occurs, Δd , and the speed of travel of the irrigation system, ωR (for pivots), through the scaling equation $\Delta t < \Delta d/(\omega R)$, where ω is the rotation rate of the pivot and R is the outer radius of the pivot. Specifically, the built prototype uses an Arduino microcontroller connected to an ultrasonic sensor HC-SR04 module and DC motor. The motor rotates the drop-tube around a water swivel to raise or lower the nozzle's position. The entire system is controlled by a C++ program coded within the Arduino, which directs the operation of the sensors and DC motors. The system was constructed to carry out the system tests described below. We focused our effort on the low-cost sensor as it provides the critical data input and would be operated in new conditions. Photographs of the components and entirely constructed DESA prototype are presented in Fig. 1. The Arduino UNO R3 Mega 2560 (< \$15) was selected for the present study for sensor designs and control. The sensor is positioned 0.2 m above the nozzle to protect the sensor from the water, and all electronic parts are secured inside the high-density polymer enclosures. This basic design contains flange, 0.019 m (45°) elbow, 0.077 m (90°) elbow, PVC Expansion fitting, and other parts made by a laser cutter and a 3-D printer. For a detailed description of the prototype, see Al-agele et al. (2020).

3.2. HC-SR04 ultrasonic sensor

The HC-SR04 ultrasonic sensor works by measuring the time of flight of a high-frequency (40 kHz) sound wave echo. Madli et al. (2015) assessed the accuracy of the HC-SR04 and found it to be ± 0.2 m within a range of 4 m at an observation angle of $\leq 15^\circ$. The sensor experiments were conducted to test the sensor accuracy when measuring canopies. The principal concern is that the $\leq 15^\circ$ view angle constraint may be violated since the leaf angle distribution of a canopy can span all angles from 0° to 90° (Vicari et al., 2019). Thus, our experiment tested the sensor's performance for a variety of canopy observation angles.

The details of the sensor integration for controlling the motor and adjusting nozzle height is illustrated (Fig. 2). The nozzle is positioned at the height of (50 cm) with respect to the datum and 20 cm lower than the sensor position. Fig. 2 shows the details of signal transmission, and the algorithm (flow chart) followed to control the functioning of the motor.

3.3. Experimental design

3.3.1. Pilot testing

This experiment was first performed on the DESA prototype in the NEWAg lab at Oregon State University. Three prevalent summer crops (corn, clover, and potato) were grown, commencing from March 2017, with ten replicates for each individual observation angle. The HC-SR04

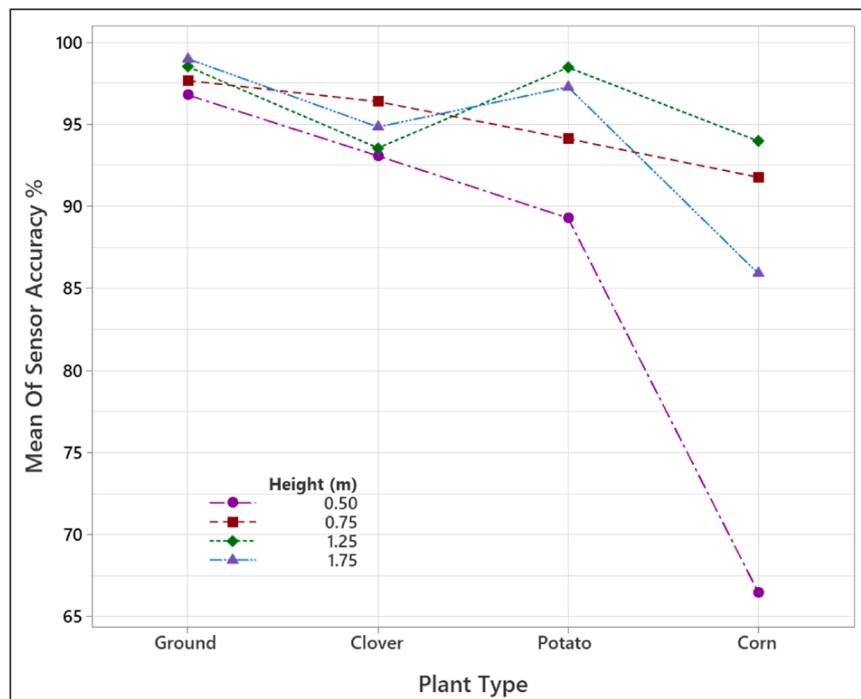


Fig. 3. Two-way interactions on mean sensor accuracy for plant type and height.

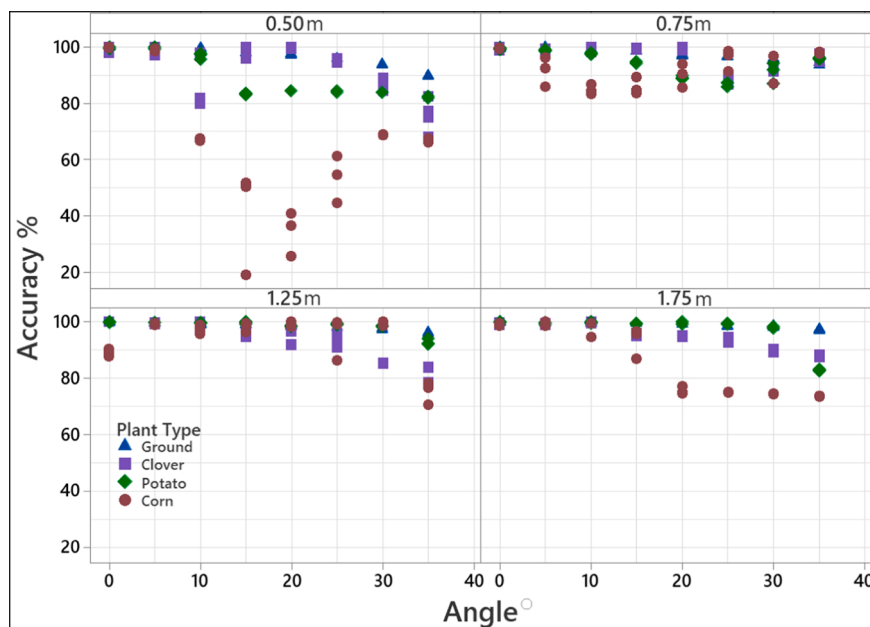


Fig. 4. Three-way interactions of sensor accuracy on the angle by height and plant type.

sensor was evaluated with respect to the datum (i.e., ground) before further tests and analysis of the canopy. A scientific ruler positioned orthogonal w.r.t datum was used for measurements and recording of the values for comparison and analysis. The testing was performed at eight view angles for each height. Heights were 0.5-m, 0.75-m, 1.25-m, and 1.75-m, and the sensor pitch angle was varied from 0° (straight down) to 35° at increments of 5° , measured using a digital level.

3.3.2. Field testing

Field measurement was performed using the DESA prototype at Oregon State University's horticultural fields. Four crops (green beans, green peppers, eggplant, and grass) and bare ground were measured on

Sep. 26-2019. These measurements were informed by the lab tests and concentrated on the view angles with high accuracy (0° , 5°) and three heights (0.5-m, 0.75-m, and 1.25-m). Ten replicate measurements were taken using the prototype (Fig. 1a) for each combination of canopy, height, and view-angle. The sensor was also tested with the irrigation system operating, and the water droplets passed through the sensor's line of sight. The canopy was wet prior to and during the measurements.

3.4. Data analysis

To evaluate how the sensor is accurate, Eq. (1) was used to create the dependent variable, which is sensor accuracy (SA), for further analysis

Table 5
Summary of ANOVA for the field-testing experiment.

Source of Variance	df	MS	F	P
Plant (ground, grass, eggplant, green beans, and green peppers)	4	194.89	5.92	< 0.001*
Height (0.5, 0.75, 1.25)	2	11.33	0.34	0.71
Angle (0, 5)	1	8.07	0.24	0.62
Plant×Height	8	90.08	2.74	0.006*
Plant×Angle	4	75.27	2.29	0.06*
Height×Angle	2	54.31	1.65	0.19
Plant×Height×Angle	8	152.90	4.64	< 0.001*
Error	870	32.93		

* Significant at the 95% confidence level.

of both lab and field tests:

$$\text{Sensor Accuracy (SA)} = 100 - ((\text{abs}(\text{observed measurment} - \text{actual height}) / \text{actual height}) \times 100) \quad (1)$$

For the lab test, a General Linear Model (GLM) was chosen for this experiment to explore the interactions between the independent variables (Jashami et al., 2020). GLM can easily accommodate categorical and continuous variables (Barlow et al., 2019). Three independent variables are included in the experiment: 1) plant type, which has four levels (ground, corn, clover, and potato); 2) four levels of height (0.5-m, 0.75-m, 1.25-m, and 1.75-m); and 3) Angle as a continuous variable. Table 1 shows the mean (M) and standard deviation (SD) values for SA for each level of every independent variable.

For the field test, a factorial design $5 \times 4 \times 2$ was chosen for this data set. Similarly to the lab experiment, three independent variables were included in the model: 1) plant type, which has five levels (ground, green beans, green peppers, eggplant, and grass); 2) three levels of height (0.5-m, 0.75-m, and 1.25-m); and 3) two levels of angle (0° and 5°). Recall that 0° is defined as sensor pointing directly downwards. Only two angles were used in the field test based on the lab's outputs, which will be discussed in the following section. Table 2 shows the mean (M) and standard deviation (SD) values for SA for each level of every independent variable. Data were analyzed in the R software package. All

tests were performed at a 95% confidence level. Three-way ANOVA was performed on the sensor accuracy to determine whether the average SA differed among the variables (Horne et al., 2019).

Finally, to test whether the accuracy of the sensor would be impacted during the irrigation time, three independent variables were also included while keeping the type of plant constant (ground only). The variables are height with the four levels, angle with three levels (0° , 5° , 10°), and method type with two levels (with water spray and without). Three-way ANOVA was also used to analyze this set of data. Table 3 shows the mean (M) and standard deviation (SD) values for SA for each level of every independent variable.

4. Analysis and results

4.1. Lab testing

A GLM was used to estimate the relationship between the independent variables and sensor accuracy. The results of the model are shown in Table 4. The R-squared was 68%, which suggests that the model was a good fit. Akaike's Information Criteria (AIC) and Bayesian Information Criteria (BIC) were used during the model selection process. The lower AIC or BIC indicates a better model. Table 4 shows the values of AIC and BIC for the presented model are 8376.80 and 8545.11, respectively,

Table 6
Summary of ANOVA during irrigation.

Source of Variance	df	MS	F	P
Method (without water, with)	1	52.27	73.66	< 0.001*
Height (0.5, 0.75, 1.25, 1.75)	3	0.32	0.45	0.71
Angle (0, 5, 10)	2	10.98	15.47	< 0.001*
Method×Height	3	16.45	23.19	< 0.001*
Method×Angle	2	11.67	16.44	< 0.001*
Height×Angle	6	1.79	2.52	0.020*
Method×Height×Angle	6	3.56	5.02	< 0.001*
Error	696	0.71		

* Significant at the 95% confidence level.

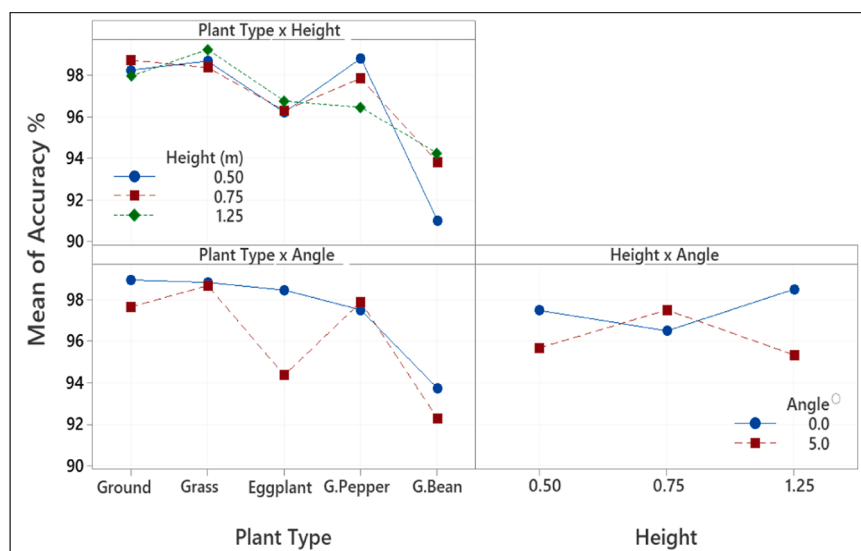


Fig. 5. Two-way interactions on mean sensor accuracy for plant type, angle, and height.

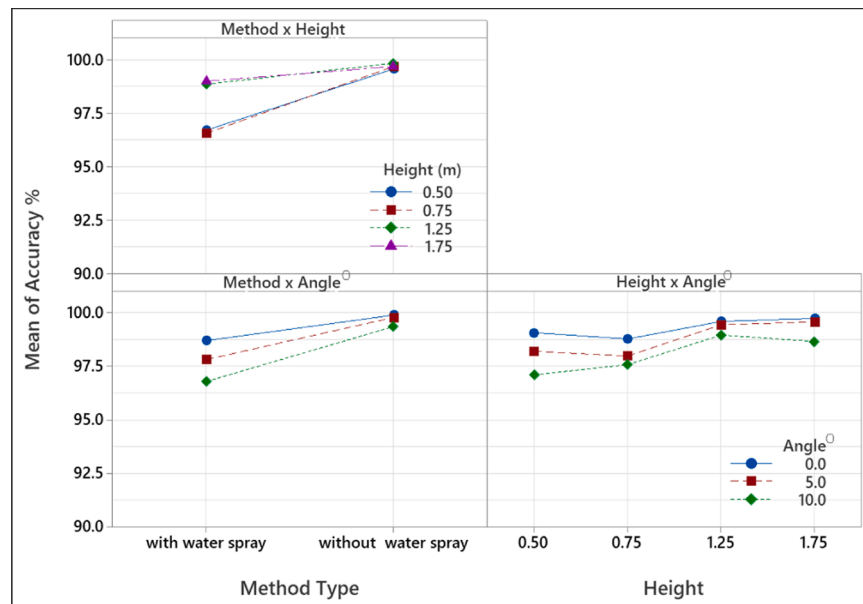


Fig. 6. Two-way interactions on mean sensor accuracy for method type, angle, and height.

which were lower than the model without the interaction effect (AIC = 9045.72 and BIC = 9091.97). The GLM for the lab testing experiment found that the height treatment was not statistically significant ($p > 0.05$) for all levels, but the angle was statistically significant ($p < 0.001$). One-unit (degree) increase in the angle, the sensor accuracy decreases by approximately half a percent. The plant type (the potato and clover level) when compared to the ground level, it was not statistically significant ($p\text{-value} > 0.05$), which suggests that the sensor accuracy was approximately similar across these types. On the other hand, corn was statistically significant ($p\text{-value} < 0.001$), and the sensor accuracy dropped almost 17% compared to ground level.

The interaction terms between the independent variables were also investigated. In the case of statistically significant effects, custom post hoc contrasts were performed for multiple comparisons using Tukey's HSD test (Horne et al., 2019). The interaction of plant and height, angle and plant, and the three-way interaction were statistically significant ($p\text{-value} < 0.001$ for all), but the interaction term between angle and height was not. Regardless of the angle, there is a strong probability that corn has lower accuracy (about 67%) at 0.5 m when compared to 0.75 m, 1.25 m, and 1.75 m (Fig. 3). The sensor accuracy was above 95% for the clover plant at 0.75 and 1.75, but the accuracy dropped almost to 93% when the height was at both 1.25 m and 0.5 m.

The three-way treatment interaction was visualized, as is shown in Fig. 4. Regardless of height and plant type, the lab experiment results showed that the sensor accuracy, on average, dropped below 85% when the 15° angle was achieved except with the corn plant. However, when the angle was below 10°, the sensor had 90% or higher accuracy for all plant types, including corn. In general, bare ground resulted in a lower loss of accuracy ($< 10\%$) with all heights and angles. The SA dropped from 90% to 80% for the potato when the height was changed from 1.25 m to 1.75 m at 35°. Hence, the angle seemed to affect the SA with the potato plant slightly. Finally, the 1.25 mm and 1.75 m height and above 20° angle generated less accuracy while testing the clover plant (around 80%).

4.2. Field testing

A 3-way ANOVA was used to estimate the relationship between the independent variables and sensor accuracy for the field experiment. The results of the model are shown in Table 5. The ANOVA results showed that the height and angle treatment were not statistically significant

($p > 0.05$ for both) for all levels, but the plant type was ($p < 0.001$). The two-way interaction resulted in two significant combinations between plant type and height ($p\text{-value} = 0.006$) and between plant type and angle ($p\text{-value} = 0.06$). Additionally, the three-way interaction was also significant ($p\text{-value} < 0.001$).

Fig. 5 plots the percentage mean SA at each level of the plant, height, and angle, as well as pairwise comparisons. Regardless of height, all types of plants had an average accuracy above 95% at both angles except for the green beans. Similarly, when the angle is held constant, the SA dropped to 91% with green beans at 0.5 m height compared to 0.75 m and 1.25 mm height. Overall, the sensor accuracy was above 90% at all treatments and their levels.

4.3. Field testing with irrigation

A 3-way ANOVA was used to estimate the relationship between the independent variables and sensor accuracy for the irrigation time. The results of the model are shown in Table 6. The ANOVA results showed that all independent variables and their two-way and three-way interactions were statistically significant ($p < 0.05$) except for the height variable ($p > 0.05$).

Fig. 6 plots the percentage mean SA at each level of method, height, and angle, as well as pairwise comparisons. Regardless of height, during the water spray method, the sensor accuracy was lower at 0°, 5°, and 10° angles than without water. Even though it was statistically different, the accuracy during water spray was 97%. Similarly, when the angle is held constant, the SA was lower (only 2%) during the water spray than without for all heights. In summary, the sensor accuracy was not altered much (minimum 96%) during the irrigation time for all heights (0.5 m to 1.75 m) and all angles (0–10°).

5. Discussion

Sensor accuracy generally decreases with increasing view angle, increasing distance, and spray activity. The highest fidelity between the set distance and the measured distance is achieved at low view angles for all heights.

The lab results show no significant differences between ground and clover and potato at $p\text{-value} > 0.05$. In comparison, corn had the lowest accuracy among all other plants. We attribute this to the top part of the canopies (the upper part) associated with clover and potato having a

relatively higher density than the top part (the upper part) of the corn canopy. Corn canopy height was measured with the lowest sensor accuracy across most view angles. We attribute this to the curved leaf shapes and less dense upper canopy relative to other crops. Lower view angles led to more accurate measurement across all crops and heights, generally. Our interpretation of these laboratory measurements led us to restrict the scope of the field tests to low view angles.

The performance of the sensor was diminished by 1.4% in field conditions relative to laboratory conditions. This is expected as wind, and other confounding factors are present in field conditions.

The sensor's performance was also diminished during active irrigation (statistically significant); however, this impact was less than the impact of viewing angle. The overall change was from > 99% accuracy (no spray) to > 97% with dynamic spray. We conclude that this impact, although statistically significant, is not sufficient to dismiss the acoustic sensor.

Our results indicate that view angles lower than 10° are more appropriate for crop canopy height (error increases 0.5% for every 1° increase in view angle). The above results are based on individual distance observations. Further improvements in accuracy can be made by averaging an ensemble of distance measures.

The information and data gathered by the DESA system may also have value to growers as it can be used to create dynamic maps of the canopy growth throughout the growing season, which could be used to identify locations of reduced vigor.

6. Conclusions

This work illustrates the potential of open, inexpensive, networked hardware combined with rapid prototyping in modern precision agriculture. Nozzle-level information and adaptive control are possible (and relatively inexpensive) with off-the-shelf components. DESA could also adapt to the presence of multiple crop canopies in a single field if a diverse planting were strategically advantageous to a grower.

Dynamic elevation spray application (DESA) is technically feasible. Canopy height can be measured with the low-cost HC-SR04 sensor. Canopy structure significantly impacts the accuracy of the distance measurements, and more crop varieties and canopy structures need to be investigated. The financial viability of DESA is still unknown, and future work will assess the costs and benefits of this approach.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was funded by NEWAg lab, Oregon State University. The authors would also like to thank John Selker, Maggie Graham, and Kyle Proctor for reviewing the paper; Alexander Krejci; Hayder Habeeb and Sahar Mamoori for their help during the laboratory tests; Jose Manuel and Christopher Michael Carlsen from Electronics Engineering at Opens Lab, BEE for assistance on code development, sensor assembly and 3-D printing at Oregon State University.

References

- Agarwal, N., Thakur, R., 2016. Agricultural robot: intelligent robot for farming. *Int. Adv. Res. J. Sci. Eng. Technol.* 3, 117–181.
- Al-agele, Hadi A., Mahapatra, D.M., Prestwich, Clarence, Higgins, C.W., 2020. Dynamic adjustment of center pivot nozzle height: an evaluation of center pivot water application pattern and the coefficient of uniformity. *Appl. Eng. Agric.* 36, 647–656.
- Arduino, S.A., 2015. Arduino. Arduino LLC.
- Balsari, P., Doruchowski, G., Marucco, P., Tamagnone, M., Van de Zande, J., Wenneker, M., 2008. A system for adjusting the spray application to the target characteristics. *Agric. Eng. Int. CIGR J.* 10, 1–12.
- Barlow, Z., Jashami, H., Sova, A., Hurwitz, D.S., Olsen, M.J., 2019. Policy processes and recommendations for unmanned aerial system operations near roadways based on visual attention of drivers. *Transp. Res. Part C: Emerg. Technol.* 108, 207–222.
- Berntsen, J., Thomsen, A., Schelde, K., Hansen, O.M., Knudsen, L., Broge, N., Hougaard, H., Hørfarter, R., 2006. Algorithms for sensor-based redistribution of nitrogen fertilizer in winter wheat. *Precis. Agric.* 7, 65–83. <https://doi.org/10.1007/s11119-006-9000-2>.
- Guo, L., Zhang, Q., Han, S., 2002. Agricultural machinery safety alert system using ultrasonic sensors. *J. Agric. Saf. Health* 8, 385–396.
- Horne, D., Jashami, H., Hurwitz, D.S., Monsere, C.M., Kothuri, S., 2019. Mitigating roadside noise pollution: a comparison between rounded and sinusoidal milled rumble strips. *Transp. Res. Part D: Transp. Environ.* 77, 37–49.
- Jashami, H., Hurwitz, D.S., Monsere, C.M., Kothuri, S., 2020. Do drivers correctly interpret the solid circular green from an exclusive right-turn bay? *Adv. Transp. Stud.*
- Jejić, V., Godeša, T., Hočevár, M., Širok, B., Malneršič, A., Štancar, A., Lešnik, M., Stajnik, D., 2011. Design and testing of an ultrasound system for targeted spraying in orchards. *Vestn. J. Mech. Eng.* 57, 587–598. <https://doi.org/10.5545/sv-jme.2011.015>.
- Kuantama, E., Setyawan, L., Darma, J., 2012. Early flood alerts using short message service (SMS). In: *Proceedings of the 2012 International Conference on System Engineering and Technology (ICSET)*. IEEE, pp. 1–5.
- Kuantama, E., Mardjoko, P., Saraswati, M.A., 2013. Design and construction of early flood warning system through SMS based on SIM300C GSM modem. In: *Proceedings of the 2013 3rd International Conference on Instrumentation, Communications, Information Technology and Biomedical Engineering (ICICI-BME)*. IEEE, pp. 115–119.
- Llorens, J., Gil, E., Llop, J., 2011. Ultrasonic and LIDAR sensors for electronic canopy characterization in vineyards: advances to improve pesticide application methods. *Sensors* 11, 2177–2194. <https://doi.org/10.3390/s110202177>.
- Madli, R., Hebbbar, S., Pattar, P., Golla, V., 2015. Automatic detection and notification of potholes and humps on roads to aid drivers. *IEEE sensors journal* 15 (8), 4313–4318.
- Mohamed, A.R.A., Wei, W.G., 2014. Real time wireless flood monitoring system using ultrasonic waves. *Int. J. Sci. Res.* 3, 2319–7064.
- Molle, B., Tomas, S., Hendawi, M., Granier, J., 2012. Evaporation and wind drift losses during sprinkler irrigation influenced by droplet size distribution. *Irrig. Drain.* 61, 240–250.
- Parod, R.W., Provaznik, R.E., Cook, K.I., 2018. Automated Adjustable Drop Hose for Mechanized Irrigation.
- Perry, C., Steduto, P., Allen, R.G., Burt, C.M., 2009. Increasing productivity in irrigated agriculture: agronomic constraints and hydrological realities. *Agric. Water Manag.* 96, 1517–1524. <https://doi.org/10.1016/j.agwat.2009.05.005>.
- Rajan, N., Maas, S., Kellison, R., Dollar, M., Cui, S., Sharma, S., Attia, A., 2015. Emitter uniformity and application efficiency for centre – pivot irrigation systems. *Irrig. Drain.* 64, 353–361. <https://doi.org/10.1002/ird.1878>.
- RANE, S., 2016. Automated irrigation system using X-Bee and labview. In: *Proceeding of the 3rd International Conference on Electrical, Electronics, Engineering Trends, Communication, Optimization and Sciences (EEECOS)*.
- Sabancı, K., Unleren, M.F.U., Aydin, C., 2017. Determination of seed volume in the seed tank of pneumatic precision seeder by using microcontroller based control system. *Int. J. Appl. Math. Electron. Comput.* 5, 7–11.
- Sadeghi, S.H., Peters, T.R., Amini, M.Z., Malone, S.L., Loescher, H.W., 2015. Novel approach to evaluate the dynamic variation of wind drift and evaporation losses under moving irrigation systems. *Biosyst. Eng.* 135, 44–53. <https://doi.org/10.1016/j.biosystemseng.2015.04.011>.
- Saraswati, M., Kuantama, E., Mardjoko, P., 2012. Design and construction of water level measurement system accessible through SMS. In: *Proceedings of the 2012 Sixth UKSim/AMSS European Symposium on Computer Modeling and Simulation*. IEEE, pp. 48–53.
- Tumbo, S.D., Salyani, M., Whitney, J.D., Wheaton, T.A., Miller, W.M., 2002. Investigation of laser and ultrasonic ranging sensors for measurements of citrus canopy volume. *Applied Engineering in Agriculture* 18 (3), 367–372.
- Vicari, M.B., Pisek, J., Disney, M., 2019. New estimates of leaf angle distribution from terrestrial LiDAR: comparison with measured and modelled estimates from nine broadleaf tree species. *Agric. For. Meteorol.* 264, 322–333.