Development and Performance Testing of a Variable-Rate Spray Control System Based on Target Leaf Area Density Parameters: Postprint

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Abstract

Variable-rate spray technology is one of the important means to improve pesticide utilization efficiency and reduce pesticide usage. To achieve the goal of reducing pesticide usage while improving efficacy in orchard spraying, this study developed a variable-rate spray control system and proposed a calculation method for leaf area density parameters and the Pulse Width Modulation (PWM) duty cycle of actuators. In this system, the host computer utilizes point cloud density detected by a LiDAR sensor to characterize leaf area density as the spraying parameter, and calculates the PWM duty cycle of the solenoid valve corresponding to each nozzle based on the spray prescription. This prescription is transmitted in real-time via RS485 communication to the Programmable Logic Controller (PLC) of the slave computer, which controls the switching frequency of the corresponding solenoid valve according to the received PWM duty cycle to regulate the spray flow rate of the nozzle. Three key system parameters were measured through experiments: spraying unit grid size, system delay time, and model parameters for the relationship between PWM duty cycle and nozzle flow rate. The results demonstrated that under pressures of 0.2, 0.3, and 0.4 MPa, the relationship between PWM duty cycle and nozzle flow rate was linear, with coefficients of determination all above 0.98. Finally, the effectiveness of the variable-rate spray prototype was validated through spray tests. The test results indicated that the minimum number of droplets per unit area (cm^2) on water-sensitive paper at sampling points was 35, achieving effective spraying. When the ratio of target canopy width to total canopy width was 39.9%, the variable-rate spray mode reduced pesticide usage by 71.96% compared to continuous constant spraying, and by 29.72% compared to target-switching spraying, thereby achieving the pesticide reduction effect.

Development and Performance Test of Variable Spray Control System Based on Target Leaf Area Density Parameter

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Abstract: Variable spray technology is an important means to improve pesticide utilization and reduce pesticide consumption. To achieve pesticide reduction and efficiency improvement in orchard applications, this study developed a variable spray control system and proposed calculation methods for leaf area density parameters and the pulse width modulation (PWM) duty cycle of actuators. In this system, the upper computer uses point cloud density detected by a LiDAR sensor to characterize leaf area density as the spraying parameter. Based on the spray prescription, it calculates the PWM duty cycle for each solenoid valve corresponding to each nozzle, and transmits the prescription in real-time via RS485 communication to the lower computer's programmable logic controller (PLC). The lower computer then controls the switching frequency of the corresponding solenoid valves based on the received PWM duty cycle to regulate the spray flow of each nozzle. Three key system parameters were measured through experiments: the spray unit grid size, system delay time, and model parameters between PWM duty cycle and nozzle flow. The results showed a linear relationship between PWM duty cycle and nozzle flow under pressures of 0.2, 0.3, and 0.4 MPa, with linear goodness-of-fit values all above 0.98. Finally, spray tests verified the effectiveness of the variable spray prototype. The test results indicated that the minimum number of droplets per unit area (cm^2) on water-sensitive paper at sampling points was 35, exceeding the 25 droplets defined for effective spray coverage in conventional air-assisted sprayers. When the ratio of target canopy width to total canopy width was 39.9%, the variable spray mode saved 71.96% of pesticide compared to continuous constant spraying, and 29.72% compared to target-switch spraying, achieving significant pesticide reduction.

Keywords: variable spray; LiDAR; leaf area density; control strategy; pulse width modulation

1 Introduction

Currently, pest and disease control in Chinese orchards relies primarily on chemical pesticides. Traditional constant-rate, continuous spraying methods cause severe waste of chemical solutions, with runoff affecting orchard environmental safety, ecological security, and operator health [1]. Precision variable-rate spraying technology is an important means to save pesticide and improve utilization, reducing pesticide consumption by over 25% compared to conventional continuous spraying methods [2-4].

Precision variable-rate spraying technology adjusts spray volume in real-time based on crop canopy information to achieve pesticide savings and on-demand application [2,5-7]. Sensor-based non-destructive detection technology is fundamental to precision spraying. Researchers have conducted relevant studies on fruit tree target detection using infrared sensors [8,9], ultrasonic sensors [10-12], Light Detection and Ranging (LiDAR) sensors [13,14], and stereo vision [15,16]. Rosell and Sanz [17] comprehensively summarized the advantages and disadvantages of these detection sensors, noting that 2D LiDAR offers high detection accuracy and speed, making it one of the most promising application technologies. Liu and Zhu [18] used LiDAR sensors to detect the shape contours of complex targets. Li Qiujie et al. [19] employed 2D LiDAR sensors to detect the distance to the canopy center and calculate canopy volume.

Accurate detection of fruit tree targets and extraction of precise spraying parameters are prerequisites for providing spray prescriptions to variable-rate spraying control systems. With breakthroughs in detecting external characteristic information such as orchard target position and shape contour, future research directions will focus on internal characteristics like branch and leaf density distribution [20]. Sanz et al. [21] used 2D LiDAR to construct 3D point cloud maps of targets, finding a strong linear relationship between the number of laser points on canopy branches and leaves and the actual leaf area. Palleja and Landers [11,12] detected vineyards and apple orchards using ultrasonic sensors, demonstrating a positive correlation between ultrasonic echo intensity and target branch/leaf density. Li Longlong et al. [22] used unit volume and density models as the basis for adjusting fog and air volume, developing an automatic adjustment orchard air-assisted sprayer. Test results showed the sprayer met orchard pest control requirements. Li Qiujie et al. [23] proposed a method for calculating leaf area density based on mobile LiDAR technology, establishing a linear regression model between total grid area and actual leaf area with a goodness-of-fit of 0.9090. Xue Xiuyun et al. [24] designed a variable-rate spraying system for fruit trees based on Leaf Wall Area (LWA), combining point cloud density and partition area within zones to adjust pesticide application in real-time. Test results proved this spraying model achieved effective spraying while saving 68.34% of pesticide compared to continuous constant spraying.

Research on calculating sprayer application parameters based on target leaf area density is still in its early stages both domestically and internationally. Therefore, this study designed a spray control system that adjusts spray volume in real-time based on target leaf area density information. By transplanting it onto a traditional sprayer, the study conducted experimental research to verify the pesticide reduction and efficiency improvement effects of the new precision variable-rate air-assisted sprayer.

2 Variable Spray System Structure

2.1 Hardware System Structure

The overall structure of the variable spray system is shown in Figure 1 [Figure 1: see original paper], consisting of three main components: a target detection system, a spray control system, and a spray system. The LiDAR sensor in the target detection system is used to detect fruit tree targets, while the PC serves as the upper computer for sensor data acquisition and processing. The programmable logic controller (PLC) in the spray control system acts as the lower computer, receiving spray prescriptions from the upper computer and controlling relay-driven solenoid valve actions. The spray system maintains constant pesticide supply and achieves variable-rate spraying under controller action.

The spray system divides the liquid flow into three stages, as shown in Figure 2 [Figure 2: see original paper]. First, the solution in the tank is pumped out by the diaphragm pump. At the primary flow divider, it splits into two parts: one flows into the main pipeline, while the other returns to the tank through a jet device to agitate the solution. Then, the solution in the main pipeline flows through the secondary flow divider (5-way pipe splitter) into five branch pipelines. Finally, the solution in the branch pipelines is divided by the tertiary flow divider into 22 pipelines (11 atomization units on each side) and delivered to each atomization nozzle via solenoid valves. In the system, the 22 nozzles are divided into five groups by height to reduce pressure differences between nozzles at the same height on both sides. The distance between the 22 solenoid valves and nozzles is within 0.1-0.2 m to reduce spray lag caused by long liquid transport pipelines.

The platform for the variable spray system is an M604L-E Lovol tractor mounted with a 3WGF-500A suspended air-assisted sprayer. The modified variable spray prototype is shown in Figure 3 [Figure 3: see original paper], including a LiDAR sensor (LMS111-10100), incremental encoder (DBS36E), diaphragm pump (MB480/3.0), 5-way pipe splitter (SKD), pressure sensor (0-1.0 MPa), solution tank (500 L), atomization units (including trial pipelines, solenoid valves, and atomization nozzles), PLC controller (S7-200 Smart), power supply (24VDC), and other components.

2.2 Software System Structure

The software system includes upper computer software and lower computer software. The upper computer software was developed using Visual Studio 2019 and Microsoft Foundation Class (MFC) multi-threaded programming technology, comprising three threads: a dialog main thread, a data processing thread, and a serial communication thread. The dialog thread handles human-machine interface display and spray parameter settings; the data processing thread processes LiDAR point cloud data and calculates application parameters; and the serial communication thread handles data communication between upper and lower computers. The lower computer software was developed using STEP 7-MicroWIN SMART, including data acquisition from the encoder and pressure sensor and generation of control signals. The upper computer' s COM port connects to the lower computer' s RS485 physical port, establishing communication following the Modbus RTU protocol. The developed user interfaces for upper and lower computers are shown in Figure 4 [Figure 4: see original paper].

2.2 Variable Spray System Control Method

Compared with constant continuous sprayers, variable-rate sprayers enable individual nozzle flow control. Based on the hardware and software platform, the variable spray system control method adjusts the flow of corresponding nozzles in real-time according to leaf area density changes within the target application area for each nozzle, thereby achieving variable-rate spraying. Nozzle flow control employs Pulse Width Modulation (PWM) technology, which does not require changing spray system pressure and has minimal impact on spray characteristics. Before sprayer operation, the target area must be divided into grids based on nozzle spray width. Each grid unit is a spray unit with the same volume but different internal leaf area densities. The following sections elaborate on the leaf area density calculation method within spray units and the PWM duty cycle calculation method for actuator solenoid valves.

2.2.1 Leaf Area Density Calculation Method for Spray Units

Fruit tree targets are three-dimensional spaces where branch and leaf densities vary by location within the canopy at the same time. The ideal spraying state adjusts application volume according to local density. The target grid schematic is shown in Figure 5 [Figure 5: see original paper]. The grid parameters to be determined are height H and transverse width W. The height division principle is generally based on the number of nozzles corresponding to the target area. If the sprayer has N nozzles on one side and the canopy height is H1, the canopy is evenly divided into N regions in the y-direction, giving h = H1/N. The transverse width W is determined through spray testing.

Previous research by the team established that, assuming relatively small leaf area changes within each spray unit, the leaf area density parameter can be calculated through coefficient transformation based on a determined functional equation between point cloud count and leaf count [25]. Therefore, by calculating the cumulative point cloud count k_i (i = 1, 2, ···, n) within each spray unit, the leaf area density parameter _i can be obtained as:

 _i = f(k_i)

The number of point clouds in the target area is affected by LiDAR sensor scanning frequency, prototype operating speed, distance from LiDAR sensor to target, and operating environment. The sensor frequency is fixed, and the non-uniform distribution of 3D point cloud data caused by uneven sprayer speed along the tree row centerline has been compensated using interpolation algorithms from the team’ s previous research [26].

2.2.2 PWM Duty Cycle Calculation Method

More point clouds within a spray unit indicate more leaves and denser canopy, requiring greater spray volume. The maximum application volume Q_{max} (in L) corresponds to the maximum leaf area density _{max}. The application volume for each spray unit is:

Q_i = Q_{max} × (_i / _{max}), i = 1, 2, ···, n

where Q_i is the total pesticide volume applied to the region (L).

The nozzle flow rate q_i (in L/min) for a spray unit is the ratio of Q_i to operation time t:

q_i = Q_i / t, i = 1, 2, ···, n

Drawing on relevant research experience, a linear relationship exists between individual nozzle flow rate q_i and duty cycle X_i [27,28]:

q_i = aX_i + b, i = 1, 2, ···, n

where a is the slope and b is the intercept.

From equations (2)-(4), the PWM duty cycle calculation formula for the solenoid valve controlling the corresponding nozzle is:

X_i = (Q_{max} × f(k_i) / (f(k_{max}) × t) - b) / a, i = 1, 2, ···, n

where k_{max} is the maximum number of laser points that can be output when the LiDAR output frequency is determined; k_i is calculated in real-time based on sensor feedback data; Q_{max} is determined by sprayer pressure and nozzle model; and a and b are obtained by fitting linear functions from spray test data.

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3 Key Parameter Measurement Tests

The variable spray control system comprises multiple modules. Before integrated testing, key parameters must be determined through experiments, including spray unit grid size, system delay time, and model parameters between PWM duty cycle and nozzle flow.

3.1.1 Spray Unit Grid Size

The transverse width W of the spray unit was measured through static spraying onto a mesh screen. The mesh effectively filters small drifting droplets during spraying, with grid dimensions of 1.1 mm × 1.1 mm. Based on an orchard row spacing of 5 m, the test set the mesh screen at 2.5 m from the sprayer prototype center, as shown in Figure 6 [Figure 6: see original paper]. After the sprayer operated for a period, the width of the droplet coverage area was manually measured. Taking the average of three tests, the measured transverse width W of the spray unit was 0.45 m.

3.1.2 System Delay Time

Accurate real-time calculation of dynamic delay time is essential for achieving precise variable spraying. Dynamic spray delay time is determined by spray system response time, distance between LiDAR sensor and nozzle, and sprayer operating speed. The dynamic delay time calculation formula is:

T_{py} = tsysterm + L / v

where T_{py} is the system delay time (s), L is the distance between LiDAR sensor and nozzle (m), tsysterm is the spray system response time (s), and v is the sprayer operating speed (m/s). The dynamic spray delay is implemented via software timer, requiring L/v > tsysterm.

The spray system response time tsysterm was measured using a high-speed camera set at 2000 frames/s with a shutter speed of 1/20,000 s. It was obtained by calculating the frame difference between when the light spot just disappeared from the imaging area and when the nozzle fully ejected spray, as shown in Figure 7 [Figure 7: see original paper]. Taking the average of three tests, tsysterm was measured as 0.154 s.

3.1.3 Model Identification Between PWM Duty Cycle and Nozzle Flow

The solenoid valve in the system has a fixed frequency of 10 Hz, and the nozzle is a German Lecher No. 4 cone nozzle. Under spray pressures of 0.2, 0.3, and 0.4 MPa, a nozzle flow meter measured nozzle flow rates at different PWM duty cycles (0%-100% in 10% increments). The test results are shown in Figure 8 [Figure 8: see original paper].

The results showed that at 10% duty cycle, the solenoid valve closed and nozzle flow was 0, because the current 接通 time within the unit period was too short to drive the solenoid valve. At constant spray pressure, PWM duty cycle (20%-80% range) showed a good linear relationship with nozzle flow. At 80%-100% duty cycle, spray flow increased slowly, with linear goodness-of-fit values all above 0.98. Model equations were obtained through linear fitting at different pressures.

At 0.2 MPa pressure: $q = 0.011X + 0.1539$, $R^2 = 0.9861$

At 0.3 MPa pressure: $q = 0.0143X + 0.1272$, $R^2 = 0.9847$

At 0.4 MPa pressure: $q = 0.016X + 0.1735$, $R^2 = 0.9841$

3.2 Spray Performance Verification Test

3.2.1 Test Conditions

Variable spray performance verification tests were conducted at the Institute of Agricultural Facilities and Equipment, Jiangsu Academy of Agricultural Sciences. The test orchard measured 9 m in length with a row spacing of 5 m. The measurement indicators included droplet deposition coverage density and spray volume.

The fruit tree targets consisted of six simulated trees divided into three groups with canopy dimensions of 1.2 m × 1.1 m, 1.3 m × 1.2 m, and 1.2 m × 0.8 m. Within the 2.4 m height range of the canopy area, eight nozzles (Nos. 3-10) on one side of the sprayer corresponded to the target, while nozzles 1, 2, and 11 were set to closed status. Spray system parameters were set as follows: spray pressure 0.4 MPa; spray unit grid size 0.45 m × 0.30 m; tractor speed approximately 0.34 m/s.

3.2.2 Test Materials and Methods

The main test materials included the variable-rate air-assisted sprayer, an SP500 3D wind speed and direction automatic recorder, a WatchDog 2900ET weather station, and water-sensitive paper (35 mm × 110 mm) with droplet scanning analysis software. The specific implementation steps were:

(1) Before testing, use an anemometer to measure the test environment to ensure testing under 0-level wind conditions (calm wind, wind speed less than 0.2 m/s). Use the weather station to measure ambient temperature and humidity, ensuring humidity below 80% during testing.

(2) Layout according to standard orchard row spacing of 5 m × 3 m, with 3 m spacing between the three target groups. The sprayer center position was 2.5 m from the targets, with a spray length of 9 m, as schematically shown in Figure 9 [Figure 9: see original paper].

(3) Water-sensitive paper layout. The target canopy was divided into four layers according to the number of nozzles used, with three water-sensitive papers placed in each layer (12 papers per target group). Papers were fixed to simulated leaves using paper clips. Papers were numbered 1-12 from top to bottom and left to right. To verify variable effects, the spacing between horizontally arranged papers needed to be greater than 0.45 m.

The water-sensitive paper layout is shown in Figure 10 [Figure 10: see original paper].

(4) During testing, the LiDAR sensor was activated 1 m before the simulated trees and deactivated 0.5 m after. Tap water was used as the test solution.

(5) After testing, once droplets had completely wet the water-sensitive papers, disposable gloves were worn to hold the edges of the papers and place them in dry sealed bottles. Direct hand contact was avoided during collection as it could affect data calculation results.

3.2.3 Test Results and Analysis

(1) **Variable spray droplet deposition coverage density analysis.** According to the national standard "Plant Protection Machinery—General Test Methods" (JB/T 9782-2014) [29], air-assisted spraying uses 25 droplets/cm^2 as the threshold for effective spray determination. Water-sensitive paper samples after variable spray system testing are shown in Figure 11 [Figure 11: see original paper].

Water-sensitive paper droplet scanning analysis software can automatically scan the total number of droplets per unit area on the paper, droplet deposition amount per unit area, and droplet count within selected regions. Data analysis results showed that the minimum number of droplets per unit area (cm^2) collected on water-sensitive paper was 35, exceeding the 25 droplets defined for effective spray coverage in conventional air-assisted sprayers, thus achieving effective spray coverage.

(2) **Variable spray volume analysis.** The spray volumes under three operating modes—continuous constant spraying, target-switch spraying, and variable spraying—were compared and analyzed. During testing, PWM duty cycle variations for nozzles 3-10 were recorded and saved as *.txt files. Three tests were conducted, with spray volumes from each nozzle collected in sealed bags during testing. The total spray volume was the sum of individual nozzle volumes, with the average of three measurements taken as the final total spray volume.

The test layout was 9 m in total length with a target canopy width of 1.2 m, giving a ratio of simulated tree target canopy width to total canopy width of 39.9%. Table 1 shows the spray volumes for continuous constant spraying, target-switch spraying, and variable spraying.

Table 1 Spray quantity of three spray modes

Spray Mode	Spray Volume (L)
Continuous constant spraying	7.23
Target-switch spraying	2.88
Variable spraying	2.02

Calculations from Table 1 show that compared to continuous constant spraying, the variable spray mode saved 71.96% of pesticide. Compared to target-switch spraying, it saved 29.72%.

Meanwhile, PWM duty cycle variations for nozzles 3-10 are shown in Figure 12 [Figure 12: see original paper]. Nozzles 3 and 6 had similar PWM duty cycle values, as did nozzles 4 and 5, with nozzles 3 and 6 having lower duty cycles than nozzles 4 and 5. Observing the target canopy, the canopy areas corresponding to nozzles 3 and 6 had more gaps, while those corresponding to nozzles 4 and 5 had fewer gaps. Nozzle 7 had a smaller duty cycle, as it only partially corresponded to the target according to the segmentation method. Nozzles 8-10 had zero duty cycle, as there was no target at the corresponding height according to the segmentation method. These nozzle PWM duty cycle variations conformed to the density distribution of the target canopy.

4 Conclusions and Outlook

This study designed and developed a variable spray control system and successfully transplanted it onto a traditional orchard air-assisted sprayer, achieving variable spraying based on target leaf area density changes. The spray performance of this variable spray control system was verified and evaluated. The main conclusions are:

(1) A hardware and software development scheme for variable-rate sprayers was proposed, efficiently integrating LiDAR sensors, PLC controllers, and a spray system capable of variable flow output.

(2) A control method for the variable spray system was proposed. Point cloud density within target spray units can be converted to leaf area density parameters through functional calculation. Based on the principle that higher leaf area density requires greater spray volume, a nozzle flow calculation method based on leaf area density was derived. The final control variable—PWM duty cycle calculation method—was obtained through model identification.

(3) The spray performance of the variable-rate sprayer was verified through testing. Results showed that water-sensitive paper sampling analysis measured a minimum of 35 droplets per unit area (cm^2), achieving effective spray coverage. When the ratio of target canopy width to total canopy width was 39.9%, the variable spray mode saved 71.96% of pesticide compared to continuous constant spraying and 29.72% compared to target-switch spraying.

The variable-rate sprayer developed in this study is a first-generation prototype that requires further field testing verification and optimization improvements, mainly including:

(1) Integrating Beidou autonomous navigation system to enable autonomous navigation driving of the variable-rate sprayer, eliminating LiDAR ranging errors caused by manual operation deviating from the centerline trajectory between tree rows, and further improving the measurement accuracy of the target detection system.

(2) Field operating environments are harsh with uneven road surfaces, causing significant speed variations. Integrating multiple sensors such as Beidou navigation system and encoders to measure sprayer operating speed can calculate more accurate system delay times and improve the real-time performance and targeting accuracy of the entire variable spray system.

(3) Further testing and evaluation of variable-rate sprayer performance, including measurement parameters such as droplet distribution density, droplet deposition amount, and droplet drift amount.

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