

Feedback regulation system for spraying parameters based on online droplet mass deposit measurements

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Abstract: In order to effectively optimize and regulate spraying parameters based on actual spraying performance and improve pesticide utilization rate, in this research, a feedback regulation system for the regulation of spraying parameters was designed based on droplet mass deposit online measurement. The system consisted of an online droplet mass deposit measurement module, wireless transmission module, decision module, and spraying parameters regulation module. First, the droplet mass deposits on the sampling points were measured. Based on the deviation between the measured and expected droplet mass, the expected spraying parameters were determined by the decision module. The spraying parameter was regulated to the expected value by regulating the pulse duty cycle on the pump motor using a micro control unit and a relay. Evaluation tests were conducted indoors using an indoor spraying platform and outdoors using an unmanned aerial vehicle. The results showed that the relative errors between the expected and measured droplet mass deposit after regulation were 6.84% and 11.48% for the indoor and outdoor tests, respectively. Therefore, an optimal spraying performance was observed after regulation. This research provided an experimental platform to quickly optimize spraying parameters and also provided technical references for precision spraying.

Keywords: spray, droplet mass deposit, online measurement, wireless transmission, duty cycle, feedback regulation

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1 Introduction

Variable-rate spraying is an important technique in precision pesticide application^[1]. The variable-rate spraying technique can regulate the spraying flow rate automatically based on the detection of the sprayer velocity, crop feature, degree of diseases, and insect pests^[1-4]. And the variable-rate spraying technique can thereby reduce pesticide residues and environmental pollution^[1]. The variable-rate spraying technique has become an important development direction for pesticide application^[5,6].

Researches on the variable-rate spraying can be divided into two categories^[1].

One category is based on the crop prescription map method^[7,8]. First, the spraying prescription map is generated based on the situation involving pests and diseases. Using the prescription map, the spraying flow rate is regulated based on the GPS positioning information, the travelling velocity information, the flow rate and pressure information of the sprayer.

In the other category, the crop features parameters and parts of the spraying parameters are detected by the sensors; then, along with the detected information, the spraying parameters are decided and regulated based on the models such as ground area (GA) model^[9], leaf wall area (LWA) model^[10] and tree row volume (TRV) model^[11]. For this category of variable-rate spraying technology, a sprayer prototype using ultrasonic sensors was

investigated by Gil et al.^[12,13], and the spraying flow rate was regulated based on canopy size variations measured by the sensors. He et al.^[14] designed an orchard automatic-target sprayer based on infrared detection technology. Zhu et al.^[15,16] designed an air-assisted five-port sprayer. The spraying flow rate was regulated based on tree canopy volume and density information detected by a laser sensor. Yan et al.^[17] designed a system using the binocular vision technology. The system could detect the depth of grape leaf curtain, calculate the canopy volume, and regulate the flow rate to the required value. Wang et al.^[18] developed a system using the pulse width modulation technique to regulate the flow rate based on the UAV velocity. Cen et al.^[19] developed a system using the proportional-integral-derivative (PID) controller to regulate the flow rate based on the UAV velocity.

Therefore, to achieve the needed droplet mass deposit on the target (called expected droplet mass deposit), the spraying parameters were regulated primarily based on the crop prescription map, crop features and parts of the sprayer working parameters (e.g., the velocity) for the current variable-rate spraying system. However, various factors would affect the droplet mass deposit. These factors may include environmental temperature and humidity. Under the influence of these factors, there may be a deviation between the measured and expected droplet mass deposit.

In view of this problem, a spraying parameters regulation method based on the deviation between the measured and expected droplet mass deposit was investigated in this research. The measured droplet mass deposit approached the expected values after spraying parameters regulation. This research provides technical reference for variable-rate spraying technique.

The objectives of this research were to (1) design the spraying parameter feedback regulation system based on the online measurement of the droplet mass deposit, and (2) conduct the test to evaluate the performance of the designed system.

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2 Materials and methods

2.1 Overall design scheme of the system

The system consists of a droplet mass deposit online measurement module, a decision module, a wireless transmission module, and a spraying parameter regulating module, as shown in Figure 1.

The online droplet mass deposit measurement module comprises the droplet collection device, the solution conductivity sensor, and the conductivity transmitter. The module combines the functions of droplets collection and online measurements together. This module provides decision data for the regulating system.

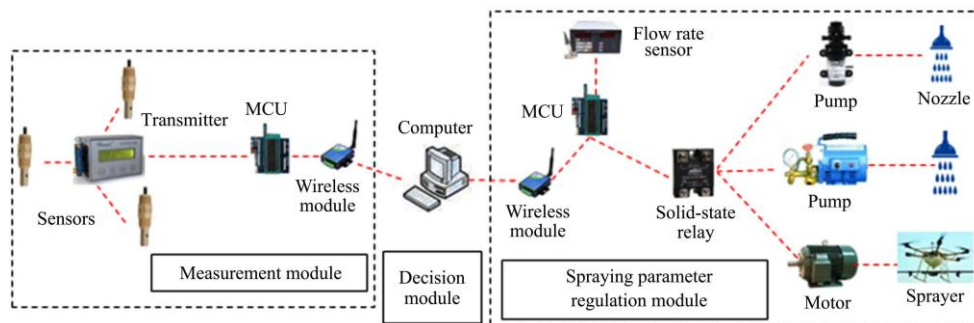


Figure 1 Schematic of the system

The feedback regulation process can be divided into three steps.

(1) The related factors that affect the droplet mass deposit are analyzed. The mathematical model for the droplet mass deposit and the related factors is constructed. The feedback regulation decision model based on the deviation of measured and expected droplet mass deposit is constructed.

(2) The droplet mass deposit under the initial spraying parameters is measured.

The detailed methods are as follows: the droplet mass deposit online measurement devices are placed on the sampling points. The spraying process is conducted under the initial spraying parameters. After this, the measured droplet mass deposit and the used initial spraying parameters are sent to the decision module via wireless transmission module.

(3) The spraying parameters are regulated.

The detailed methods were: the expected droplet mass deposit is decided based on the crop feature and disease situation, and the expected value was input to the host computer. The expected spraying parameters are decided by the decision module based on the expected and measured droplet mass deposit, the used initial spraying parameters and the feedback regulation decision model. The expected spraying parameters are sent to the spraying parameter regulating module by wireless transmission module, and finally the spraying parameters are regulated to the expected values.

2.2 Design of droplet mass deposit online measurement module

The research uses the droplet mass deposit online measurement module^[20] based on the solution conductivity. According to the principles of electrochemistry, when environmental factors such as the pressure and electrolytic cell are stable, and the solution concentration is low, there is a good linear relationship between the solution conductivity (κ) and the concentration (C)^[21].

$$\kappa = aC + b \quad (1)$$

where, coefficients a and b are determined by calibration tests for different electrolytes.

The initial mass of the pure water in the container is m_0 . After the spraying solution is collected, the mixed solution concentration C is $mc_0/(m+m_0)$ (the accumulated mass is m , and the

The decision module consisted of the host computer and the software system. The module can determine the expected spraying parameters based on the deviation between the measured and expected droplet mass deposit, and the spraying decision model.

The spraying parameter regulating module consists of the micro control unit (MCU), the solid-state relay, and the actuator (the pump). The I/O port of the MCU outputs the pulse signals with different duty cycles. The solid-state relay is triggered by a weak signal of the MCU, and the on-off switching speed attains the millisecond level. Using both the relay and the MCU, it is convenient to regulate the pulse duty cycle on the pump motor.

concentration is c_0). The solution conductivity before and after spraying (κ_1 and κ_2) is measured using a sensor, and the accumulated droplet mass deposit (m_1 and m_2) before and after spraying is calculated using Equation (1). The mass difference ($m_2 - m_1$) is the droplet mass deposit of this current spraying. After an amount of pure water was added into the droplet collection box, the measurement module can be used to measure the droplet mass deposit for several times.

The droplet mass deposit measurement module^[20] comprises the droplet collection box, the conductivity sensor and the transmitter (model DDG-3023, Chengci Company, China), as shown in Figure 2. The sensor and the transmitter are configured with a temperature sensor. When the temperature changes, the measurement result of the solution conductivity is calibrated automatically. The sensor and the transmitter have good stability and corrosion resistance as well as a wide application range and can be used for most electrolyte solutions (e.g. seawater). A micro pump is installed inside the box. The solution in the box is pumped to the pipe around the box inlet and then flows out from the holes along the pipe. Finally, it flows back into the box, forming a water curtain on the side wall of the box. In this way, the droplets on the side wall of the box are brought into the box; the droplets and the solution in box were quickly and uniformly mixed. The spraying solution can be the solutions of strong electrolytes such as KNO_3 and the pesticides of large conductivity; for the pesticides of small conductivity, the strong electrolyte tracers can be added^[22]. The concentration of the spraying solution is determined based on the measurement requirement.

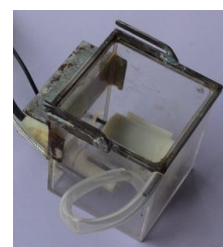


Figure 2 Droplet mass deposit measurement module

2.3 Design of wireless data transmission module

The wireless data transmission module is used to share data among modules in the system. It consists of the MCU (STC89C52) and the wireless communication module (HC-12). The communication distance of HC-12 was 1000 m, its working frequency varies from 433 to 458.5 MHz and can operate under 255 communication channels. It supports one-to-one, one-to-many, and many-to-many data communication patterns. The analog signal of the solution conductivity sensor is converted into the digital signal and sent to the MCU. Next, the MCU transmits the data to the host computer by the wireless transmission module. The host computer determines the expected spraying parameters based on the measured and expected droplet mass deposit, and the feedback regulation decision model. The expected spraying parameters are sent to the regulating module, and finally, the parameters of the sprayer are regulated to the expected values.

2.4 Feedback regulation decision model construction and analysis

To realize feedback regulation, it is important to analyze the factors related to the droplet mass deposit, construct the mathematical model between the droplet mass deposit and the related factors, and construct the feedback regulation decision model based on the deviation of measured and expected droplet mass deposit.

Generally, the relation among the droplet mass deposit on unit area, the flow rate, the spraying velocity is expressed as Equation (2)^[18]:

$$Q = \frac{DWv}{k} \tag{2}$$

where, Q represents the pump flow rate, L/min; D represents droplet mass deposit per unit area, $\mu\text{L}/\text{cm}^2$; W represents the spraying swath width, m; v represents the sprayer velocity, m/s. Here the variable k represents the conversion coefficient, which is related to environmental factors such as temperature, humidity, and wind velocity. If the environmental factors vary not big, the variable k can be regarded as constant.

The feedback regulation decision model based on the deviation of the measured and expected droplet mass deposit is further discussed in this section.

Sprayers were used in sampling regions. When the current spraying flow rate is Q_0 and the velocity is v_0 , the corresponding detected droplet mass deposit is D_0 . According to Equation (2):

$$Q_0 = \frac{D_0 W v_0}{k_0} \tag{3}$$

Assuming that the expected flow rate is Q_{exp} and the expected velocity is v_{exp} to achieve the expected droplet mass deposit D_{exp} , it can be obtained that:

$$Q_{\text{exp}} = \frac{D_{\text{exp}} W v_{\text{exp}}}{k_1} \tag{4}$$

If the time interval for the spraying event before and after spraying parameters regulation was not big, the environment factors can be considered basically unchanged, and therefore, the variable k_0 is equal to the variable k_1 , then the following equation can be obtained:

$$\frac{Q_{\text{exp}}}{v_{\text{exp}}} = \frac{D_{\text{exp}} Q_0}{D_0 v_0} \tag{5}$$

Specially, if the sprayer velocity was kept constant in the test, Equation (5) was further simplified as:

$$Q_{\text{exp}} = \frac{Q_0 D_{\text{exp}}}{D_0} \tag{6}$$

This equation was the strategy for the feedback regulation.

2.5 Design of spraying parameters regulating module

The spraying parameters regulating module comprises of the MCU (STC89C52), the solid-state relay (model JQC, bestep Company) and the actuator (the pump). Using the MCU and the relay, the flow rate was regulated by changing the duty cycle on the pump.

2.5.1 Regulation principle

The methods used to determine the relationship between the flow rate and the duty cycle on the pumps were as follows: the nozzle (model TYI), the pump (model Yulu, Sanmu company) and the clean water were used as test materials. The spraying droplets were collected with a container, the mass was measured using a balance, and the spraying time was set by a relay (model YBD_06). The flow rate of the nozzle was the ratio of the total mass of the collected droplets and the setting time. The flow rates in the different duty cycles were recorded, and the curve expressing the relationship between the flow rate and the duty cycle is shown in Figure 3. The logarithmic expression was used to fit the data, and the square of the correlation coefficient (R^2) was 0.9988. This revealed that it was proper to use the logarithmic expression. The relationship of the flow rate and the duty cycle can be expressed as:

$$Q = p \ln(R) + q \tag{7}$$

where, Q represents the flow rate, L/min; R represents the duty cycle, %; and p and q represent coefficients, which are determined by calibration.

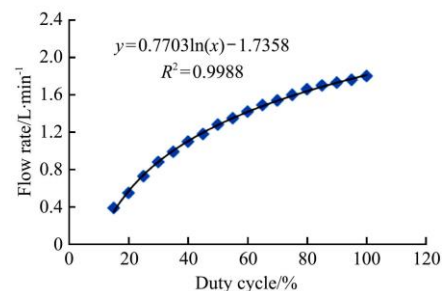


Figure 3 Fitting curve for flow rate and duty cycle on the pump motor

Based on Equation (7), the relationship between the initial flow rate and duty cycle before regulation is:

$$Q_0 = p \ln(R_0) + q \tag{8}$$

The relationship between the expected flow rate and the duty cycle is:

$$Q_{\text{exp}} = p \ln(R_{\text{exp}}) + q \tag{9}$$

Equations (6), (8) and (9) are used to calculate the expected duty cycle, which was calculated as follows:

$$R_{\text{exp}} = e^{\frac{p D_{\text{exp}} \ln R_0 + q (D_{\text{exp}} - D_0)}{p D_0}} \tag{10}$$

When the initial duty cycle R_0 before regulation is regulated to the expected value R_{exp} , the initial flow rate Q_0 is regulated to the expected flow rate Q_{exp} .

2.5.2 Regulation method

The pulses output from the I/O port of the MCU are used to control the solid-state relay to be on or off, and consequently, the working time of the pump motor in a pulse period is changed; thus, the flow rate is regulated.

The methods to regulate the duty cycle using the MCU are as follows: certain amount of time (the time length was T) is set by the MCU timer. Each time the setting time was up, the interruption

Table 2 Comparison between expected and measured droplet mass deposit after regulation for test outdoors

Expected droplet mass deposit/ $\mu\text{L cm}^{-2}$	Measured droplet mass deposit after regulation/ $\mu\text{L cm}^{-2}$							Average/ $\mu\text{L cm}^{-2}$	Relative error/%
	1	2	3	4	5	6	7		
0.119	0.067	0.094	0.125	0.162	0.124	0.094	0.070	0.105	11.43
0.168	0.071	0.149	0.174	0.248	0.193	0.140	0.075	0.150	10.81
0.201	0.087	0.162	0.211	0.281	0.226	0.173	0.101	0.177	11.52
0.267	0.120	0.210	0.256	0.435	0.288	0.221	0.115	0.235	12.15
Average									11.48

respectively, and the droplet mass deposits were different, therefore, it revealed that the droplet mass deposit could also be regulated by changing the travelling velocity. The relative error of the indoor test was smaller than that of the outdoor test. This was because the environment factors such as the temperature, the humidity and the wind were more stable indoors. If the relative error is still large after regulation, a second regulation can be conducted. The relative error threshold can be set in the program based on need, and in this research, it was set as 15% for the designed system.

4 Conclusions

In this study, a spraying parameter regulating system based on online droplet mass deposit measurements was designed.

Tests to evaluate the designed system performance were conducted indoors and outdoors. The results showed that the relative errors between the expected and measured droplet mass deposit after regulation were 6.84% and 11.48% for the indoor and outdoor tests, respectively. The measured droplet mass deposit after regulation approached the expected values, indicating the designed system had a good performance. This research provided an experimental platform to quickly optimize spraying parameters, and provided technical references for precision spraying.

In addition, as the pump worked within a flow-rate range, and only by regulating the flow rate, the regulation range for the expected droplet mass deposit was limited when the sprayer was at a certain velocity. If the expected droplet mass deposit was out of the regulation range, the velocity and the flow rate were required to be regulated simultaneously. In the actual spraying process, the droplet mass deposit was affected by environmental factors (e.g., the temperature and humidity), and the feedback regulation could be carried out at intervals to optimize the spraying parameters.

In this research, only the feedback regulation that was based on the droplet mass deposit was investigated; besides, there were other evaluation indices (e.g. the droplet size and the uniformity of the droplet mass distribution) to evaluate the spraying performance. The feedback regulation based on these evaluation indexes will be future work.

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[References]

[1] Qiu B, Yan R, Ma J, Guang X P, Ou M X. Research progress analysis of variable rate sprayer technology. *Transactions of the CSAM*, 2015; 46(3): 59–72. (in Chinese)

[2] Blackmore S. Precision farming: an introduction. *Outlook on Agriculture*, 1994; 23(4): 275–280.

[3] Rockwell A D, Ager P D. Variable rate sprayer development and evaluation. *Applied Engineering in Agriculture*, 1994; 42(1): 233–240.

[4] Lee W, Alchanatis V, Yang C, Hirafuji M, Moshou D, Li C. Sensing technologies for precision specialty crop production. *Computer and Electronics in Agriculture*, 2010; 74(1): 2–33.

[5] Zhou L F, Xue X Y, Zhou L X, Zhang L, Ding S M, et al. Research situation and progress analysis on orchard variable rate spraying technology. *Transactions of the CSAE*, 2017; 33(23): 80–92. (in Chinese)

[6] Gu C C, Wang X, Wang X L, Yang F Z, Zhai C Y. Research progress on variable-rate spraying technology in orchards. *Transactions of the ASABE*, 2020; 36(6): 927–942.

[7] Qiu B J, Li Z P, Wu H, Sha J Y. Experimental study on variable-rate spraying equipment response capability. *Transactions of the CSAE*, 2007; 23(11): 148–152. (in Chinese)

[8] Carrara M, Comparetti A, Febo P, Santo O. Spatially variable rate herbicide application on durum wheat in Sicily. *Biosystems Engineering*, 2004; 87(4): 387–392.

[9] Weisser P, Koch H. Expression of dose rate with respect to orchard sprayer function. *Aspects of Applied Biology*, 2002; 66(2): 353–358.

[10] Friessleben R, Rosslenbroich H, Elbert A. Dose expression in plant protection product field testing in high crops: Need for harmonization. *Pflanzenschutz Nachrichten Bayer*, 2007; 60(8): 85–96.

[11] Byers R, Hickey K, Hill C. Base gallonage per acre. *Virginia Fruit*, 1971; 60(8): 19–23.

[12] Gil E, Escola A, Rosell J R, Planas S, Val L. Variable rate application of plant protection products in vineyard using ultrasonic sensors. *Crop Protection*, 2007; 26(8): 1287–1297.

[13] Gil E, Llorens J, Llop J, Fabregas X, Escola A, Rosell-Polo J R. Variable rate sprayer Part 2-Vineyard prototype: Design, implementation, and validation. *Computer and Electronics in Agriculture*, 2013; 95(3): 136–150.

[14] He X K, Yan K R, Chu J Y, Wang J, Zeng A J, Liu Y J. Design and testing of the automatic target detecting, electrostatic, air assisted, orchard sprayer. *Transactions of the CSAE*, 2003; 19(6): 78–80. (in Chinese)

[15] Chen Y, Zhu H, Ozkan H. Development of a variable-rate sprayer with laser scanning sensor to synchronize spray outputs to tree structures. *Transactions of ASABE*, 2012; 55(3): 773–781.

[16] Chen Y, Ozkan H E, Zhu H, Derksen R C, Krause C R. Spray deposition inside tree canopies from a newly developed variable-rate air-assisted sprayer. *Transactions of the ASABE*, 2013; 56(6): 1263–1272.

[17] Yan C G, Xu L M, Yuan Q C. Design and experiments of vineyard variable spraying control system based on binocular vision. *Transactions of the CSAE*, 2021; 37(11): 13–22. (in Chinese)

[18] Wang D S, Zhang J X, Li W, Xiong B, Zhang S L, Zhang W Q. Design and test of dynamic variable spraying system of plant protection UAV. *Transactions of the CSAM*, 2017; 48(5): 86–93. (in Chinese)

[19] Cen Z Z, Yue X J, Wang L H, Ling K J, Cheng Z Y, Lu Y. Design and test of self-adaptive variable spray system of UAV based on neural network PID. *Journal of South China Agricultural University*, 2019; 40(4): 100–108. (in Chinese)

[20] Sun C D, Qiu W, Ding W M, Gu J B. Design and experiment of a real-time droplet accumulating mass measurement system. *Transactions of the ASABE*, 2017; 60(3): 615–624.

[21] Levine I N. *Physical chemistry*. Beijing: Tsinghua University Press, 2012; pp.493–497.

[22] Sun C D. Design and application of measurement system for droplet quantity based on solution conductivity principle. PhD dissertation. Nanjing: Nanjing Agricultural University, 2017; 141p.