DESIGN AND TESTING OF A VARIABLE SPRAY SYSTEM BASED ON PTO PROTOCOLS
/
基于PTO 协议的变量喷雾系统设计与试验

Lei LIU$^{1)}$, Fanxia KONG*$^{1)}$, Lili YI$^{1)}$, Yubin LAN$^{1,2)}$, Xin HAN$^{1)}$, Jie ZHAO$^{3)}$, Jie LIU$^{1)}$, Pengcheng LV$^{1)}$, Minhui ZHANG$^{1)}$
$^{1)}$ College of Agricultural Engineering and Food Science, Shandong University of Technology, Zibo/China
$^{2)}$ National Sub-Centre for International Collaboration Research Centre for Agricultural Aviation Intelligent Equipment, Zibo/China
$^{3)}$UNDOF Procurement Service Station No.4, Shenyang/China
Tel: +8618653372858; E-mail: kfx0309@163.com
Corresponding author: Fanxia Kong
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ABSTRACT

The aim of this research is to address the issues of low precision in variable spraying within the existing farmland application system, whereby nozzles cannot be controlled independently and low pesticide utilisation is observed. A variable spraying system based on PTO protocol has been designed. The system comprises an STM32 microcontroller as the control core, including the host computer, multi-channel controller, electronic switch, and electromagnetic spray nozzle. The master control unit receives the spray amount set by the user and calculates the duty cycle of the corresponding nozzle, which is then sent to the multiplex controller in real time through CAN communication. The multiplex controller adjusts the on-off frequency and duty cycle of each electromagnetic nozzle in real time according to the duty cycle of the corresponding nozzle it receives, thus enabling the nozzles to be controlled independently. This study offers theoretical and technical support for the independent control of spray nozzles and the optimisation of pesticide utilisation for variable spray systems based on PTO protocols.

摘要

针对现有农田施药系统变量喷雾精准化程度低、喷头不能独立控制及农药利用率低等问题，该研究设计了一种基于PTO 协议的变量喷雾系统。系统以STM32 单片机为控制核心，包括上位机、多路控制器、电子开关、电磁喷头等。主控接收用户设置的喷药量并计算对应喷头的占空比，通过 CAN 通讯实时发送到多路控制器；多路控制器根据接收的对应喷头的占空比，实时调节各个电磁喷头的通断频率与占空比，从而实现喷头的独立控制。该研究为基于PTO 协议的变量喷雾系统提供了实现喷头独立控制和提高农药利用率的理论和技术支持。

INTRODUCTION

The control of crop pests, diseases, and weeds is one of the most important aspects of agricultural production. At present, the use of pesticides is still an important means of controlling pests, diseases, and weeds, and for achieving stable and high yields *(He et al., 2020; Qi et al., 2022; Feng et al., 2021; Qiu et al., 2015)*. With the advancement of intelligent agricultural production and mechanization, crop protection machine operations have gradually replaced traditional manual spraying operations, improving the efficiency and safety of spraying. However, traditional crop protection operations do not take into account the uneven distribution of pests, diseases, and weeds in the operation area and typically use the same amount of pesticide across the entire area. This practice can lead to pesticide overuse, ecological degradation, and other problems. Variable spraying technology can adjust the dosage in real time according to the target information, thus reducing the amount of liquid used *(Chu et al., 2021; He et al., 2019; He et al., 2022)*.

Experts from both within and outside the field have conducted comprehensive research on variable spraying technology from a variety of perspectives. *Wang et al., (2022),* conducted research using fuzzy control technology to investigate the influence of vehicle speed on spraying volume per unit area. This led to the development of a speed-following adaptive variable spray system. *Li et al., (2016),* designed a pulse-width modulated spraying system operating at frequencies exceeding 20 Hz, with the objective of studying the effects of PWM frequency and duty cycle on spraying characteristics. This research provides a theoretical basis for the application of high-frequency solenoid valves in PWM variable application systems and parameter selection.

Ramon et al., (2021), employed PWM technology to regulate the solenoid valve and, consequently, the flow rate of the nozzle, with the objective of reducing the quantity of pesticides utilised, thus minimising environmental pollution and cutting down agricultural costs. *Butt et al., (2019),* conducted an investigation on the impact of various nozzle types and duty cycles on the pressure at the nozzle orifice. The findings indicated that solenoid valve pulses result in pressure loss at the nozzle. *Li et al., (2022),* investigated the impact of PWM duty cycle and frequency on spray drift characteristics. Their findings indicated that the duty cycle has a greater influence on spray drift than the frequency. They demonstrated that PWM duty cycles set in the range of 20% to 70% can effectively reduce the potential for drift in PWM spray.

A solenoid valve is a quick-acting suction mechanism that is operated by electromagnetism. The electromagnetic force is generated when the solenoid coil is energized. This force overcomes the spring force, causing the spool to move away from the valve and the valve to open. Conversely, when the solenoid coil is de-energised, the spring force pushes the spool towards the valve, closing the valve. The variable flow rate is achieved by rapidly controlling the valve in and out *(Liu et al., 2022; Fan et al., 2021)*.

The aim of the study was to address the issues of low precision and low effective utilisation of pesticides in the current variable spraying system. To achieve this end, a variable spraying system based on PTO protocol was designed. The control system primarily consists of a host computer, an STM32 microcontroller, a multi-channel controller, electronic switches, and electromagnetic spray nozzles. The generation of multi-channel PWM signals, which independently control the frequency and duty cycle of each spray nozzle, enables precise control of the spray operation. This is done to assess the performance of the electromagnetic nozzle and to achieve independent control of the nozzle, thereby enhancing the precision of variable spraying.

MATERIALS AND METHODS

Variable spray control system design

Design Requirements for Variable Spray Control System

Aiming at the issues of low precision in variable spraying in the current agricultural application system, the inability to control the nozzle independently, and low pesticide efficiency, this paper designs a variable spraying system based on PTO protocol. The variable spray system developed based on the PTO protocol is installed on the spray bar of a self-propelled high clearance sprayer. Since the spraying width of the self-propelled high clearance sprayer is wide, the amount of pesticide applied within the spraying area is different and needs to be adjusted according to the speed, crop, pest and disease, etc., so each nozzle is independently controlled to achieve real-time and accurate adjustment of the amount of pesticide applied *(Wang et al., 2023)*. To meet the sprayer's basic spray parameters and the need for independent nozzle control, the control system must output multiple PWM signals to independently control the frequency and duty cycle of each nozzle. In order to ensure the accuracy and performance of independent control of the nozzle, an electromagnetic nozzle is proposed, as detailed in Table 1 of the technical specifications.

Table 1

Electromagnetic nozzle main technical indicators

Parametric	Numerical value
Pressure range / MPa	0.15~0.8
Flow range / (L•min^{-1})	0~6.0
Rated voltage / V	12
Duty Cycle Range / %	0~100
Open time / ms	15
Close time / ms	10
Frequency ranges / Hz	0~25

Variable Spray Control System Components

The variable rate spray system based on the PTO protocol mainly consists of a host computer, a main controller, a multiplex controller, an electronic switch, an electromagnetic spray nozzle, etc., as shown in Fig. 1. The host computer is used to input the spray rate and send it to the master controller. RTK_GNSS implements RTK differential positioning via UM482, which collects the position and speed information of the equipment in real time and transmits it to the main controller through the serial port. The main controller uses the STM32F103c8t6 chip as its core, calculates the required frequency and duty cycle information according to the received spray rate and operating speed information, integrates it into a complete data according to the custom PTO protocol format and transmits it to the multiplexer controller via CAN bus. The multiplexing controller utilizes the STM32F407vet6 chip as the core, and according to the received PTO protocol data, performs CRC check, extracting frequency and duty cycle information, and then outputs this data to the electronic switches, controlling multiple electronic switches to turn on and off. The electromagnetic nozzle is connected to the electronic switch, when the electronic switch is open, the nozzle opens, and the liquid is sprayed, when the electronic switch is closed, the nozzle closes, and the liquid stops spraying. The amount of spray can be adjusted by modifying the duty cycle and frequency of the PWM signal via the PTO protocol.

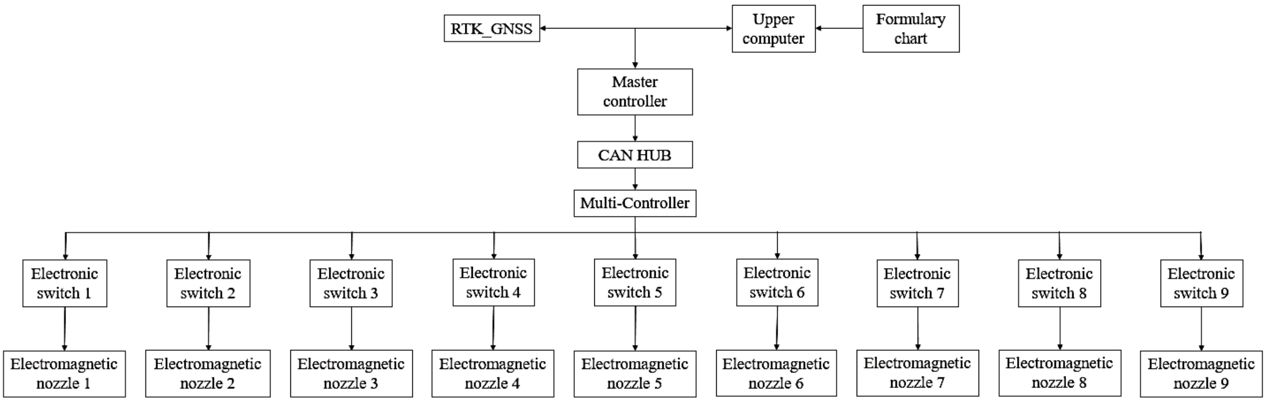


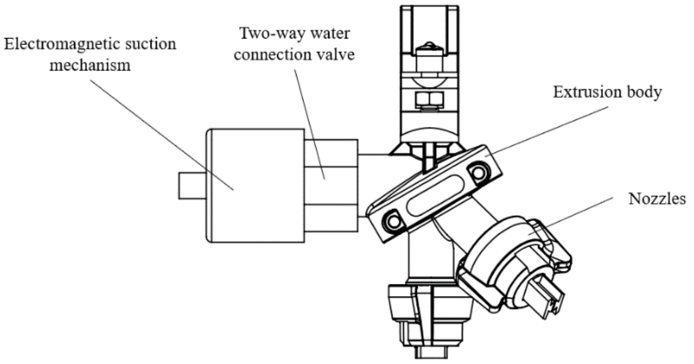
Fig. 1 – PTO protocol variable spray system components

Hardware Design

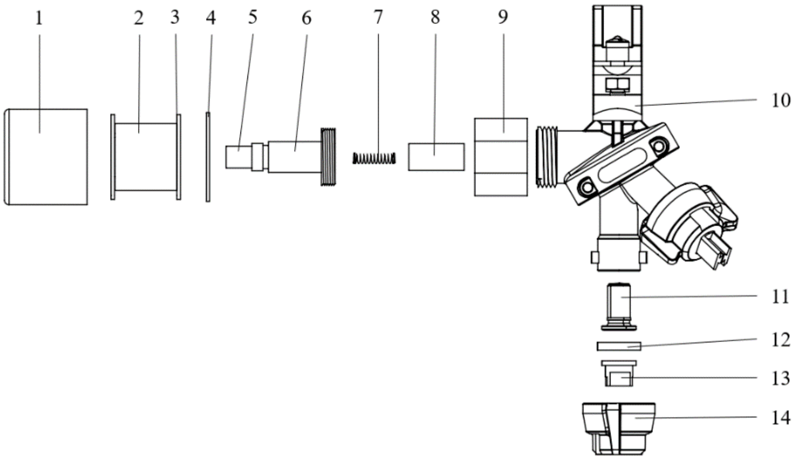
Electromagnetic nozzles

As shown in Fig.2, the electromagnetic nozzle mainly consists of an electromagnetic suction mechanism, a two-way water connection valve, a spray body, nozzles and other components. Among them, the solenoid suction mechanism adopts a 2W025-08 solenoid valve, which mainly includes a solenoid coil housing, solenoid coil, winding skeleton, fixed iron core, return spring, valve spool, and so on. The ring is installed inside the solenoid coil case to secure the solenoid coil and winding skeleton; the fixed iron core is fixedly connected to the sleeve by a snap, and both of them are placed inside the solenoid coil; the valve spool is positioned in the inner cavity of the sleeve, which can slide freely; the valve spool and the fixed iron core are equipped with reset springs between them; the other end of the sleeve is connected to the threaded two-way water connection valve. The two-way water connection valve features a central hole in the centre for the two-way water connection valve outlet, surrounded by 12 holes for the two-way water connection valve inlet, the two-way water connection valve on both sides of the thread connecting the electromagnetic suction mechanism and the spray body. Spray body model ARAG 4012747, the spray body has three ports, inlet, return port, outlet, return port including the inner cavity and is set in a ring on the outside of the inner cavity of the outer cavity, the inner cavity is connected to the outlet of the two-way water connection valve, the outer cavity is connected to the inlet of the two-way water connection valve, the spray body also includes the nozzle converter part, rotating can be used to select the use of three nozzles, respectively, with SF11006, SF11008, CFA11006 fan nozzle, spray angle being 110°.

The working principle is that when the electromagnetic suction mechanism of the coil is energised, its internal magnetic field magnetises the fixed iron core and the valve core, the valve core is attracted away from the bidirectional water connection valve outlet by the magnetic force, and the liquid is sprayed from the nozzle outlet; when the electromagnetic coil is de-energised, the magnetic field disappears, and the valve core moves away from the iron core under the action of the return spring, blocking the central through hole of the bidirectional water connection valve, and the liquid is blocked. By adjusting the PWM duty cycle, i.e. the on/off time within a single cycle of the nozzle, the spray flow rate can be adjusted and the on/off frequency of the nozzle can be controlled by adjusting the on/off frequency of the solenoid valve.



a. Electromagnetic nozzle assembly diagram

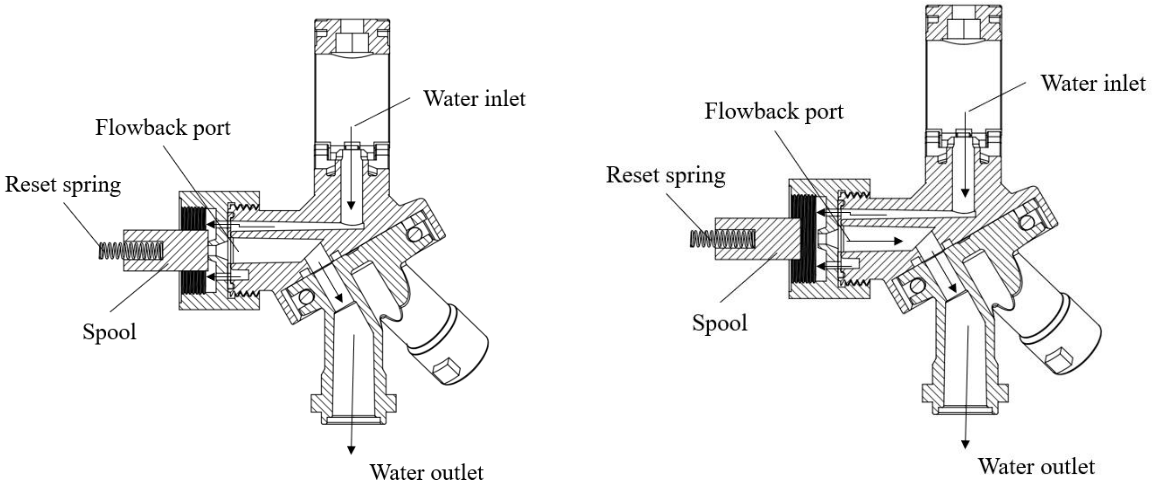


b. Electromagnetic nozzle main parts

Fig. 2 – Electromagnetic nozzle structure

1 - Solenoid shell; 2 - Solenoid coil; 3 - Winding skeleton; 4 - Fixed iron core; 5 -Sleeve; 6 - Reset spring; 7 - Valve spool; 8 - Gasket; 9 - Two-way through the water connection valve; 10 - Spray body; 11 - Screen; 12 - Gasket; 13 - Nozzle cap; 14 - Nozzle cap

For the automatic opening and closing of the sprayer body, a return port is designed to include an inner chamber and an outer chamber arranged in an annular shape on the outside of the inner chamber. The water inlet and outlet are connected to the outer and inner return port cavity. Since the direct use of the spool directly blocking the return port sealing is poor, the two-way water connection valve is designed to enhance the sealing. The two-way water connection valve features a central hole and 12 holes evenly distributed around the hole for the two-way water connection valve outlet and water inlet, respectively. The water inlet is connected to the outer cavity of the return port, and the water outlet is connected to the inner cavity of the return port.



a. Closed state internal structure *b. On-state internal structure*

Fig. 3 – Internal structure of two-way water connection valve and spray body section

Figure 3 displays the two-way water connection valve and the internal structure of the sprayer body. Closed state, the valve spool blocks the outlet, preventing the liquid from the water inlet, flow to the two-way water connection valve is blocked; conductive state, the valve spool moves away from the two-way water connection valve outlet, allowing the liquid to flow from the two-way water connection valve outlet out of the water, into the spray body outlet.

Calculate the radius of the outlet of the bi-directional through-connection valve according to the maximum flow rate required by the technical specifications.

$$Q = K_L A \Delta p^m \tag{1}$$

Q is the flow rate through the outlet of the bi-directional water connection valve, [l/min];

K_L – throttle factor;

A – throttle port flow area, [m^2];

Δp – differential pressure before and after throttle orifice, [N/m^2];

m – throttle port shape factor

In the formula throttle coefficient according to experience usually take 0.7, throttle port shape coefficient, elongated holes $m=1$, thin-walled holes $m=0.5$. After calculating, this paper bidirectional flow through the water connection valve outlet cross-section radius of 2 mm.

Microcontroller Selection

The control system STM32 microcontroller selected STM32F103c8t6 chip from STMicroelectronics, a total of 48 pins, the maximum clock frequency of 72MHz; the main control of the multi-controller selected STM32F407vet6 chip from STMicroelectronics, a total of 100 pins, the maximum clock frequency of 168MHz. This controller can communicate with CAN bus interface, I2C, 485, SPI, and USART. It can also output PWM signals and operates within a temperature range of -40°C ~ 85°C. The microcontroller has the advantages of high working stability and reliability, efficient code efficiency, many peripheral interfaces, and low power consumption, which can adapt to withstand the harsh environment of agricultural environments and fulfil the requirements of variable rate spray control.

Multiple controllers

The multiplex controller serves as the core of the PTO protocol variable spray system. It receives the PTO protocol sent by the STM32 microcontroller for CRC check and extract the frequency and duty cycle information of the relevant PWM channel, and then outputs the PWM frequency and duty cycle through the electronic switch to control the on-off frequency and duty cycle of the electromagnetic nozzle, so that the medicine is sprayed according to the set spray volume. The multiplex controller uses STM32F407vet6 chip as the central processor, TJA1050 as the CAN communication chip, PMOS tube as the electronic switch, in addition to the clock circuit, reset circuit, and so on. The schematic block diagram of the multiplexer is shown in Fig. 4, and the physical diagram is shown in Fig. 5.

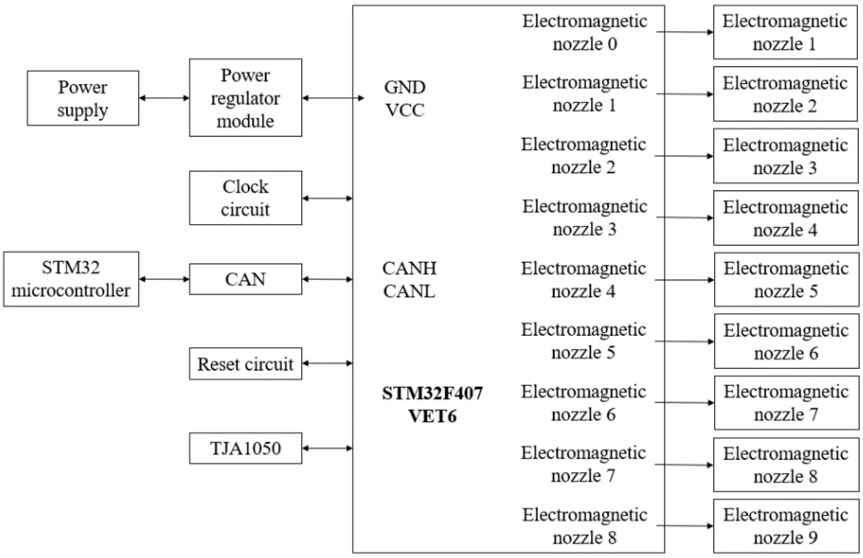


Fig. 4 – Multi-Controller block diagram

The power supply is connected to the microcontroller through the power regulator module to ensure stable power supply during operation. The STM32 microcontroller is linked to the multiplexer via the CAN bus module to transmit the integrated PTO protocol to the multiplexer. During the spraying operation, according to the PTO protocol data is received in real time, it extracts the corresponding frequency and duty cycle information of the channel and controls the on/off time of each electronic switch by adjusting the frequency and duty cycle of the PWM signal, thus controlling the on/off time of each electromagnetic nozzle and realising the control of the spray flow of each nozzle.

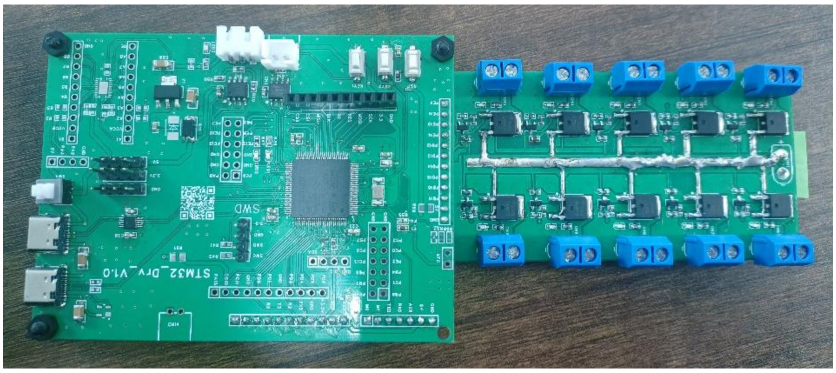


Fig. 5 – Multi-Controller Physical Diagram

The multiplex controller contains nine electronic switches, with each switch controlling a group of nozzles. The circuit diagram for the electronic switch circuit diagram is shown in Fig. 6. Each electronic switch consists of one PMOS tube, one transistor, four resistors, and one LED. Through the RC port input level signal controls the electronic switch to turn on and off. When the RC port input high level signal, the electronic switch is closed, the LED light is open, the electromagnetic nozzle suction, the nozzle spray liquid; RC port output low level signal, the electronic switch is disconnected, the LED light is closed, the electromagnetic nozzle is closed, the nozzle stops spraying liquid.

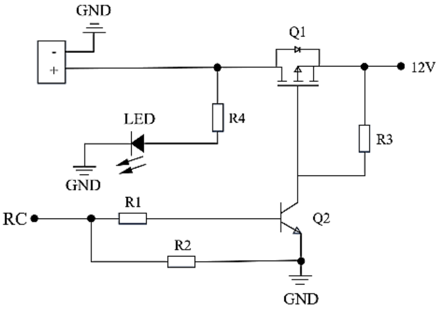


Fig. 6 – Electronic switch circuit diagram

Software system design

Programme design

The variable-rate spraying control program was developed based on the MDK5 development environment, in accordance with the basic operational requirements of variable-rate spraying and specifications such as the flow control algorithm. The workflow of the variable-rate spraying system was designed in accordance with the PTO protocol. Upon initialisation of the system, the STM32F103 MCU first receives the spray rate input from the host computer, converts the spray rate into a PWM duty cycle, and incorporates the frequency and duty cycle information into the PTO protocol, as shown in Fig. 7. The data then transmitted to the STM32F407 microcontroller through the CAN bus. The STM32F407 microcontroller performs CRC checksum data parsing on the received PTO protocol and extracts the relevant frequency and duty cycle information. Subsequently, the microcontroller receives the frequency and duty cycle information, which it uses to regulate the on/off switch of each electronic switch. Each electronic switch is responsible for regulating the on/off operation of an electromagnetic nozzle. The spraying of liquid occurs when the electromagnetic nozzle is open, and the liquid ceases to be sprayed when the electromagnetic nozzle is closed. By adjusting the on/off time of the electromagnetic nozzle in relation to the unit of time, the spray rate can be modified in order to achieve variable spraying.

The development of the PTO protocol variable spray control program is described in this paper, which also outlines the process of downloading the program to STM32F103 and STM32F407 microcontrollers using the ST-LINK V2 downloader for debugging and experimental verification. The workflow is depicted in Fig. 8.

Data header	Frequency	Duty cycle 1	。 。 。	Duty cycle 9	CRC	Data tail

Fig. 7 – PTO protocol data format

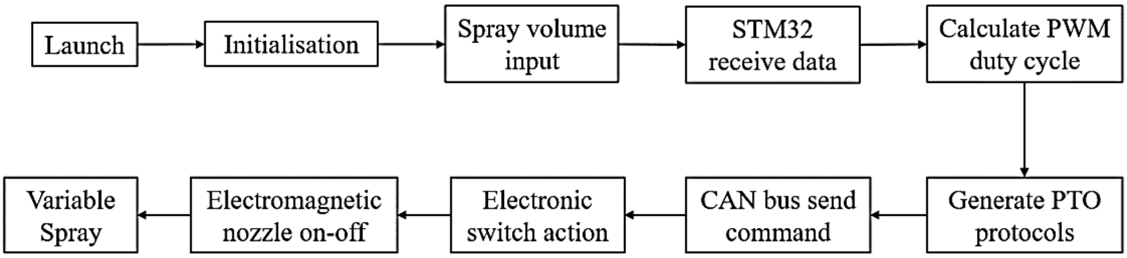


Fig. 8 – PWM signal output process

Flow regulation algorithm

In this study, a multiplex controller is utilized to receive and process the PTO protocol data and generate a multiplex adjustable PWM signal to regulate the variable spray nozzle, thereby achieving variable spray. Fig. 9 illustrates the PWM digital signal, the PWM duty cycle for a single pulse cycle, and the pulse period ratio (*Yin et al., 2022*). The pulse signal duty cycle calculation formula is as follows:

$$\alpha = \frac{t_0}{T} \times 100\% \tag{2}$$

α is the duty cycle of the pulse signal, [%];

t_0 — the on-time (high level output time), [s];

T — the pulse period, [s]

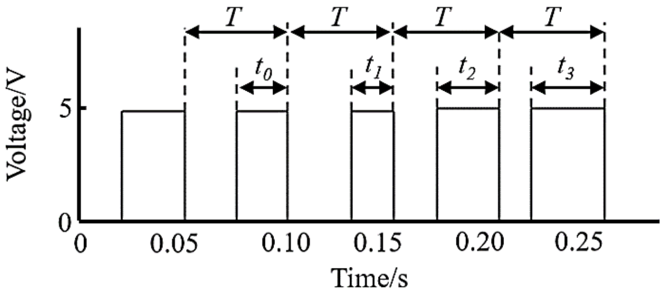


Fig. 9 – PWM digital signal

It can be observed that as the PWM duty cycle increases, the high-level output time also increases, as does the electromagnetic nozzle length and the number of nozzle sprays per unit time. Conversely, a shorter high-level output time leads to a shorter electromagnetic nozzle and a reduction in the number of nozzle sprays per unit time. Consequently, the actual flow rate of the nozzle, the duty cycle of the pulse signal, and the maximum flow rate of the nozzle are related as follows:

$$Q_0 = a \cdot \alpha + b \tag{3}$$

Q_0 is the actual flow rate of the nozzle, [l/min];

a, b - the constant

During the operational process, the machine's travel speed is subject to change. This results in a corresponding change in operating speed, which in turn affects the uniformity of drug application per unit area. In order to maintain a consistent spray effect, it is essential dynamically adjust the spray flow in real time in response to changes in speed.

The optimal demand flow rate of the outlet line is designated as $q(t)$ at the present moment t. The demand flow rate is calculated from the real-time vehicle speed obtained from the speed sensor. The following relationship exists between machine forward speed, application rate, spray width, and spray flow rate:

$$q(t) = m\frac{Qv'(t)W}{60000} \tag{4}$$

$q(t)$ is the demand flow at time t, [l/min];

Q — the amount applied per unit area, [l/min];

$v'(t)$ — the speed at which the machine is travelling at time t, [km/h];

W — the nozzle spacing, [cm];

m — the number of nozzles

Operational performance test

In order to evaluate the operational performance of the designed variable spray control system based on the PTO protocol for electromagnetic spray nozzles, a variable spray test bench was constructed and the developed control system then installed on the spray test bench. The effectiveness of the control system and the performance characteristics of the electromagnetic spray nozzle were assessed at the Precision Agriculture Laboratory of Shandong University of Technology in May 2024.

Test set-up

The test equipment includes a microcomputer-controlled nozzle, a comprehensive performance precision test bench, a high-speed camera, a filling light, a data acquisition system, a computer, an electromagnetic nozzle, a multi-channel controller, and other components, as shown in Fig.10. The physical diagram of the electromagnetic nozzle is depicted in Fig. 11. The nozzles connected to the nozzle were SF11006, SF11008, CFA11006 fan nozzle, spray angle of 110°, pressure range of 0.15 ~ 0.8 MPa. The test was performed on the CFA11006 fan nozzle.

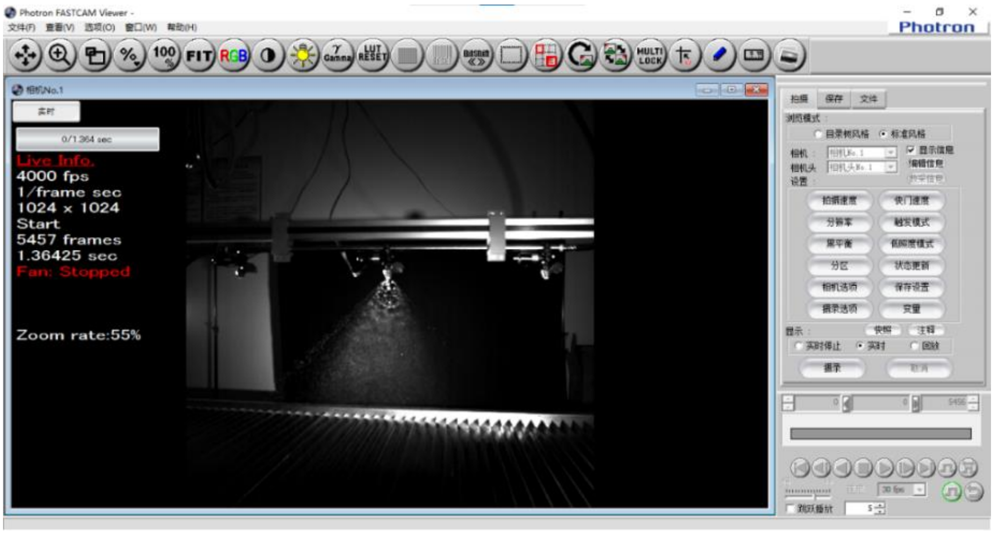
The precision test bench consists of a hydraulic spraying system, a mist collection tank, a pressure monitoring system, and other components. During operation, the computer sends the PWM duty cycle and frequency to the main control through the serial port, which is then transmitted to the multi-channel controller via the CAN bus. setup enables the nozzle flow to be controlled through the opening and closing time of the control spool. The operator enters the required frequency and duty cycle in accordance with the test requirements. The duty cycle is the primary parameter of PWM precision spray technology, as it directly determines the size of the spray flow. If the on-time of the nozzle in a single cycle differs significantly from the set on-time, it will result in a reduction in spray precision. In order to verify the control accuracy of the designed PWM electronically controlled precision spray control system, the actual duty cycle of the nozzle spray was tested. This involved measuring the spray time of the electromagnetic spray nozzle in a single cycle under different pressures. This was done by a high-speed camera in order to verify the designed electromagnetic spray nozzle's working performance. The high-speed camera employed was the Photron FASTCAM Mini AX, which boasts excellent light sensitivity, high-quality imaging capabilities, and versatility, allowing for real-time display on both analogue and digital monitors.

Fig. 10 – Test bench

Fig. 11 – Electromagnetic nozzle physical picture

Test methods

In order to verify the linear relationship between the spool conduction duty cycle and the set duty cycle, the designed solenoid nozzle was installed on the test bench, and the solenoid nozzle on-off test was carried out in the pressure range of 0.2 to 0.8 MPa. The pulse width modulation (PWM) signal frequency was set to 10 Hz, and the pressure values were set to 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 MPa, respectively. A high-speed camera is employed to capture images, and the number of images containing spray droplets in a single cycle is multiplied by the frame length of the high-speed camera to obtain the on-time of the electromagnetic nozzle in a single cycle. During the test, the pulse-width modulation (PWM) duty cycle is incremented from 0 to 100% by 1% each time. The spraying time is then measured for 5-6 cycles under each duty cycle. The average value of the middle 3 sets of on/off time data is taken to find the spraying time and the corresponding spool on/off duty cycle in a single cycle. This is then compared with the set duty cycle. The high-speed camera is capable of capturing images at a rate of 4000 frames per second, with each pixel measuring 1024×1024. The interface for shooting is illustrated in Fig. 12. A single pulse-width modulation cycle under a high-speed camera captures the electromagnetic nozzle spray process, as illustrated in Fig. 13.



Live Info.
4000 fps
1/frame sec
1024 x 1024
Start
5457 frames
1.36425 sec
Fan: Stopped

Zoom rate:55%

Fig. 12 – High-speed camera shooting interface

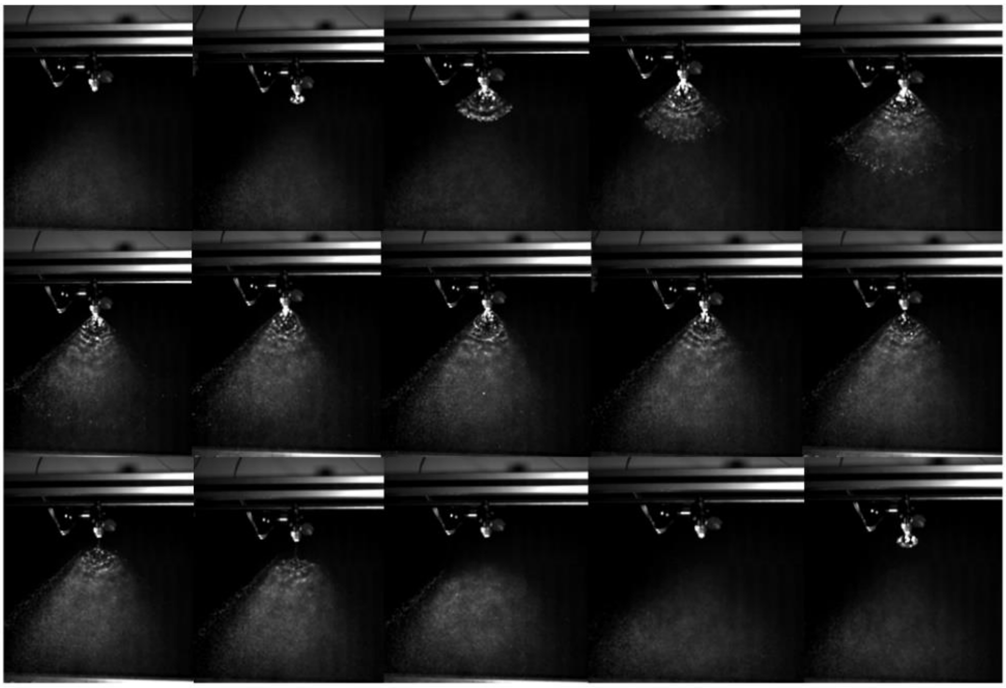


Fig. 13 - Spraying process with a single PWM cycle of the electromagnetic nozzle

RESULTS

The range of duty cycles at which the electromagnetic nozzle can operate at different pressures is presented in Table 2. At a pressure of 0.2 to 0.3 MPa, the minimum duty cycle at which the electromagnetic nozzle can be activated is 8%. At a pressure of 0.4 MPa, the minimum duty cycle is 9%. At a pressure of 0.5 to 0.6 MPa, the minimum duty cycle is 10%. Finally, at a pressure of 0.7 to 0.8 MPa, the minimum duty cycle is 11%. In the range of 0.2 to 0.8 MPa, the maximum duty cycle that can be closed by the electromagnetic nozzle is 94%. This phenomenon can be attributed to the two-way water connection with the spool side, which is subject to liquid pressure. The spool is reset in order to overcome the pressure of liquid reset, and the pressure is relatively low. This makes it easier to completely close the nozzle. However, as the pressure increases, the spool is reset with greater difficulty, and it becomes more challenging to completely close the nozzle.

Table 2

Electromagnetic printhead operating duty cycle range

System pressure（MPa）	0.2	0.3	0.4	0.5	0.6	0.7	0.8
Duty Cycle Range（%）	8~94	8~94	9~94	10~94	10~94	11~94	11~94

The selected duty cycle range for the electromagnetic nozzle work performance test was 11% to 94%. The actual duty cycle error of the electromagnetic nozzle under different pressures is shown in Table 3. At a duty cycle of [11%, 94%], the maximum value of the maximum relative error of the actual duty cycle on-time is 137%, the maximum value of the average relative error is 17%, the maximum value of the maximum absolute error is 19.7 ms, and the maximum value of the root mean square error is 9.8 ms. At a duty cycle of [15%, 94%], the maximum value of the maximum relative error of the actual duty cycle on-time is 75.2%, the maximum value of the average relative error is 16.4%, the maximum value of the maximum absolute error is 19.7 ms, and the maximum value of the root-mean-square error is 9.5 ms. At a duty cycle of [20%, 94%], the maximum value of the maximum relative error of the actual duty cycle on-time is 38.2%, the maximum value of the average relative error is 12.1%, the maximum value of the maximum absolute error is 19.7 ms, and the maximum value of the root-mean-square error is 9.1 ms. When the duty cycle is [20%, 94%], the relative errors of the actual duty cycle on-time under different pressures are all low, indicating that the spray system has poor control effect on the electromagnetic nozzle in the range of duty cycle [11%, 20%], and has good control stability and reliability in the range of duty cycle [20%, 94%], which is able to meet the basic requirements of variable spraying.

Table 3

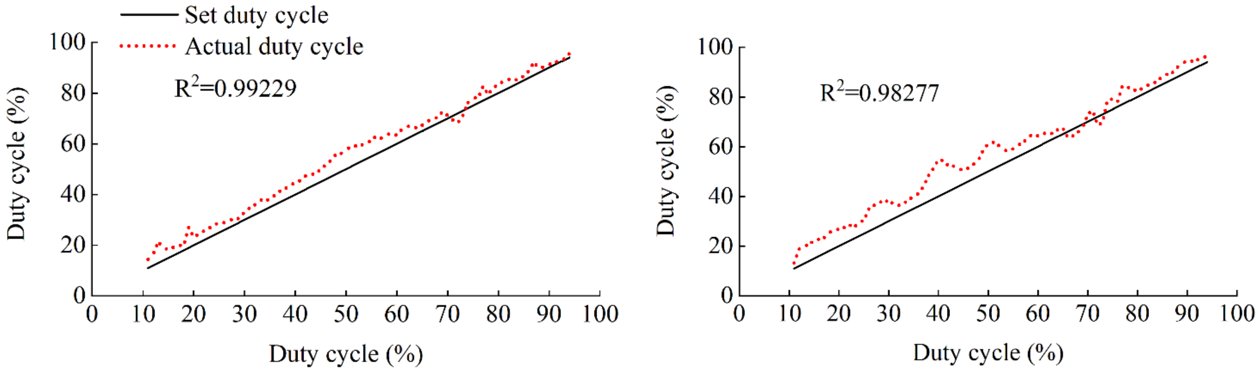
Analysis of the actual duty cycle on-time error of electromagnetic nozzle

Spray pressure / MPa	**Duty cycle range**	**Maximum relative error / %**	**Average relative error / %**	**Maximum absolute error / ms**	**RMSE / ms**
0.2	[11%, 94%]	64.6	6.42	8.4	3.7
	[15%, 94%]	42.8	4.31	8.1	3.3
	[20%, 94%]	16.4	3.27	8.1	2.9
0.3	[11%, 94%]	57.2	12.7	14.9	8.2
	[15%, 94%]	51.4	11.4	14.9	7.9
	[20%, 94%]	36.8	10.5	14.9	7.4
0.4	[11%, 94%]	54.2	8.6	9.2	4.7
	[15%, 94%]	54.1	4.3	9.2	4.7
	[20%, 94%]	14.3	2.1	5.3	2.2
0.5	[11%, 94%]	60.3	10.8	12.8	7.1
	[15%, 94%]	44.7	6.7	12.8	6.5
	[20%, 94%]	31.8	3.9	11.4	4.2
0.6	[11%, 94%]	80.7	8.2	17.4	6.5
	[15%, 94%]	75.2	4.2	17.4	6.2
	[20%, 94%]	382	4.1	17.4	5.8

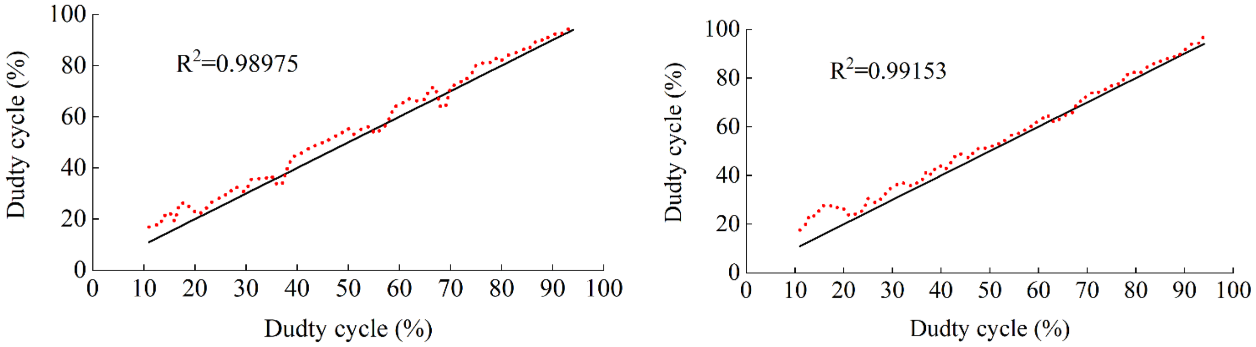
Spray pressure / MPa	Duty cycle range	Maximum relative error / %	Average relative error / %	Maximum absolute error / ms	RMSE / ms
0.7	[11%, 94%]	45.4	14.8	15.1	8.4
	[15%, 94%]	36.8	14.3	12.9	8.2
	[20%, 94%]	32.6	9.6	11.4	7.1
0.8	[11%, 94%]	137	17.0	19.7	9.8
	[15%, 94%]	68.3	16.4	19.7	9.5
	[20%, 94%]	26.9	12.1	19.7	9.1

A comparison of the PWM set duty cycle the actual duty cycle at different pressures is presented in Fig.14. This can be observed by combining Table 3 and Fig.14a, Fig.14c, Fig.14d, and Fig.14e. At system pressures of 0.2, 0.4, 0.5, and 0.6 MPa, the average relative error between the actual duty cycle and the set duty cycle in the range of [11%, 94%] is 6.42%, 8.6%, 10.8%, and 8.2%, respectively. These values are considered unsuitable for practical applications due to their significant magnitude. The relative errors between the actual duty cycle and the set duty cycle in the range of [20%, 96%] are less than 4.1%, and the linearity is high, with the linear regression coefficients of determination exceeding 0.98. When combined with Table 3 and Fig.14b, Fig.14f, and Fig.14g, it can be observed that the actual duty cycle is greater than the set duty cycle in the range of [11%, 94%] at the system pressures of 0.3, 0.7, and 0.8 MPa, with average relative errors of 12.7%, 14.8%, and 17%, respectively. However, the data exhibits a high degree of linearity, with the coefficient of determination of the linear regression exceeding 0.98.

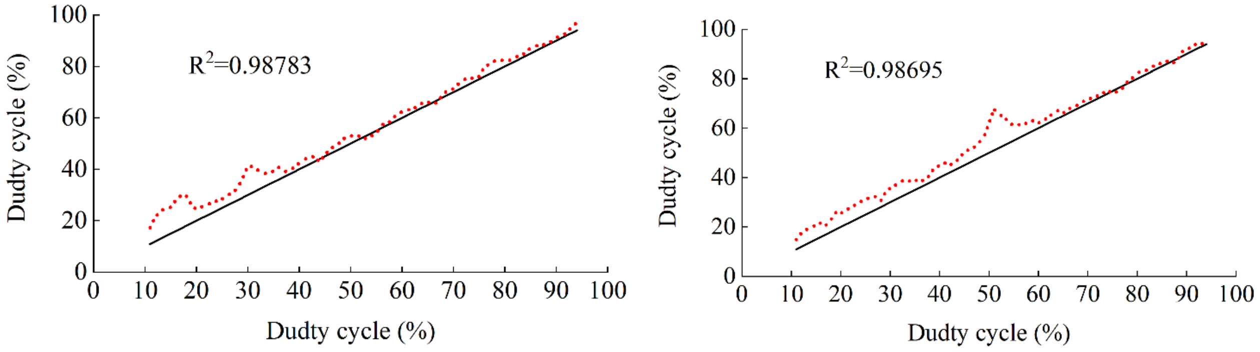
After repeated tests, the analysis shows that during the spool closure process, the liquid creates a certain resistance to the spool, and the pressure in the spray body and the spring work together to produce a resetting force on the spool. When the system pressure is 0.3 MPa, the low pressure in the spray body results in a small resetting force. After the electromagnetic force disappears, the resetting force cannot overcome the resistance of the liquid in time to close the spool. Similarly, when the system pressure is 0.7 MPa and 0.8 MPa, the liquid resistance is too great, preventing the spool from closing in time. However, when the system pressure is 0.2 MPa, due to the liquid resistance to the spool being insufficient, the spring reset force can close the spool in time. Conversely, when the system pressure is 0.4, 0.5, and 0.6 MPa, the reset force is sufficient, and the liquid resistance to the spool is minimal, allowing the spool to close in a timely manner.



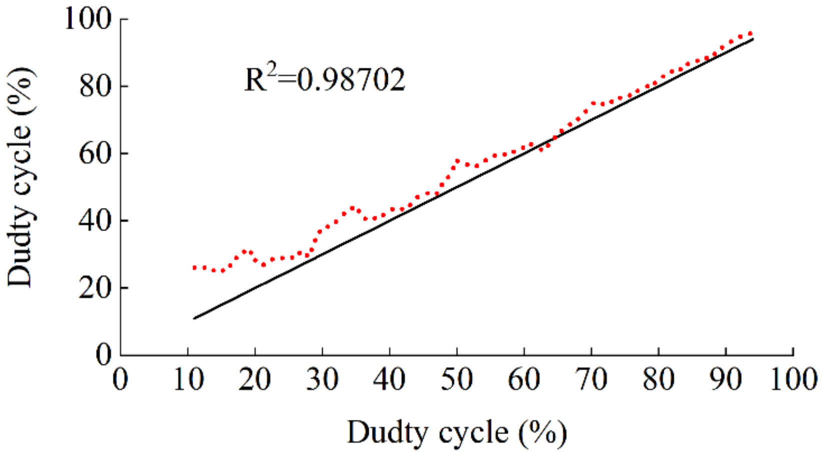
a. 0.2MPa *b. 0.3MPa*



c. 0.4MPa *d. 0.5MPa*



e. 0.6MPa *f. 0.7MPa*



g. 0.8MPa

Fig. 14 – Set duty cycle and actual duty cycle at different pressures of electromagnetic nozzle

CONCLUSIONS

The aim of this study was to address the limitations of the existing farmland application system, which is characterised by low precision in variable spraying. The design and analysis of a variable spraying system based on the PTO protocol were conducted, and the results were verified through experimental testing. This system is capable of independently controlling the spray amount of each spray nozzle according to the application demand, offering a potential solution to the aforementioned issues.

In the designed variable spray system, the upper computer inputs the spray amount and sends it to the main controller. RTK_GNSS, using the um482, achieves RTK differential positioning, collecting the real-time position and speed information of the equipment and sending it to the main controller via the serial port. The main controller, with the STM32 at its core, calculates the required frequency and duty cycle based on the received spray amount and speed information, and sends this data via the CAN bus to the multiplex controller. The multiplex controller extracts the corresponding frequency and duty cycle information and outputs it to the electronic switches, controlling the on-off states of multiple switches. This controls the PWM duty cycle and frequency of each electromagnetic nozzle, achieving independent regulation of each nozzle's flow.

The test results for the electromagnetic nozzle at a PWM frequency of 10 Hz are as follows: at a pressure of 0.2 to 0.3 MPa, the minimum duty cycle for the electromagnetic nozzle is 8%; at a pressure of 0.4 MPa, the minimum duty cycle is 9%; at a pressure of 0.5 to 0.6 MPa, the minimum duty cycle is 10%; Finally, at a pressure of 0.7 to 0.8 MPa, the minimum duty cycle is 11%.

In a pressure range of 0.2 to 0.8 MPa, the maximum duty cycle that can be achieved by the electromagnetic nozzle is 94%. When the PWM signal frequency is 10 Hz, the system pressure at 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 MPa is as follows: when the duty cycle is between 11% and 94%, the average relative error between the actual duty cycle and the set duty cycle is 6.42%, 12.7%, 8.6%, 10.8%, 8.2%, 14.8%, and 17.0%, respectively. When the duty cycle is between 20% and 94%, the average relative error between the actual duty cycle and the set duty cycle is 3.27%, 10.5%, 2.1%, 3.9%, 4.1%, 9.6%, and 12.1%, respectively.

The results demonstrate that the spray system exhibits inadequate control of the electromagnetic nozzle in the duty cycle range of 11% to 20%. Conversely, it exhibits optimal control stability and reliability in the duty cycle range of 20% to 94%. This performance is sufficient to meet the fundamental requirements of variable spraying.

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