DESIGN AND EXPERIMENTAL STUDY OF A VEHICLE-MOUNTED FERTILIZING AND SPRAYING MACHINE
/
车载式施肥喷药机的设计与试验研究

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ABSTRACT
In order to solve the problems of low efficiency of fertilization and spraying in the hilly mountains of China, a vehicle-mounted fertilization and spraying machine was designed. The whole structure and working principle of the machine were described, and the key components of fertilization and spraying are designed. The kinetics and kinematics of fertilizer particles and droplets were modeled by theoretical analysis of their motion characteristics in the air. The fertilization and variable spraying control system based on the core controller MCU (Microcontroller Unit) was set up. And the system can adjust the rotational speed of the disc and can automatically change the spraying volume by real-time detection of forward speed to achieve a constant spraying volume per unit area. The test results showed that: when the disc speed was greater than 90 r/min, the uniformity coefficient of variation was less than 15%, which satisfied the operational requirements; the uniformity coefficient of variation reached the minimum value of 10.03% when the disc rotation speed was 180 r/min, and the best fertilization performance was achieved at this time. In the spraying system, the actual spraying volume increased with the increased forward speed, and the relative error between the theoretical flow rate and the actual flow rate was 6.25% at most, and the average error was 5.94%, which could achieve the purpose of variable spraying. The research results can provide technical reference for the design and development of fertilization and spraying machinery in hilly areas.

摘要
针对中国丘陵山区施肥、喷药效率低的问题，设计了一种车载式施肥喷药机。介绍了该机的整机结构和工作原理，对施肥、喷药的关键部件进行了设计。通过对肥料颗粒和液滴在空气中的运动特性进行了理论分析，建立了其动力学和运动学模型。搭建了以单片机为核心控制器的施肥与变量喷药控制系统，该系统可调节圆盘转速，并能通过实时检测前进速度自动改变喷药量，实现单位面积喷药量恒定作业。试验结果表明: 当圆盘转速大于 90r/min 时，均匀性变异系数均小于 15%，满足作业要求；当圆盘转速为 180r/min 时,均匀性变异系数达到最小值 10.03%，此时施肥性能最好。喷药系统中，实际喷药量随前进速度的增大而增大，理论流量与实际流量的相对误差最大为 6.25%，平均误差为 5.94%，能够达到变量喷药的目的。研究结果可为丘陵山区施肥与喷药机械的设计与研制提供技术参考。

INTRODUCTION
Fertilization and spraying are important and effective ways to meet planting requirements and improve crop yield and quality in agricultural production (*Mueller et al., 2012; Owen-Smith et al., 2019*). According to reports, the consumption of fertilizers and pesticides in agricultural production in China is increasing year by year, and its average consumption is much higher than the global level (*Chen et al., 2015; Gargari et al., 2019; Chen et al., 2018*). However, the current utilization rate of fertilizers and pesticides in China is not high. Among them, the utilization rate of chemical fertilizers is only 30%-40%, and the utilization rate of pesticides is only 30%-50% (*Yang et al., 2020; Mei et al., 2016*). Therefore, it is necessary to achieve efficient fertilization and spraying by using machines to improve agricultural productivity and protect the environment.

In the research of fertilizer applicators, some scholars designed a layered and quantitative fertilization device and optimized its parameters, and field experiments showed that the device meets the requirements of fertilization (*Liu et al., 2021*).

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Some scholars developed a double-disc centrifugal variable rate fertilizer spreader by combining discrete element simulation and control algorithm (*Abbou-ou-Cherif et al., 2019*). Other scholars have designed a multi-reflux variable spraying control system. The control system can adjust the proportional control valve according to the driving speed of the spraying machine, and then change the spraying flow to realize the variable spraying (*Wang et al., 2019*).

The above research is mainly focused on the research of large and single operation machinery. However, it is difficult for large-scale fertilizer spreaders and sprayers to carry out field operations due to the complicated terrain in hilly areas of China (*Reyes et al., 2015; He, 2020*). Consequently, this paper proposes a vehicle-mounted fertilizing and spraying machine to meet the needs of agricultural production, which is small in size and light in weight. And it can improve people's work efficiency.

MATERIALS AND METHODS

General structure and operational principle

The vehicle-mounted fertilizing and spraying integrated machine was composed of four parts: control system; fertilization device; spraying device and walking device. Its general structure is shown in Fig.1.

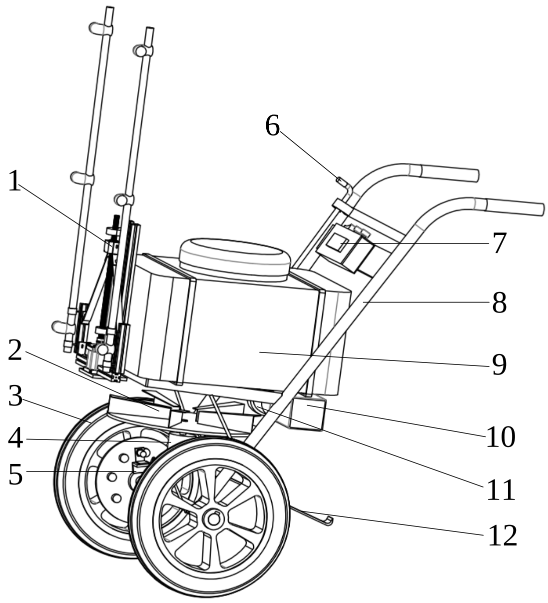


Fig. 1 - Structural diagram of vehicle-mounted fertilizer spreading and spraying machine

1. Multi-directional adjustable spray rod device; 2. Fertilizing disc; 3. Wheel; 4. DC motor of row of fertilizer; 5. Hall speed measuring device; 6. Fertilizer adjustment lever; 7. Control system; 8. Rack; 9. Water/Fertilizer box; 10. Battery; 11. Pump; 12. Brace

When the machine is running, fertilization or spray operations should be independently chosen by the staff according to their actual needs. If people choose fertilization operations, they can manually control the fertilizer adjustment rod to adjust the size of the opening of the fertilizer mouth, and the rotation speed of the fertilizer disc is set by manually adjusting the knob. The fertilizer falls onto the disc by gravity and is spread by the centrifugal force of the disc. If people want to carry out spraying operations, the angle of spread between the spray bars can be adjusted electrically through the knob, and users can independently select three different spraying modes: horizontal, vertical and tilt, in order to improve the coverage of fog drops. The amount of spray per unit area is set by the potentiometer, and the wheel speed is collected by the control system to change the amount of spray in real time, so as to achieve the purpose of variable spray.

Fertilizer application mechanism design

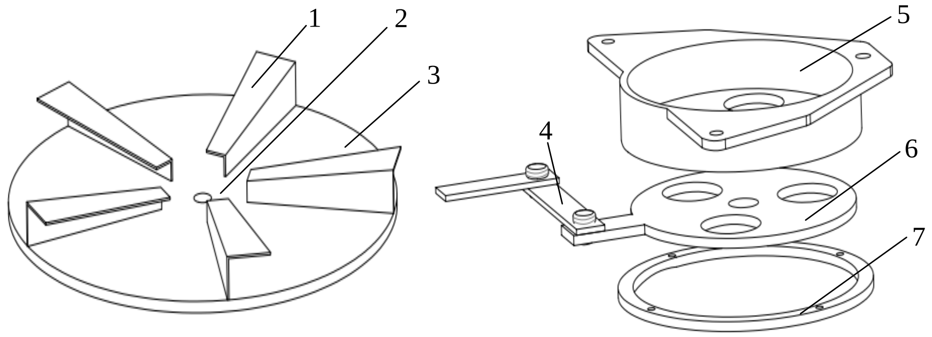
Fertilizer application mechanism mainly includes the fertilizer spreading disc and fertilizer volume adjustment device. Its structure is shown in Fig. 2. The fertilizer spreading disc is mainly composed of the disc, fertilizer bearing area and the blades. The fertilizer adjustment device mainly includes a fixed plate, moving plate, fixed ring and adjusting lever, which are used to adjust the fertilizer application amount by controlling the mutual position of the moving plate and the fixed plate.

Kinematics Analysis of fertilizer granules in air

According to theoretical mechanics, the centrifugal force on the fertilizer particle must be greater than or equal to its friction force in order for it to be thrown from the disk, which satisfies the formula:

$$\begin{cases} mr\omega^2 \geq \mu mg \\ \omega = 2\pi n \end{cases} \tag{1}$$

where: m is the mass of fertilizer particles, g; r is the distance between fertilizer particles and the center of the disc, mm; μ is the friction coefficient between the particles and the disc; ω is the rotational angular speed of the disc, rad/s; n is the rotational frequency of the disc, s^{-1}.



(a) Fertilizer spreading disc *(b)Fertilizer adjustment device*

Fig. 2 - The structure of fertilizer application mechanism

1. Disc; 2. Fertilizer bearing area; 3. Blade; 4. Adjusting lever; 5. Fixed plate; 6. Moving plate; 7. Fixed ring

Then, according to Equation (1), the rotation frequency n of the disk needs to meet:

$$n \geq \frac{1}{2\pi}\sqrt{\frac{\mu g}{r}} \tag{2}$$

Assuming that the rotation of the particles themselves and the influence of wind speed in the environment on fertilizer spreading are ignored, the fertilizer particles thrown into the air are mainly subjected to the action of air resistance F and gravity G and fall to the ground along a parabola (*Shi et al., 2018; Shi et al., 2021*). As shown in Fig. 3, the motion state can be divided into two stages: upthrow and descent. Then, the gravity and air resistance of the fertilizer particles, respectively, are:

$$\begin{cases} F = \frac{1}{2}\rho SCV^2, \quad S = \frac{\pi d^2}{4} \\ G = mg, \quad m = \frac{\pi}{6}\rho d^3 \end{cases} \tag{3}$$

where: C is the air resistance coefficient, sphere $C = 0.44$; ρ is the air density, kg/m^3; S is the windward area of fertilizer particles, m^2; V is the relative velocity of fertilizer particles with air, m/s.

In the upthrowing stage, the air resistance and gravity decomposition of fertilizer particles can be divided into horizontal and vertical directions. According to Newton's second law, it can be obtained:

$$\begin{cases} F_{X1} = \frac{\rho SC}{2}\sqrt{V_{X1}^2 + V_{Z1}^2}V_{X1} \\ \frac{\mathrm{d}^2 X_1}{\mathrm{d}t_1^2} = -\frac{F_{X1}}{m} \\ F_{Z1} = \frac{\rho SC}{2}\sqrt{V_{X1}^2 + V_{Z1}^2}V_{Z1} \\ \frac{\mathrm{d}^2 Z_1}{\mathrm{d}t_1^2} = -\frac{F_{Z1}}{m} - g \end{cases} \tag{4}$$

It can be obtained from Equation (4) that:

$$\begin{cases} t_1 = \sqrt{\frac{2mZ_1}{F_{Z1} + mg}} = \sqrt{\frac{4mZ_1}{\rho SC\sqrt{V_{X1}^2 + V_{Z1}^2}V_{Z1} + 2mg}} \\ X_1 = \frac{F_{X1}t^2}{2m} = \frac{\rho SC\sqrt{V_{X1}^2 + V_{Z1}^2}V_{X1}Z_1}{\rho SC\sqrt{V_{X1}^2 + V_{Z1}^2}V_{Z1} + 2mg} \end{cases} \tag{5}$$

where: V_{X1} is the horizontal component of the velocity of fertilizer particles in the upthrowing stage, m/s;

V_{Z1} is the vertical component of the velocity of fertilizer particles at the upthrowing stage, m/s;

t_1 is the movement time of the upthrowing stage, s;

Z_1 is the vertical displacement of fertilizer particles in the upthrowing stage.

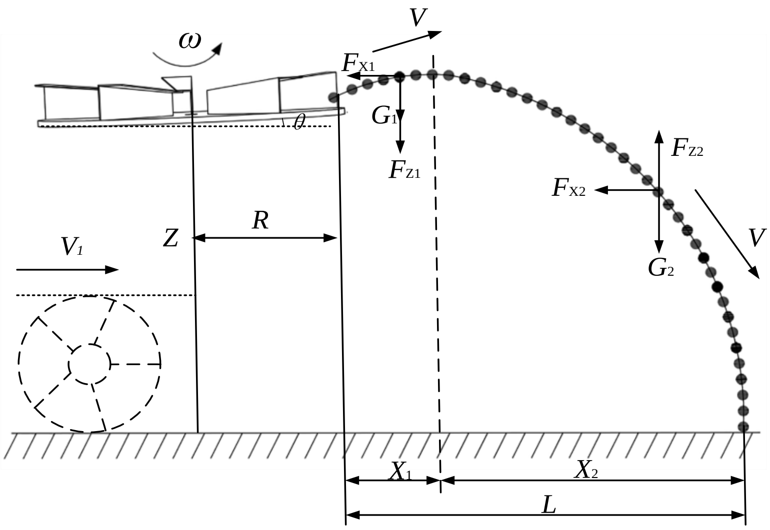


Fig. 3 - Analysis of movement and force of fertilizer particles in air

In the descending stage, the air resistance and gravity of fertilizer particles can also be decomposed in the horizontal and vertical directions. According to Newton's second law, it can be obtained:

$$\begin{cases} F_{X2} = \dfrac{\rho SC}{2}\sqrt{V_{X2}^2+V_{Z2}^2}V_{X2} \\ \dfrac{\mathrm{d}^2X_2}{\mathrm{d}t_2{}^2} = -\dfrac{F_{X2}}{m} \\ F_{Z2} = \dfrac{\rho SC}{2}\sqrt{V_{X2}^2+V_{Z2}^2}V_{Z2} \\ \dfrac{\mathrm{d}^2Z_2}{\mathrm{d}_2{}^2} = \dfrac{F_{Z2}}{m} - g \end{cases} \tag{6}$$

According to Equation (6), the time and horizontal displacement of the descending stage can be calculated as:

$$\begin{cases} t_2 = \sqrt{\dfrac{2mZ_2}{F_{Z2}+mg}} = \sqrt{\dfrac{4mZ_2}{\rho SC\sqrt{V_{X2}^2+V_{Z2}^2}V_{Z2}+2mg}} \\ X_2 = \dfrac{\rho SC\sqrt{V_{X2}^2+V_{Z2}^2}V_{X2}Z_2}{2mg-\rho SC\sqrt{V_{X2}^2+V_{Z2}^2}V_{Z2}} \end{cases} \tag{7}$$

Where, V_{X2} is the horizontal component of fertilizer particle velocity in descending stage, m/s; V_{Z2} is the vertical component of fertilizer particle velocity in descending stage, m/s; t_2 is the movement time of descending stage, s; Z_2 is the vertical displacement of fertilizer particles in descending stage.

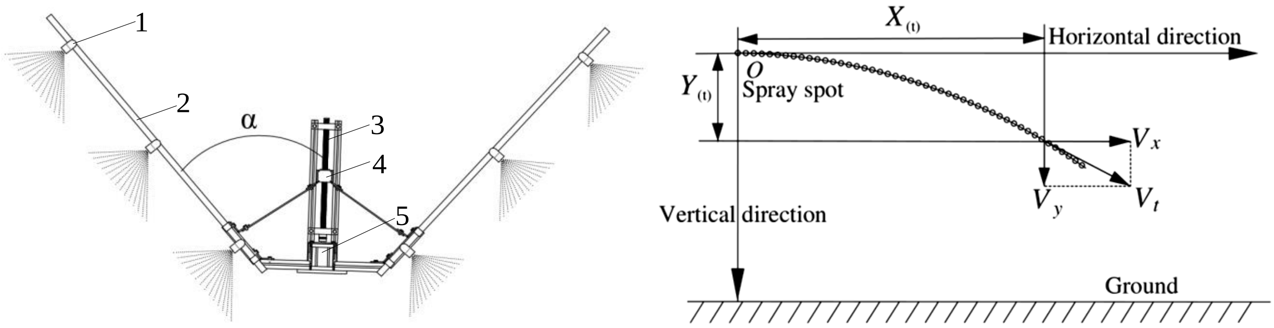
From the above equations (5) and (7), the total time t and total displacement L of fertilizer particles moving in the air can be obtained as:

$$\begin{cases} t = t_1 + t_2 \\ L = X_1 + X_2 \end{cases} \tag{8}$$

According to the above equations (5), (7) and (8), it can be seen that the main factors affecting the distance and time of fertilizer particles are the motion speed and the height of the fertilizer disc in the process of scattering. Based on agronomic requirements and design experience, the diameter and height of the fertilizing disc were set to 250 mm and 500 mm respectively.

Adjustable spray rod mechanism design

The adjustable spray rod mechanism is mainly used to adjust the angle of spray rod expansion by a stepper motor and ball screw mechanism. Its structure is shown in Fig. 4(a). The nozzle is installed on the spray rod and it can be rotated, and the distance between the nozzles is 40 cm. The spray rod is installed on the spray rod, and its horizontal expansion length is 200 cm. The slider and the spray rod are connected by a connecting rod, and the spray rod is installed on the crank. And the control system can move the slider up and down by controlling the forward and reverse rotation of the stepper motor to realize the adjustment of different spray modes.



(a) Structure drawing of adjustable spray rod *(b) Droplet trajectory*

Fig. 4 - Structure drawing of adjustable spray rod
1. Nozzle; 2. Spray rod; 3. Screw rod; 4. Slider; 5. Stepping motor

Kinematics Analysis of droplets in air

When the liquid droplet is ejected from the nozzle, it will make a variable speed movement in the air. Its movement trajectory is shown in Fig. 4(b). The volume and mass of the droplet during its motion are assumed to be constant. Considering that the droplets are fluid, it is known from fluid mechanics that if a single droplet is taken as the research object, the droplet is mainly affected by viscous resistance and gravity in the air. Decomposing the viscous drag f into two directions such as horizontal and vertical, the following formula can be obtained according to Newton's second law.

$$\begin{cases} f_x = -CV_x = m\dfrac{\mathrm{d}V_x}{\mathrm{d}t} \\ f_y = mg - CV_y = m\dfrac{\mathrm{d}V_y}{\mathrm{d}t} \end{cases} \tag{9}$$

where: C is the coefficient of viscous resistance; V_x is the partial velocity in the horizontal direction; V_y is the partial velocity in the vertical direction.

Given that the initial condition is $V_x=V, V_y=0$, the velocity of the droplet motion at moment t can be obtained by integrating equation (9) in the 0-t moment.

$$\begin{cases} V_x = Ve^{-\frac{C}{m}t} \\ V_y = \dfrac{mg}{C}\left(1-e^{-\frac{C}{m}t}\right) \end{cases} \tag{10}$$

The displacement of the droplet in the horizontal and vertical directions can be calculated.

$$\begin{cases} X_{(t)} = V_t\dfrac{m}{C}\left(1-e^{-\frac{C}{m}t}\right) \\ Y_{(t)} = \dfrac{m^2 g}{C}\left(\dfrac{t}{m}+e^{-\frac{C}{m}t}-\dfrac{1}{C}\right) \end{cases} \tag{11}$$

The solve function in MATLAB is used to solve (11), and the trajectory equation of the droplet movement in the air can be obtained as:

$$Y_{(t)} = -\frac{mg}{CV}X_{(t)} - \frac{m^2 g}{C^2}\ln\left(1-\frac{C}{mV}X_{(t)}\right) \tag{12}$$

As can be seen from the droplet motion track equation (12) above, when the droplet ejection height is certain, the droplet spray width in the horizontal direction mainly depends on the initial velocity V of the droplet when it leaves the nozzle. So, the droplet spray speed can be adjusted by changing the PWM duty cycle through the control system to improve the droplet coverage.

Hardware design of control system

According to the general principle of modular division, the control system of the vehicle-mounted fertilization and spraying machine is mainly composed of six parts: main control chip (STC89C52 microcontroller), user setting module, velocity detection module, prompt and alarm module, LCD display in module and motor drive module.

The design block diagram is shown in Fig. 5. These modules are described in detail below in turn.

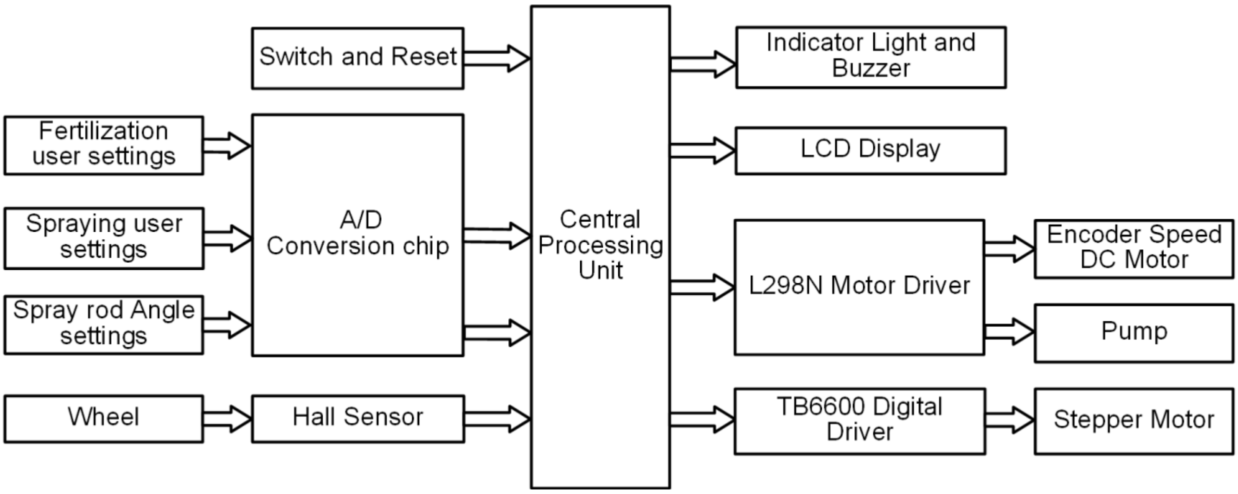


Fig. 5 - Schematics of control system of variable-rate spray

User setting module

User setting module includes three parts: setting unit of rotation speed of fertilization disk, setting unit of spraying volume per unit area and setting unit of spreading angle of spray rod. The operator adjusts the output voltage of the potentiometer by rotating the knob, and the signal is transmitted to the microcontroller through the A/D converter chip. As shown in Fig. 6 (a). The microcontroller receives the signal and outputs PWM pulse signals to control the operation of the coded DC gear motor, water pump and stepper motor after internal timer and counter calculation.

Velocity detection module

In order to achieve variable spraying, the forward speed of the vehicle needs to be collected. The speed detection module consists of a wheel and a Hall sensor mounted on the wheel hub, and a number of magnets are mounted on the disk directly opposite to the Hall sensor, as shown in Figure 1. When the disc rotates with the wheel, the magnetic induction signal received by the Hall sensor (A3144E) is input to the MCU. And the internal timer of the MCU can calculate, by processing the pulse frequency of the Hall sensor and combining with the wheel radius, the vehicle forward speed.

Prompt and alarm module

The prompt and alarm module is mainly composed of a buzzer and LEDs, and its circuit schematic is shown in Fig. 6(c) and (d). Since the operating voltage of the buzzer is so large that the output voltage of the microcontroller I/O cannot be driven directly, a triode amplifier circuit is used to drive it. In addition, the circuit module is designed with current-limiting resistors to prevent excessive current to ensure system safety. By setting the normal human walking speed of 0.4~1.2 m/s in the system, when the system detects that the forward speed is not within the normal operating range, the microcontroller controls the buzzer to make a sound and the LED light flashes continuously to prompt the operator to adjust the operating speed.

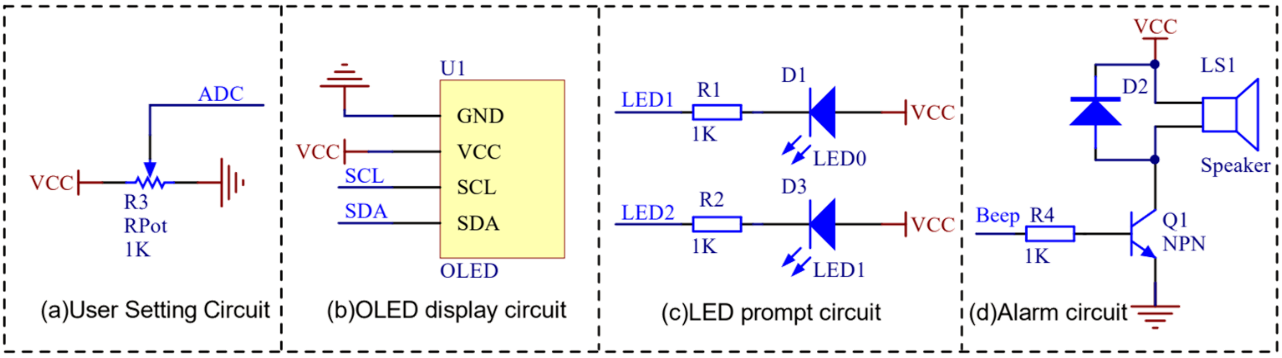


Fig. 6 - Control system submodule circuit schematic

OLCD display module

In order to monitor the operation status of fertilization and spraying operation in real time and facilitate human-computer interaction, liquid crystal display is used to display information such as forward speed, disc speed and spraying volume per unit area, as shown in Fig. 6(b). Since OLED has the advantages of self-illumination and high contrast, 0.96-inch OLED display is used as the display of the human-machine interaction interface. The SCL and SDA interfaces of the OLED display are connected to the I/O ports of the microcontroller, and the data display function can be realized through one-way data transmission.

Motor drive module

The motor drive module includes a DC geared motor drive circuit, a water pump drive circuit and a stepper motor drive circuit. The DC geared motor and the water pump are driven by the L298N motor drive module, and the speed of the motor can be adjusted by adjusting the PWM duty cycle of the MCU output. The DC geared motor has its own Hall encoder, which can measure the speed in real time and is mainly used to drive the rotation of the fertilizer spreading disc. The water pump changes the spraying flow rate in real time according to the forward speed detected by the system and the spraying volume per unit area set by the user to realize variable spraying. The stepper motor is driven by TB6600 digital driver. And the operator mainly uses the knob to control the output of the high and low level signals of the microcontroller to control the operation of the stepper motor.

Software system design

The software system is written in C language, and the modular design is based on the hardware circuit. The flow chart of the system control program is shown in Fig. 7.

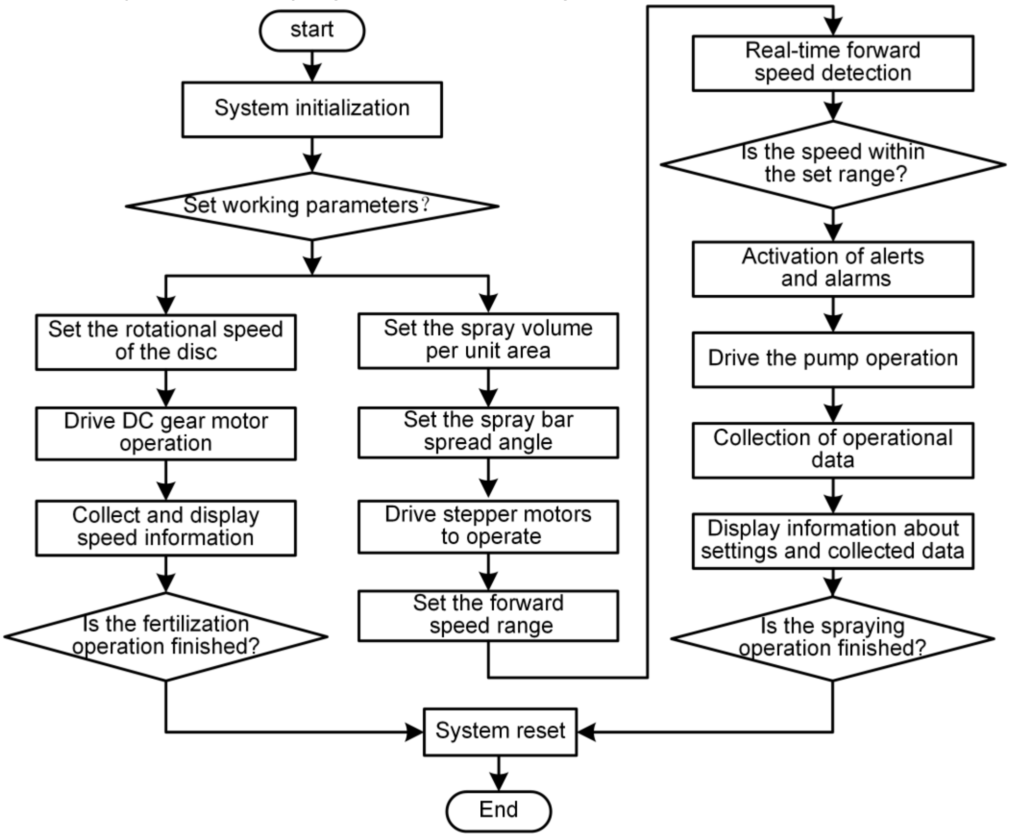


Fig. 7 - Software system flow chart

Firstly, the system is initialized after being powered on, the user selects either fertilizer application or spraying operation. For fertilizer application, the speed of the DC motor is set and the fertilizer spreading disc is driven to rotate for fertilizer application. If the spraying operation is selected, the spraying volume per unit area and the spraying angle of the spray rod are set first. After the system enters the operation state, the forward speed is detected automatically and the pump is controlled to carry out variable spraying. If the detected speed is not within the setting range, the system automatically enters the prompt and alarm program. In addition, the data information during fertilization and spraying is transmitted to the display screen in real time for display.

RESULTS AND ANALYSIS

Performance test of fertilization

The uniformity of fertilizer distribution is an important index to evaluate the effect of fertilization. Generally, the coefficient of variation of uniformity is used to evaluate the uniformity of fertilization (*Yu et al., 2019*). The calculation formula is:

$$\begin{cases} C_V = \dfrac{S_D}{\bar{m}} \times 100\% \\ S_D = \sqrt{\dfrac{1}{n-1}\sum_{i=1}^{n}\left(m_i - \bar{m}\right)^2} \\ \bar{m} = \dfrac{1}{\mathrm{n}}\sum_{i=1}^{\mathrm{n}} \mathrm{m}_i \end{cases} \tag{13}$$

where: C_V is the coefficient of variation of particle distribution, %; S_D is the standard deviation of fertilizer particle quality, g; m is the average mass of fertilizer particles, g; m_i is the quantity of fertilizer particles in the collection box, g; n is the number of collection boxes.

The test material is urea fertilizer pellets with particle size of 0.9~2.8 mm, and the test site is on cement ground. The test method is based on the test method of centrifugal fertilizer spreader as specified in ISO 5690 and ASAE 341.2, and the two-dimensional matrix collection method is adopted. A total of 48 collection boxes (25cm×19cm×6.5cm) were evenly arranged in the test area, with column spacing of 1.2 and row spacing of 1 m. According to the results of the previous study, the opening degree of the fertilizer outlet was set to 60%, because the best fertilization performance was achieved at the same rotation speed of the disk at this time. At the same time, the rotation speed range of the disc was set to 90~210 r/min, and the trolley was run at a certain speed through the collection area after stabilization. After the test, the mass of fertilizer particles in the collection box was weighed using an electronic scale, and the coefficient of variation of uniformity was calculated. The test was repeated three times to take the average value, and the results are shown in Table 1. The test scene is shown in Fig. 8.

Table 1

Test result of fertilizer uniformity

Number of test	Rotation speed of the fertilizer spreading disc /(r/min)				
	90	120	150	180	210
1	17.18	15.16	11.52	10.28	13.56
2	17.86	14.58	10.88	9.45	12.36
3	16.57	14.97	11.05	10.37	13.88
Average value/%	17.20	14.90	11.15	10.03	13.27

As shown in Table 1, the coefficient of variation of uniformity tended to decrease and then increase when the rotation speed of the disc was set to 90~210 r/min, indicating that too low or too high rotating speed of the disc would affect the uniformity of fertilizer spreading. When the rotation speed of the disc was greater than 90 r/min, the uniformity coefficient of variation was less than 15%, which satisfied the relevant regulations for fertilizer application machinery operation (*NYT1003-2006*). Therefore, the rotation speed of the disc should be set above 90 r/min as far as possible in the actual operation. The coefficient of variation of uniformity reached a minimum value of 10.03% when the disc speed was 180 r/min, indicating that the best performance of spreading fertilizer was achieved at this time.

Fig. 8 - Performance test of fertilization

Fig. 9 - Variable spraying performance test

Performance test variable spray

The variable spraying performance test was conducted with reference to the relevant national standard JB/T 9782-2014 "Equipment for crop Protection-General test methods". And the spraying performance was evaluated by using the spraying volume error per unit area *(Luck et al., 2015; Hussain et al.,2020)*. Assuming that the theoretical spraying amount per hectare (1000m²) is K_0, it can be obtained:

$$Q_1 = \frac{K_0 v L}{600} \tag{14}$$

where:

Q_1 is the system's theoretical spray volume per minute, L/min;

K_0 is the unit area spray volume, L/hm²;

v is the forward speed, km/h; L is the spray width, m.

In order to conduct the test more conveniently and accurately, the water liquid was used instead of the medicine solution, and the test was carried out in manual mode. When the test was turned on, the unit area spraying volume was set as 600 L/hm², the forward speed was set as 0.4, 0.8 and 1.2 m/s respectively, and the test time was set as 2 min. A bucket was used to take up the water solution flowing from the pump, and the electronic scale was used to weigh the mass of the water solution collected in the bucket. Finally, the test data is brought into equation (15) to calculate the actual flow rate value, and the test results are shown in Table 2, and the test scenario is shown in Fig. 9.

$$Q_2 = \frac{V}{t} = \frac{6m}{1000\rho} \tag{15}$$

where:

Q_2 is the actual flow, L/min; m is the mass of the water liquid, g;

ρ is the volume mass of water, kg/L; t is the time of the spray work, s.

Table 2

Test result of variable spray control precision

Forward speed (m/s)	Theoretical flow (L/min)	Actual flow (L/min)	Relative error (%)	Average error (%)
0.4	3.60	3.78	5.83	5.94
0.8	7.20	7.65	6.25	
1.2	10.80	11.42	5.74	

The test results show that: the actual spraying volume increases with the increase in forward speed when the variable spraying system is operating under the condition of setting the amount of spray per unit area. And the relative error between the theoretical flow and the actual flow is 6.25% at most, with an average error of 5.94%, which indicates that the system is reasonably designed and can achieve the purpose of variable spraying.

CONCLUSIONS

In this paper, a vehicle-mounted fertilization and spraying machine suitable for operation in hill and mountain operations, with contributions mainly reflected in three aspects.

(1) The structure and operating principle of the whole machine were determined, and the design and description of the fertilization device and the adjustable spray rod device were carried out. The kinetic analysis of the movement of fertilizer particles and droplets in the air was also carried out to determine the key design parameters.

(2) The hardware circuit was designed using a modular design method, and a control system with a microcontroller as the core controller was built. The system can adjust the disc speed in real time for fertilizer application operation; and can change the spraying volume according to the forward speed by setting the unit area spraying volume system to realize variable spraying operation.

(3) Fertilizer application and spraying performance tests were conducted on the developed prototype. The test results showed that the coefficient of variation of uniformity was less than 15% when the rotation speed of the disk is greater than 90 r/min, and the coefficient of variation of uniformity reached the minimum value of 10.03% when the rotation speed of the disk was 180 r/min, and the fertilizer application performance is the best at this time. In the spraying system, the actual spraying volume increased with the increased forward speed, and the relative error between the theoretical flow rate and the actual flow rate was 6.25% at most, and the average error was 5.94%, which could achieve the purpose of variable spraying.

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