Computers and Electronics in Agriculture 169 (2020) 105149

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Design and study on lightweight organic fertilizer distributor

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ARTICLE INFO

Keywords:
Organic fertilizer distributor
Upper row type
Horizontal scraper
Control system

ABSTRACT

Long-term large-scale use of chemical fertilizers will destroy soil fertility, reduce fertilizer efficiency of chemical fertilizers, and lead to crop yield reduction. The application of organic fertilizer can improve soil fertility, provide favorable conditions for crop growth, and promote crop yield. In order to improve the utilization rate and operation efficiency of organic fertilizer in hilly areas and promote the sustainable development of agriculture, this paper designs and studies a lightweight organic fertilizer distributor combined with the current situation of fertilization in hilly areas of China. The lightweight organic fertilizer distributor studied in this paper adopts the top-row row fertilizer method, which mainly consists of the top-row fertilizer apparatus with horizontal scrapers, the horizontal scraper elevating mechanism, the control system and the subsidiary mechanism. In this paper, the mechanical model of horizontal scraper is established and the mathematical model of fertilizer output of fertilizer dispenser is built by analyzing the principle of fertilizer dispensing. The design of each hardware circuit has been completed and the fertilizer control algorithm of the fertilizer applicator has been determined. The performance test of the fertilizer dispenser and the performance test of the whole fertilizer dispenser are carried out. The results show that the control system works steadily and reliably. When the forward speed of the fertilizer applicator is normal (0.5–1.2 m/s) and the set amount of fertilizer application is 900–2100 kg/hm^2, the fertilization amount is accurate, the maximum deviation between the actual amount of fertilizer application and the set amount of fertilizer application is less than 10%; the fertilization uniformity is good and the variation coefficient of uniformity is less than 7%, the actual amount of fertilizer application per unit area, the uniformity of fertilizer application and the forward speed of the fertilizer applicator are good. It has nothing to do with the design requirements.

1. Introduction

Fertilization is an important measure to increase soil nutrients and improve crop growth conditions. However, the utilization of fertilizer in China is about 330 kg/hm^2, which is much higher than the world average level of 120 kg/hm^2 (National Bureau of Statistics, 2017; Food and Agriculture Organization of the United Nations, 2017; Sun and Xue, 2016). Long-term and large-scale utilization of chemical fertilizers will lead to the decline of soil organic matter stocks and negative impact on the survival of soil microorganisms, which would not only destroy soil fertility, but also reduce fertilizer efficiency of chemical fertilizers and crop yield. Varied from chemical fertilizer, organic fertilizer has a multiple kinds of microorganisms, as well as enzymes and stimulants secreted by various microorganisms. The application of organic fertilizer can effectively develop the number and types of soil microorganisms and improve soil fertility (Lal, 2006; Komatsuzaki and Ohta, 2007).

Therefore organic fertilizer, other than chemical fertilizer, can improve the ecological environment and realize an increase in crop yield in a more effective way. At present, most of the fertilizer applicators are exclusive for chemical fertilizers, and there are relatively few machines that can meet the application of organic fertilizer. Consequently, it is necessary to design a widely applicable organic fertilizer applicator to make the adoption of organic fertilizer universe.

In recent years, the international machinery and equipment for the use of organic fertilizers are mainly developing towards large-scale and automation and a variety of fertilizer applicators with high automation and reliability have been developed in European and American countries after a large number of experimental studies. At present, the organic fertilizer applicators are mainly divided into: centrifugal fertilizer

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https://doi.org/10.1016/j.compag.2019.105149
Received 16 June 2019; Received in revised form 2 December 2019; Accepted 4 December 2019

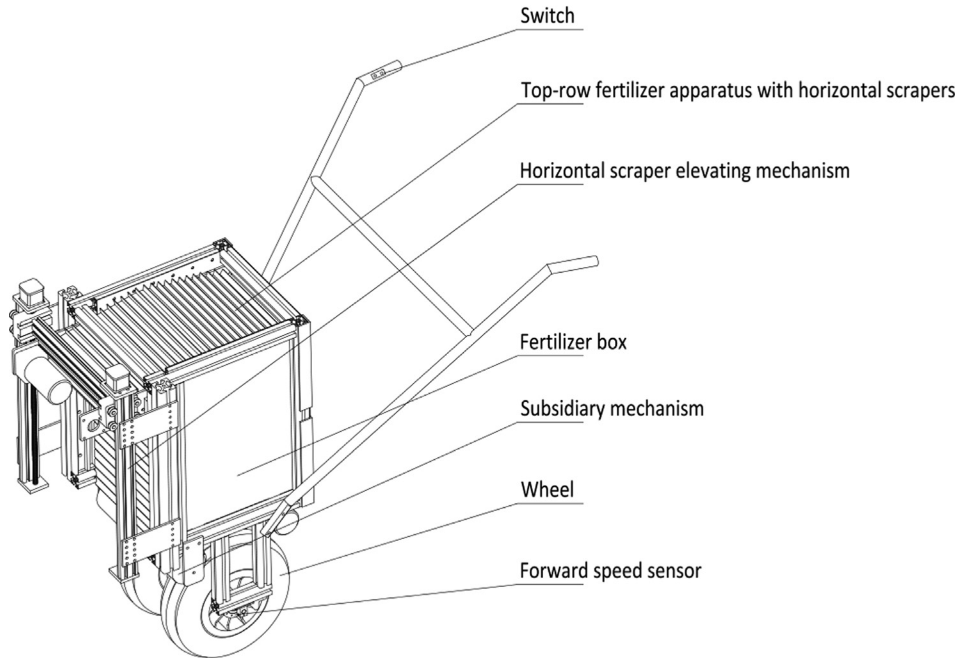

Fig. 1. Block diagram of fertilizer distributor's working principle.

spreader (Patterson and Reece, 1962; Inns and Reece, 1962; Olieslagers et al., 1996; Dintwa et al., 2004; Liedekerke et al., 2009), paddle fertilizer spreader (Bin, 2010), hammer fertilizer spreader (Bin, 2010) and so on.

Centrifugal fertilizer spreader is based on the centrifugal force generated by the high-speed rotating fertilizer plate to throw fertilizer into the field. The advantage of the method is high effectiveness, and the structure of fertilizer tray can be designed single or double. In 1962, Patterson, Reece, Inns (Patterson and Reece, 1962; Inns and Reece, 1962) researched the movement of fertilizer particles on the disk, which has become the theoretical basis of the mathematical model of the disk fertilizer machine. In 1996, R. Olislagaers, H. Ramon (Olieslagers et al., 1996) established a simulation model of the distribution mode of the disk spreader and studied the parameters affecting the distribution of fertilizer. Since then, Edward dintwa (Dintwa et al., 2004); Liedekerke (Liedekerke et al., 2009), et al. have conducted in-depth studies on the distribution of fertilizer particles. Nowadays, one of the most successful products is Sperzier DPX Prima fertilizer spreader from the company Gregor-Besson in France. The maximum capacity of the fertilizer spreader is 2100*L*, with an adjustable throwing distance between 18 and 24 m and an adjustable maximum throwing capacity between 3 and 1000 kg/hm^2. The whole machine weighs 300 kg with the speed of power transmission shaft of 540 r/min. However, the flaw of the equipment is the uneven distribution of fertilizer along horizontal and vertical. The distribution of fertilizer in a single operation is not uniform along with the horizontal and vertical direction, so it is necessary to improve the uniformity by overlapping operation.

The paddle fertilizer spreader (Bin, 2010) is to throw fertilizer into the field through the high-speed rotation of the paddle. There is a certain angle between the throwing paddle and the rotating axis, which makes the scattered fertilizer have a larger width, but it will also produce the same defects as the disc type fertilizer spreader. Typical paddle type fertilizer spreader type - ProPush2000 series, which tails push fertilizer spreader of KUHN Company in France, applies hydraulic propulsion to replace the scraper chain which reduces the moving parts and realizes rapid unloading.

The principle of the hammer type fertilizer spreader (Bin, 2010) is that when the material moves to the discharge port, each hammer will crush the material and scatter the material rhythmically from top to bottom. The throwing feature of this method is that the material is evenly and continuously scattered and the farther away from the body, the thinner the fertilizer is scattered. ProTwin8510 fertilizer spreader invented by CUHN Company is a typical hammer fertilizer spreader, which owns 18 hammers.

However, centrifugal fertilizer spreader, paddle fertilizer spreader, hammer fertilizer spreader are mostly suitable for plain fields. In order to apply fertilizer spreader to more terrain, Zhang (Zhang et al., 2012); Xu (Xu et al., 2018) invented a new type of chain conveyor fertilizer device. Liu (Liu and Dong, 2010); Abrizi (Abrizi et al., 2014), Zhang (Zhang et al., 2012) et al. developed fertilizer applicator for greenhouse orchard, Xia (Xia et al., 2010) developed fertilizer applicator for paddy field. In addition, Li (Li et al., 2018) and Liu (Liu, 2012) realized high-precision fertilization through intelligent algorithm.

There are great differences in fertilization equipment between plain area and hilly area. The fertilizer applicators utilized in plain area are wider and larger with high fertilization efficiency. On the other hand, due to the terrain limitation, most fertilizer applicators utilized in hilly area cannot effectively utilize organic fertilizer, whereas only a few organic fertilizer applicators can make full use of fertilizer in hilly area, with the quality of fertilization still needed a lot to be desired. Combining with our national conditions, especially the actual situation of mountainous and hilly areas in southwest China, this paper tries to study and design a lightweight organic fertilizer distributor, which can effectively improve the quality of organic fertilizer application in Hilly areas, reduce labor intensity and improve the efficiency of fertilization in Hilly areas.

The paper is divided as follows: Section 2.1 describes the overall design of the fertilizer applicator; Section 2.2 introduces the parameters of the top-row fertilizer apparatus with horizontal scrapers in detail; Section 2.3 throws light upon the control system of the fertilizer dispenser; Section 3 elaborates the performance test of the fertilizer discharger and the whole machine at large and provides outcomes and analysis; Section 4 summarizes the main conclusions of the study.

2. Materials and methods

The following paragraphs introduce the main mechanical structure, working principle and control system.

2.1. Overall design

In accordance with the design principles and requirements of solid organic fertilizer applicator, an electric fertilizer applicator for solid organic fertilizer has been designed and manufactured. As is shown in Fig. 1 of the three-dimensional model, the fertilizer applicator consists of a top-row fertilizer apparatus with horizontal scrapers, a horizontal scraper elevating mechanism, a forward speed sensor of fertilizer applicator, a control system, a fertilizer box, a power supply, two wheels and a subsidiary mechanism.

When switching off, the fertilizer applicator enters the working state where is driven by work force. The control system tests the set amount of fertilizer and the speed of the fertilizer applicator. At the same time, the control system automatically adjusts the amount of fertilizer discharged per unit time according to the forward speed of the fertilizer applicator and the amount of fertilizer applied, so that the fertilizer applicator can apply fertilizer steadily and reliably according to the requirements.

2.2. Top-row fertilizer apparatus with horizontal scrapers

The organic fertilizer is physically characterized by the poor fluidity, high moisture content and easy overhead. The traditional organic fertilizer applicator sends organic fertilizer to the discharging roller or rotary disc by conveying mechanism, and sprays organic fertilizer by high-speed rotation. For all its stability and reliability, the method consumes large volume, weight and power. As a consequence, it is difficult for the traditional solid-state organic fertilizer applicator to meet the design requirements of miniaturization and lightweight.

This paper has proposed a top-row fertilizer apparatus with horizontal scrapers, the structure map of which is shown in Fig. 2. The top-row fertilizer apparatus with horizontal scrapers consists of fertilizer apparatus with horizontal scrapers, horizontal scraper elevating mechanism, shutter and auxiliary mechanism. When the fertilizer dispenser starts working, the fertilizer is discharged from the top of the fertilizer dispenser which at the same time is fallen. The fertilizer dispenser always discharges the upper fertilizer in the fertilizer box. The precise control of fertilizer discharge is realized by controlling the descending speed of the fertilizer dispenser and the horizontal movement speed of the horizontal scraper.

Horizontal scraper, as an important component of fertilizer dispenser, is directly connected with the organic fertilizer. It is necessary to establish a mechanical model for its working stress. The horizontal scraper group extracted from the fertilizer discharger is shown in Fig. 3.

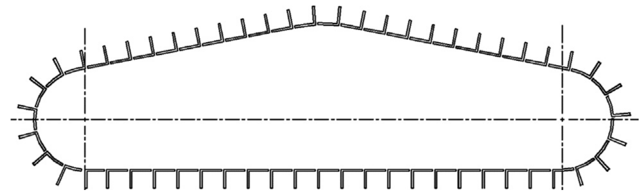

Fig. 3. Horizontal scrapers.

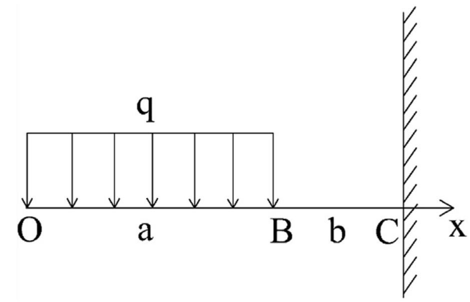

Fig. 4. Force analysis diagram of horizontal scraper.

Owing to the constant spacing of horizontal scrapers, it can be assumed that there is same amount of fertilizer before each horizontal scraper. Hence, if *a* is the depth of fertilizer inserted into the horizontal scraper and *b* is the remaining height, the force of fertilizer on the horizontal scraper is considered as a uniform load with a concentration of *q*. In order to facilitate calculation, it rotates 90 degrees and establishes a coordinate system as is shown in Fig. 4.

According to the static equilibrium equation, the sum of left shear algebra of any section on *OB* segment is

$$F_{OB} = -qx_1 \tag{1}$$

where F_{OB} is the algebraic sum of left shear force on section (kN); q is the load setting of horizontal scraper (kN/mm); x_1 is the distance between the section and point O (mm).

The sum of the left moment algebra of the section is

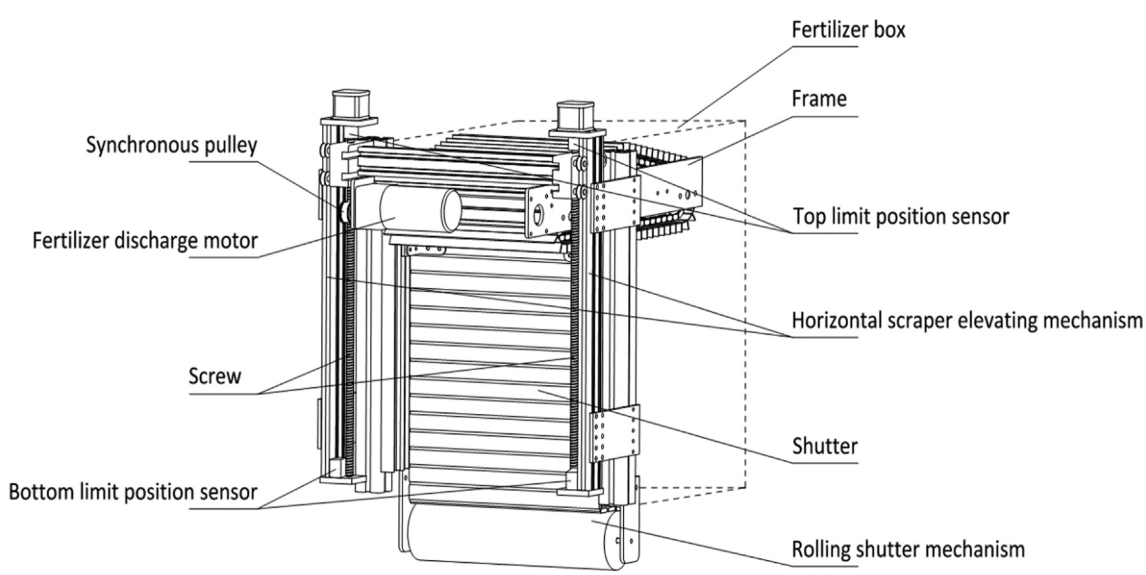

Fig. 2. Structure of top-row fertilizer apparatus with horizontal scrapers.

$$M_{OB} = -\frac{1}{2}qx_1^2 \tag{2}$$

where M_{OB} is the algebraic sum of bending moments to the left of cross section (kN.mm),

The sum of the left shear algebra of any section on the *BC* segment is

$$F_{BC} = -qa \tag{3}$$

where F_{BC} is the algebraic sum of left shear force on section (kN); q is the load setting of horizontal scraper (kN/mm); a is the insertion depth of horizontal scraper (mm).

The sum of the left moment algebra of the section is

$$M_{BC} = -qa\left(x_2 - \frac{a}{2}\right) \tag{4}$$

where M_{BC} is the algebraic sum of bending moments to the left of cross section (kN.mm),

In applications of practical engineering, since the deflection is generally much smaller than its span, the deflection curve is generally a flat curve, thus the differential equation of the deflection curve is as follows:

$$\frac{d^2\omega}{dx^2} = \frac{M}{EI} \tag{5}$$

where ω is deflection (mm); M is bending moment (kNmm); E is tensile modulus of elasticity; I is inertial moment of material cross section to bending neutral axis (mm^4).

Formula (2) is put into formula (5). The results are as follows.

$$EI\frac{d\omega_1}{dx_1} = -\frac{1}{6}qx_1^3 + C_1 \tag{6}$$

where *C1* is a constant of integration;

Meanwhile, the deflection curve equation of *OB* segment can be obtained by integrating formula (6).

$$EI\omega_1 = -\frac{1}{24}qx_1^4 + C_1x_1 + D_1 \tag{7}$$

Similarly, the first-order integral equation of *BC* segment can be obtained

$$EI\omega_2' = -\frac{1}{6}qa\left(x_2 - \frac{a}{2}\right)^3 + C_2 \tag{8}$$

And the deflection curve equation of *BC* segment

$$EI\omega_2 = -\frac{1}{24}qa\left(x_2 - \frac{a}{2}\right)^4 + C_2x_2 + D_2 \tag{9}$$

Since both the deflection and the rotation angle at the fixed end should be equal to zero, the deflection curve should be a continuous smooth curve. Therefore we can get the boundary conditions.

(1) $x_2 = a + b, \omega_2' = 0$;
(2) $x_2 = a + b, \omega_2 = 0$;
(3) $x_1 = x_2 = a, \omega_1 = \omega_2$
(4) $x_1 = x_2 = a, \omega_1' = \omega_2'$

The equations of integral constants C_1, C_2, D_1, D_2 can be obtained by putting the above boundary conditions into formulas (6), (7), (8) and (9), respectively.

$$\begin{gathered} C_2 = \tfrac{1}{6}qa\left(\tfrac{a}{2} + b\right)^3 \\ -\tfrac{1}{6}qa\left(\tfrac{a}{2}\right)^3 + C_2 = -\tfrac{1}{6}qa^3 + C_1 \\ D_2 = \tfrac{1}{24}qa\left(\tfrac{a}{2} + b\right)^4 - C_2(a + b) \\ -\tfrac{1}{24}qa\left(\tfrac{a}{2}\right)^4 + C_2a + D_2 = -\tfrac{1}{24}qa^4 + C_1a + D_1 \end{gathered} \tag{10}$$

The integral parameters C_1, C_2, D_1 and D_2 are obtained by solving the equations and sorting them out. The relationship between the insertion depth a of the scraper and the residual height b of the horizontal scraper is as follows.

$$\begin{gathered} d_1 = -\frac{aq(71a^4 + 96a^3b - 16a^3 + 240a^2b^2 + 256ab^3 + 96b^4)}{384} \\ d_2 = -\frac{aq(a + 2b)^3(7a + 6b)}{384} \\ C_1 = \frac{7a^4q}{48} + \frac{aq(a + 2b)^3}{48} \\ C_2 = \frac{aq(a + 2b)^3}{48} \end{gathered} \tag{11}$$

Since the inclination of the deflection curve is to derive the deflection curve equation once, the integral constants of formula (11) are put into formula (6) and formula (7). Then the deflection curve equation and the section rotation equation of horizontal scraper in *OB* section can be obtained. The section rotation equation of *OB* section is as follows.

$$\theta = \frac{\frac{7a^4q}{48} - \frac{qx_1^3}{6} + \frac{aq(a + 2b)^3}{48}}{EI} \tag{12}$$

where a is insertion depth of horizontal scraper (mm); b is remaining height of horizontal scraper (mm); E is tensile elastic modulus of horizontal scraper; I is inertial moment of cross section of horizontal scraper to bending neutral axis (mm^4); θ is cross section angle of horizontal scraper in insertion section (rad).

The deflection curve equation of horizontal scraper insertion section (*OB* section) is

$$\omega_1 = -\frac{\frac{qx_1^4}{24} + \left(-\frac{7a^4q}{48} - \frac{aq(a + 2b)^3}{48}\right)x_1 + \frac{aq(71a^4 + 96a^3b - 16a^3 + 240a^2b^2 + 256ab^3 + 96b^4)}{384}}{EI} \tag{13}$$

where ω_1 is deflection of horizontal scraper at insertion depth,

The maximum deflection and the maximum cross-section angle of the horizontal scraper are located at the far end of the frame (point *O*), namely $x_1 = 0$. The maximum deflection and the maximum cross-section angle of the horizontal scraper are obtained by putting $x_1 = 0$ into the formula (13) and formula (14). The maximum deflection of the horizontal scraper is

$$\omega_{max} = \frac{aq(71a^4 + 96a^3b - 16a^3 + 240a^2b^2 + 256ab^3 + 96b^4)}{384EI} \tag{14}$$

where ω_{max} is the maximum deflection of horizontal scraper (mm),

The maximum cross-section angle of the horizontal scraper is

$$\theta_{max} = \frac{\frac{7a^4q}{48} + \frac{aq(a + 2b)^3}{48}}{EI} \tag{15}$$

where θ_{max} is maximum section angle of horizontal scraper (rad),

In order to reduce weight, the horizontal scraper is made of aluminium material, the tensile elastic modulus of which is 69 GPa. The maximum insertion depth of the scraper should be less than 15 mm because of the height of the scraper 15 mm. In this limit case $a = 14$ mm, the remaining height $b = 1$ mm, the load concentration $q = 0.157 \times 10^{-3}$ kN/mm, and the formula for calculating the moment of inertia of the horizontal scraper cross section to the bending neutral axis can be obtained. In this paper, $I = 281.25$ mm^4, and according to the formula (15), the maximum angle of rotation is 0.00051 rad, and the maximum disturbance is 0.00088 mm from formula (14), which meets the requirements.

2.3. Control system

The actuator of fertilizer applicator consists of two lifting stepping motors and a fertilizer discharge servo motor. The related sensors include the forward speed sensor of fertilizer applicator, the fertilizer

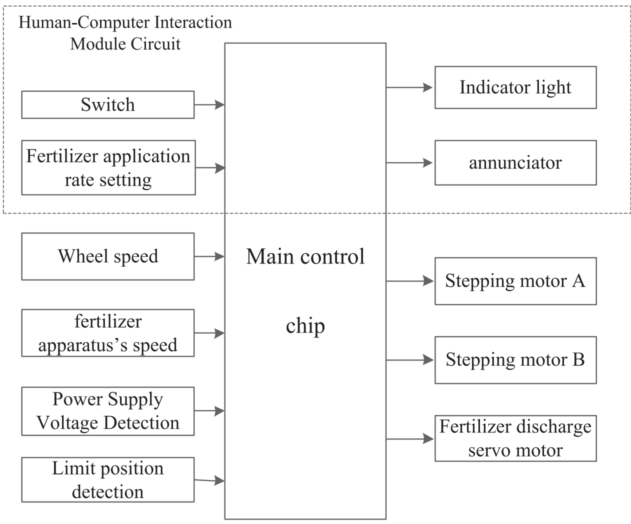

Fig. 5. Design block diagram of hardware circuit.

discharge speed sensor and the limit position sensor of the lifting mechanism. The modular design of the hardware circuit is carried out based on the function of each part of the circuit, and the design block diagram of the hardware circuit is proposed, as shown in Fig. 5.

2.3.1. Driving circuit of horizontal fertilizer discharge motor

The driving circuit of the fertilizer discharging motor is shown in Fig. 6. In order to simplify the driving circuit, the integrated motor power driver chip VNH70AS is utilized.

Because of the control logic and drive axle of the self-contained bridge circuit in VNH70AS, the MCU only needs to give forward and backward instructions, as well as PWM signals. The forward and reverse control of VNH7070 is realized by combining the level of INA port and INB port.

2.3.2. Driving circuit of lifting stepping motor

Fig. 7, as the driving circuit of the stepping motor, functions as controling the falling speed and distance of the two stepper motors independently. Two stepping motor driving modules are used. The pulse signals are provided by two I/O ports of the single chip computer. At the beginning of each fertilizer application machine, the program automatically adjusts the fertilizer arrangement to eliminate the accumulated errors caused by the manufacturing and assembly errors of the screw.

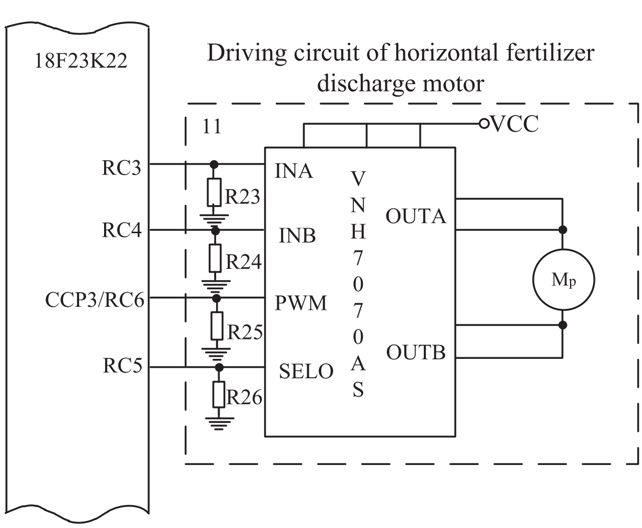

Fig. 6. Driving circuit of horizontal fertilizer discharge motor.

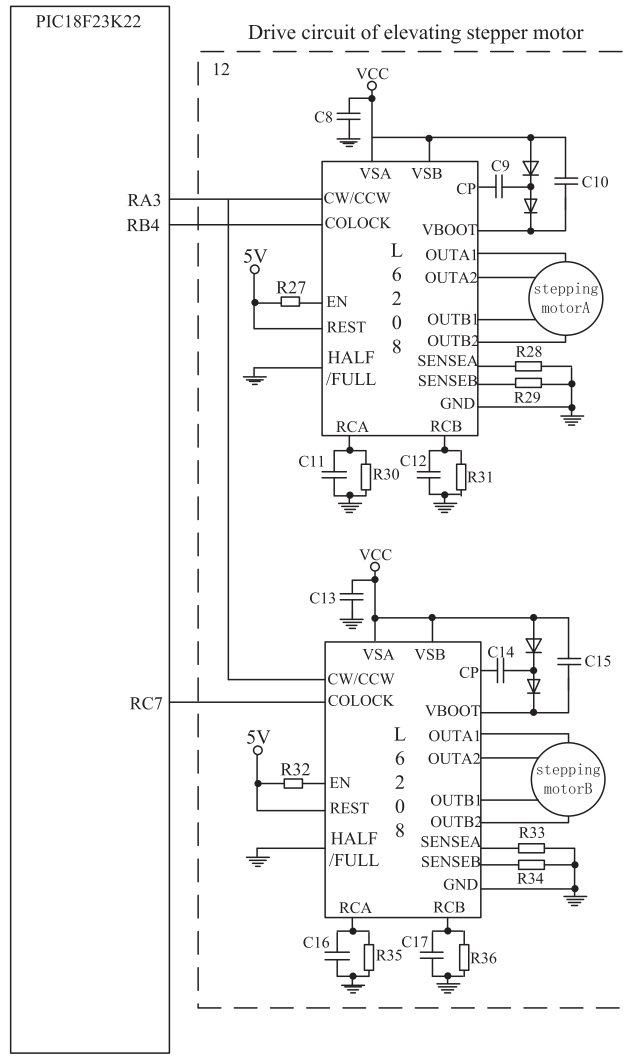

Fig. 7. Drive circuit of elevating stepper motor.

Since the two stepping motors have the same rotation, connecting the RA3 pin of 18F23K22 with two L6208 positive and reverse control pins (CW/CCW) can simultaneously control the forward and reverse of the two stepping motors.

2.3.3. Speed measuring device

In order to make the actual fertilizer amount accurate, the fertilizer amount per unit time is adjusted by the control system according to the forward speed of the fertilizer applicator; in order to make the fertilizer discharge uniform, the control system adjusts the speed of the fertilizer discharge servo motor according to the descending speed of the fertilizer applicator and the speed feedback signal of the fertilizer discharge servo motor. Therefore, the control system needs to collect the forward speed of fertilizer applicator and the rotational speed of fertilizer discharge servo motor (see Fig. 8). In this paper, the Hall switch sensor is applied to collect the speed signal and a circular ring with uniformly distributed through holes along the circumference is printed by 3D printing technology. The permanent magnet is embedded in the through holes and installed on the walking wheel of fertilizer applicator. Combining with the working principle of Hall switch sensor, the Hall sensor of fertilizer applicator will send out a pulse signal whenever the wheel rotates at a certain angle. The relationship between the frequency of the pulse signal and the speed of the wheel is as follows:

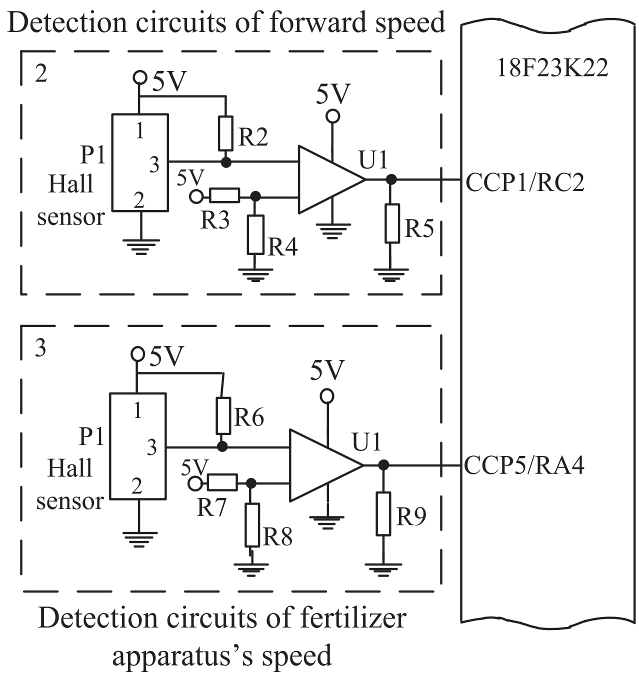

Fig. 8. Detection circuits of forward speed and fertilizer apparatus's speed.

$$n_r = 60\frac{f}{N} \tag{16}$$

where n_r is the speed of wheel (r/min); f is the frequency of pulse signal from Hall sensor (Hz); N is the number of uniformly distributed magnets on the ring.

Assuming that the diameter of the wheel is D, the relationship between the frequency of the pulse signal and the speed of the wheel is as follows

$$v = \frac{n_r}{60}\pi D = \frac{\pi D}{N}f \tag{17}$$

where V is the forward speed of fertilizer applicator (m/s),

It is known that the diameter of the walking wheel of the fertilizer applicator is $D = 30$ cm and the number of magnets is $N = 12$. Then put them into the formula (17). The relationship between the walking speed of the fertilizer applicator and the pulse signal is as follows:

$$v = 0.0785f \tag{18}$$

Because the Hall sensor is installed far away from the controller, the signal attenuation caused by the long distance of the conductor will occur. Given the reliability, a comparator is added to the controller circuit for shaping the signals emitted by Hall sensors.

2.3.4. Human-computer interactive circuit

The most important human-computer interaction functions of the fertilizer applicator are fertilizer amount setting and alarm prompt. This section will elaborate on the fertilizer rate setting circuit and alarm and prompt circuit.

The fertilizer setting circuit is shown in Fig. 9. The fertilizer amount of the fertilizer applicator is regulated by the operator's rotary potentiometer. The A/D sampling accuracy of PIC18F23K22 is 10 bits, hence it can be divided into 1023 grades between maximum and minimum fertilization. Fertilizer application can be adjusted within 900 kg/hm^2–2100 kg/hm^2, that is, 1.17 kg/hm^2 for each additional grade. Compared with its adjustment range, it can be considered that the amount of fertilizer application is continuously adjustable.

In order to reduce the interference signals from environmental factors and improve the detection accuracy of fertilizer application, a first-order low-pass RC filter is added to the output of the potentiometer.

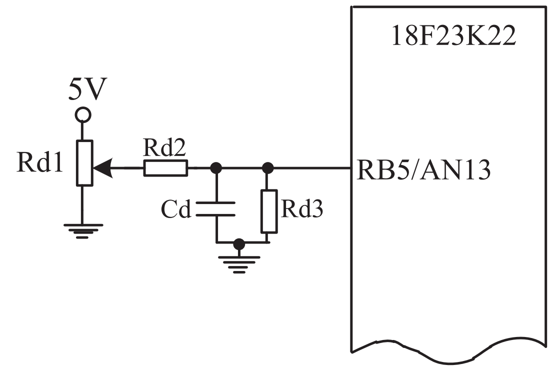

Fig. 9. Detection circuit of fertilizer application rate setting.

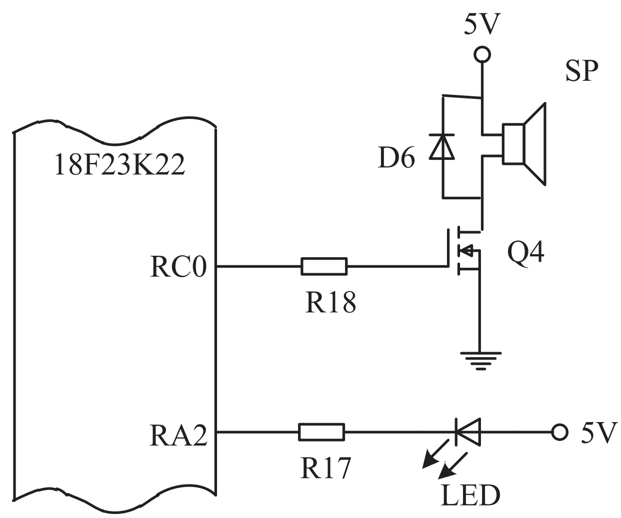

Fig. 10. Prompt and alarm circuit.

As is shown in Fig. 10, the alarm function of fertilizer applicator is mainly completed by buzzer and indicator lamp. The buzzer and indicator light emit different sound and flicker frequency according to the current state of fertilizer applicator.

Thanks to a relatively large working current of buzzer, single chip computer cannot directly drive buzzer. The buzzer is driven by a field effect transistor, and the state of the field effect transistor can be controlled by a single chip computer. Because the buzzer is an inductive load, if the buzzer is disconnected directly without protection measures, it may occur that the voltage is too high to break down the field effect transistor. Therefore, a diode is connected in parallel beside the buzzer to continue the current, so as to avoid the high voltage caused by the rapid change of the current and break down the field effect transistor.

2.3.5. Speed control algorithms of fertilizer discharge servo motor

In order to make the discharged fertilizer more uniform, it is necessary to adjust the speed of the fertilizer discharger servo motor in real time. In this paper, PWM technology is leveraged to adjust the speed of the servo motor, while closed-loop control is employed to adjust the speed of the servo motor in real time. The control system first calculates the ideal speed of the servo motor and detects the actual speed of the servo motor, then calculates the two speeds through the algorithm, so as to get the control law of the speed of the servo motor.

In order to control the speed of the fertilizer discharger servo motor in real time, a digital PID controller is designed in this paper. The control principle is shown in Fig. 11.

In the figure, *r(s)* is the ideal speed of the motor, whereas *c(s)* is the actual speed of the motor. After comparing the two, the speed error

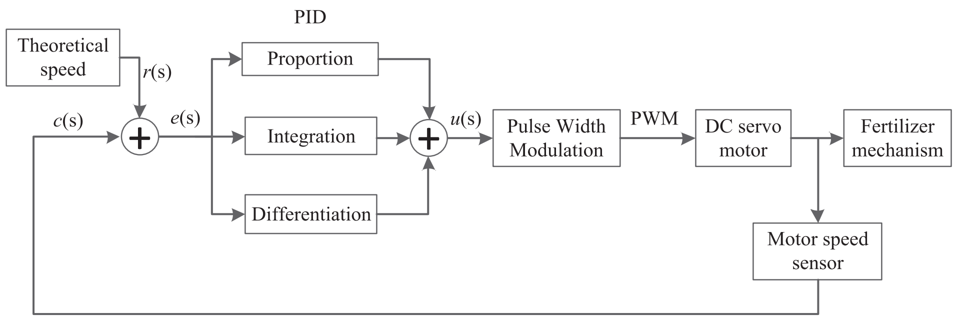

Fig. 11. Block diagram of digital pid controller.

value *e(s)* is obtained. The speed error value *e(s)* is calculated by PID and the output control quantity *u(s)* is obtained. According to the control quantity *u(s)*, the PWM duty ratio of the horizontal fertilizer discharge servo motor is adjusted to realize the speed control of the motor. The equations of PID proportional, integral and differential control are shown in the equation.

$$u_s = P\left[e_s + T_D\frac{e_s - e_{s-1}}{T} + \frac{T}{T_I}\sum_{j=0}^{k} e_j\right. \tag{19}$$

where u_s is the PID output control quantity; P is the proportional coefficient; e_s is the deviation quantity; T is the sampling time; T_I is the time integral constant; T_D is the differential time constant.

The deviation is

$$e_s = r_s - c_s \tag{20}$$

When controlling the speed of the horizontal fertilizer dispenser servo motor, the increment of control amount Δu_s can be applied to control it. Therefore, the paper adopts the incremental algorithm of PID. The PID incremental algorithm can be obtained by formula (19). The output control quantity $u_{(s-1)}$ can be obtained by formula (19).

$$u_{s-1} = P\left[e_{s-1} + T_D\frac{e_{s-1} - e_{s-2}}{T} + \frac{T}{T_I}\sum_{j=0}^{s-1} e_j\right] \tag{21}$$

By subtracting formula (19) from formula (21), we can get

$$\Delta u_s = u_s - u_{s-1} = P\left(1 + \frac{T}{T_I} + \frac{T_D}{T_I}\right)e_s - P\left(1 + 2\frac{T_D}{T_I}\right)e_{s-1} + P\frac{T_D}{T_I}e_{s-2} \tag{22}$$

Let $M = P\left(1 + \frac{T}{T_I} + \frac{T_D}{T_I}\right)$, $N = P\left(1 + 2\frac{T_D}{T_I}\right)$, $Q = P\frac{T_D}{T_I}$, then

$$\Delta u_s = Me_s - Ne_{s-1} + Qe_{s-2} \tag{23}$$

Formula (23) shows that if the sampling period of the speed is a fixed period, after M, N and Q are determined, the control system can calculate the PWM duty cycle adjustment increment of adjusting the output speed of the horizontal fertilizer discharge servo motor only by calculating the deviation of the current speed and the deviation of the first two times.

3. Experiments and analysis

3.1. Performance test of fertilizer dispenser

In order to test the actual performance of the lightweight organic fertilizer distributor, the performance test of the fertilizer discharger and the whole machine will be carried out. Fig. 12(a) is the performance test site of the fertilizer dispenser, and Fig. 12(b) is the whole machine test site.

In order to accurately detect the amount of fertilizer discharged from the fertilizer dispenser, the fertilizer dispenser is fixed and a fertilizer box is placed under the fertilizer outlet of the fertilizer dispenser to collect and weigh the discharged fertilizer. The signal generator is used to send out pulse signals to simulate the speed of the wheel. At the same time, the digital oscilloscope is used to observe the speed signal of the servo motor of the fertilizer dispenser and the pulse signal of the stepper motor of the lifting mechanism.

According to the working requirements of light and simple organic fertilizer applicator, in the field with a row spacing of 1.3 m, the range of fertilizer discharge is 900 kg–2100 kg per hectare and the walking speed of organic fertilizer applicator is 0.5–1.2 m/s.

$$P_d = 1000\bullet\frac{13}{100000}\bullet V_s P_{sa} = \frac{13000}{100000}\bullet V_s P_{sa} = 0.13 V_s P_{sa}(g) \tag{24}$$

where *Vs* is the advancing speed of fertilizer applicator (m/s); P_{sa} is the amount of fertilizer applied per hectare set by operator (kg).

The result shows that the amount of fertilizer discharged per minute by the fertilizer applicator is 3.5–19.6 kg/min. Therefore, when the fertilizer output was set at 900 kg/hm^2, 1500 kg/hm^2 and 2100 kg/hm^2, the relationship between the actual fertilizer output and the forward speed of the fertilizer applicator can be tested. During the test, the amount of fertilizer discharged is recorded in 20 s as a unit time, and the forward speed of the fertilizer applicator is simulated by pulse signal. The experimental data are shown in Table 1.

The data of input square wave frequency and fertilizer output in Table1 are analyzed by linear regression analysis. If the input square wave frequency is set to X, the amount of fertilizer discharged is Y. When the input pulse signal frequency reaches a certain value of X_i, the output fertilizer discharge measurement Y_i is obtained, and the relationship between Y_i and the input pulse signal frequency is as follows:

$$\widehat{Y_i} = a + bX_i \tag{25}$$

where Y_i is the measurements of output fertilizer discharge; X_i is the input pulse frequency at a certain time; a is the constant term of regression equation; b is the regression coefficient.

When the amount of fertilizer discharged is set at 900 kg/hm^2, the regression curve is shown in Fig. 13. The regression equation is as follows, the correlation coefficient is 0.995, and the linear regression is significant.

$$y = 0.1861x + 0.0357 \tag{26}$$

When the amount of fertilizer discharged is set at 1500 kg/hm^2, the regression curve was shown in Fig. 14. The regression equation is as follows, the correlation coefficient is 0.997, and the linear regression is significant.

$$y = 0.3054x + 0.1223 \tag{27}$$

The regression curve is shown in Fig. 15 when the fertilizer output is 2100 kg/hm^2. The regression equation is as follows, the correlation coefficient is 0.998, and the linear regression is significant.

$$y = 0.4204x + 0.2153 \tag{28}$$

In summary, the correlation coefficients between the pulse frequency of forward velocity signal and actual fertilizer discharge are 0.995, 0.997 and 0.998 when the fertilizer discharge is set at 900 kg/

(a) (b)

Fig. 12. Trial pictures of prototype, (a) field trial of fertilizer apparatus performance (b) field trial of overall unit.

hm^2, 1500 kg/hm^2 and 2100 kg/hm^2, respectively, and the linear relationship is good. The actual amount of fertilizer applied in the field is accurate and has nothing to do with the forward speed of the fertilizer applicator. The maximum deviation between the actual amount of fertilizer discharged and the set amount of fertilizer discharged is less than 6%.

3.2. Performance test of fertilizer applicator

The fertilizer amount of the fertilizer applicator can be adjusted between 900 kg/hm^2 and 2100 kg/hm^2. The set fertilizer amount is tested under the conditions of 2100 kg/hm^2, 1725 kg/hm^2, 1275 kg/hm^2 and 900 kg/hm^2, respectively. During the experiment, the forward speed of the fertilizer applicator is kept within the range of 0.5 m/s–1.2 m/s, and the test distance was 10 m. The data of the experiment are collected per meter with 1 m as a measuring unit. An electronic scale with a precision of 1 *g* is selected to measure the amount of fertilizer applied and record the actual amount of fertilizer applied.

In order to facilitate analysis, the measured fertilization data are numbered and recorded in Table 2. From Table 2, it can be seen that the actual amount of fertilizer applied by the fertilizer applicator can meet the requirements of fertilization. The error between the actual fertilizer application and the set fertilizer application is less than 10%.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{29}$$

Table 1
Performance test data sheet of fertilizer apparatus.

No	Stated fertilizer quantity/kg	Input pulse/Hz	Corresponding forward speed/(m/s)	Fertilizer quantity in 20 seconds/kg				Actual fertilizer quantity per hectare/kg
				First group	Second group	Third group	Average value	
1	900 kg/hm^2	15	1.18	2.95	2.73	2.81	2.83	899.40
2		14	1.1	2.57	2.53	2.56	2.553	870.30
3		13	1.02	2.56	2.49	2.48	2.51	922.80
4		12	0.94	2.28	2.37	2.28	2.31	921.60
5		11	0.86	2.15	2.16	2.01	2.107	918.75
6		10	0.79	1.86	1.93	1.93	1.907	905.25
7		9	0.71	1.65	1.71	1.7	1.687	891.00
8		8	0.63	1.52	1.47	1.52	1.503	894.60
9	1500 kg/hm^2	15	1.18	4.74	4.71	4.51	4.653	1478.70
10		14	1.1	4.61	4.25	4.56	4.473	1524.90
11		13	1.02	3.98	4.13	4.23	4.113	1512.15
12		12	0.94	3.79	3.94	3.62	3.783	1509.15
13		11	0.86	3.29	3.35	3.52	3.387	1476.90
14		10	0.79	3.24	3.15	3.23	3.207	1522.35
15		9	0.71	2.96	2.92	2.81	2.897	1530.15
16		8	0.63	2.52	2.62	2.54	2.56	1523.85
17	2100 kg/hm^2	15	1.18	6.57	6.84	6.28	6.563	2085.75
18		14	1.1	5.9	6.35	6.43	6.227	2122.80
19		13	1.02	5.49	5.48	5.88	5.617	2065.05
20		12	0.94	5.16	5.09	5.15	5.133	2047.80
21		11	0.86	4.78	4.89	4.71	4.793	2089.95
22		10	0.79	4.35	4.32	4.33	4.333	2056.80
23		9	0.71	4.11	3.97	4.15	4.077	2153.40
24		8	0.63	3.67	3.69	3.6	3.653	2174.40

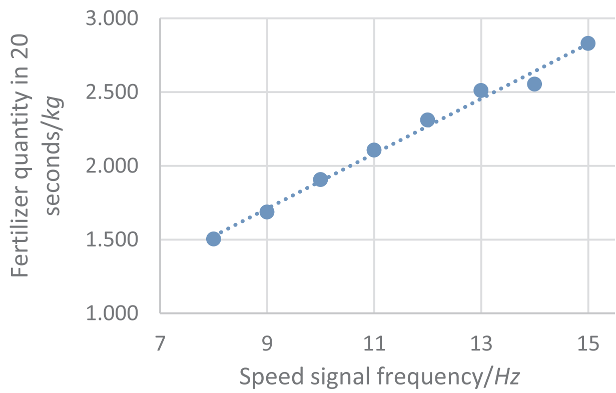

Fig. 13. Relationship between fertilizer quantity and speed signal frequency.

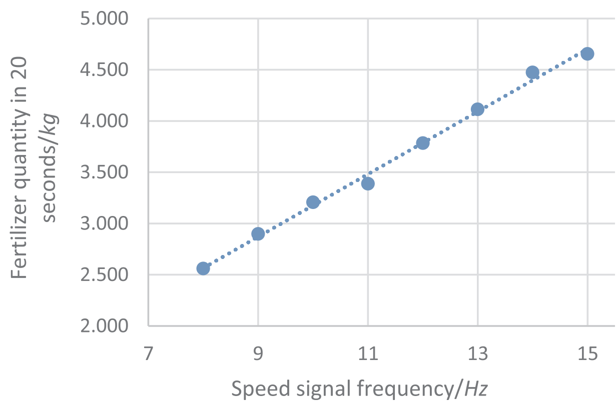

Fig. 14. Relationship between fertilizer quantity and speed signal frequency.

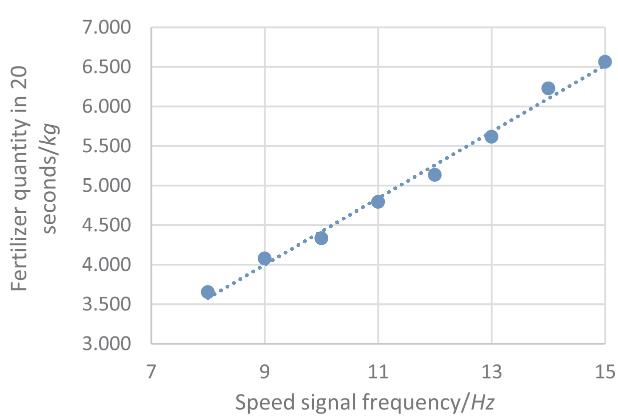

Fig. 15. Relationship between fertilizer quantity and speed signal frequency.

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (30)$$

$$V = \frac{S}{\bar{x}} \times 100 \quad (31)$$

In the formula x_i is the amount of fertilizer application in each test; $\bar{x}$ is the average value of each test; S is the standard deviation for consistency of fertilizer application rates; V is the coefficient of variation for consistency of fertilization amounts.

The coefficient of variation is 6.46% when the amount of fertilizer is set to 2100 kg/hm^2. The actual amount of fertilizer applied per meter is compared with the theoretical amount of fertilizer applied per meter as shown in Fig. 16.

The coefficient of variation is 5.61% when the amount of fertilization is set to 1725 kg/hm^2. The actual amount of fertilization per meter is compared with the set amount of fertilization as shown in Fig. 17.

The coefficient of variation is 4.36% when the fertilization rate is set to 1275 kg/hm^2. The actual fertilization rate per meter is compared with the set fertilization rate as shown in Fig. 18.

The coefficient of variation is 4.07% when the amount of fertilizer is set to 900 kg/hm^2. The comparison between the actual amount of fertilizer applied per meter and the set amount of fertilizer applied is shown in Fig. 19.

It can be seen that the fertilization amount per unit length has good consistency, the coefficient of variation is less than 7%, and the error between the actual fertilization amount and the set fertilization amount is less than 10%, which meets the design requirements.

4. Conclusion

Combining with the actual situation in Hilly areas, the design, manufacture and experimental study of lightweight organic fertilizer distributor are carried out based on the design principle of light weight, miniaturization, accuracy and controllable fertilizer application. The performance test results of the whole fertilizer applicator show that the control system works steadily and the fertilizer applicator has good fertilizer performance, which meets the design requirements.

The following conclusions are drawn from the study of lightweight organic fertilizer distributor:

(1) When the water content of organic fertilizer is high, the traditional fertilizer applicator is prone to overhead organic fertilizer and cannot reliably discharge fertilizer.
(2) The amount of fertilizer discharged by the fertilizer applicator is determined by the descending speed of the top-row fertilizer apparatus with horizontal scrapers, and the maximum amount of fertilizer discharged is positively correlated with the uniformity of fertilizer discharging and the moving speed of the horizontal scraper.
(3) The control system real-time detects the forward speed of fertilizer applicator and the rotational speed of fertilizer-discharging servo motor, which is used to control the descending speed of fertilizer-discharging mechanism and to correct the rotational speed of fertilizer-discharging servo motor, thus improving the fertilizer-discharging accuracy.
(4) Fertilizer applicator in the normal forward speed (0.5–1.2 m/s), when the set amount of fertilizer application is 900–2100 kg/hm^2, the fertilizer application is accurate and the maximum deviation between the set amount of fertilizer application and the actual amount of fertilizer application is less than 10%; the fertilizer uniformity is good and the uniformity variation coefficient is less than 7%, and the actual fertilization amount and uniformity per unit area have nothing to do with the operation speed of the fertilizer applicator.

CRediT authorship contribution statement

Jie Hu: Methodology, Software, Writing - original draft, Writing - review & editing **Jiacheng He:** Methodology, Software. **Yang Wang:** Methodology, Formal analysis. **Yanping Wu:** Validation, Investigation. **Chang Chen:** Validation, Investigation. **Zhenyu Ren:** Validation. **Xiaoxian Li:** Validation. **Shiji Shi:** Investigation. **Yipeng Du:** Investigation. **Peixiang He:** Methodology, Supervision, Resources, Project administration.

Declaration of Competing Interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service or company that could be

Table 2
Performance test data sheet of overall unit.

No	Stated fertilizer quantity /(kg/hm^2)	Theoretical fertilizer quantity per meter /g	Actual fertilizer quantity per meter/g	Deviation between theoretical fertilizer quantity and actual fertilizer quantity /%	No	Stated fertilizer quantity /(kg/hm^2)	Theoretical fertilizer quantity per meter /g	Actual fertilizer quantity per meter/g	Deviation between theoretical fertilizer quantity and actual fertilizer quantity/%
1	2100	270	272	0.74	21	1275	170	179	5.29
2			251	−7.04	22			157	−7.65
3			244	−9.63	23			166	−2.35
4			283	4.81	24			161	−5.29
5			261	−3.33	25			156	−8.24
6			244	−9.63	26			175	2.94
7			248	−8.15	27			158	−7.06
8			291	7.78	28			167	−1.76
9			283	4.81	29			163	−4.12
10			280	3.7	30			164	−3.53
11	1725	220	208	−5.45	31	900	120	118	−1.67
12			216	−1.82	32			112	−6.67
13			207	−5.91	33			122	1.67
14			222	0.91	34			122	1.67
15			199	−9.55	35			122	1.67
16			238	8.18	36			129	7.5
17			217	−1.36	37			116	−3.33
18			224	1.82	38			113	−5.83
19			234	6.36	39			118	−1.67
20			204	−7.27	40			123	2.5

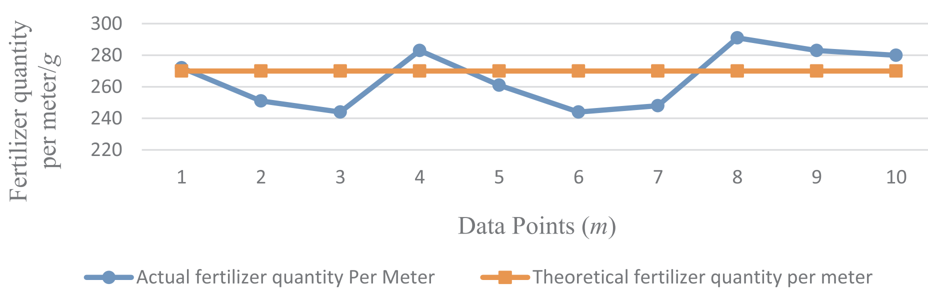

Fig. 16. Compare the actual fertilizer quantity with the theoretical fertilizer quantity (2100 kg/hm^2).

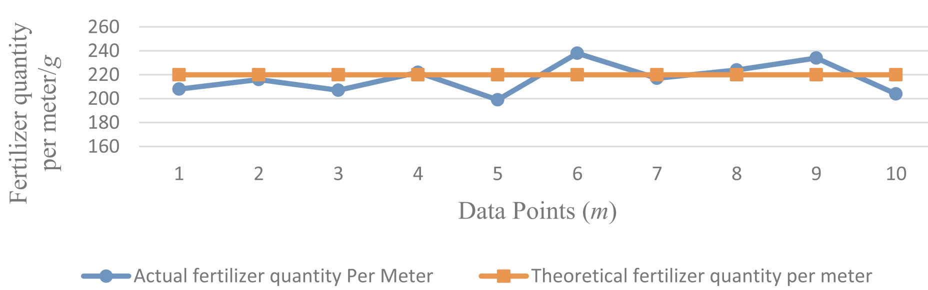

Fig. 17. Compare the actual fertilizer quantity with the theoretical fertilizer quantity (1725 kg/hm^2).

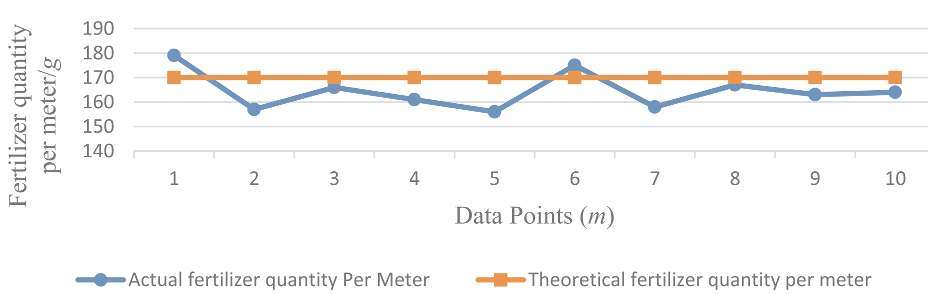

Fig. 18. Compare the actual fertilizer quantity with the theoretical fertilizer quantity (1275 kg/hm^2).

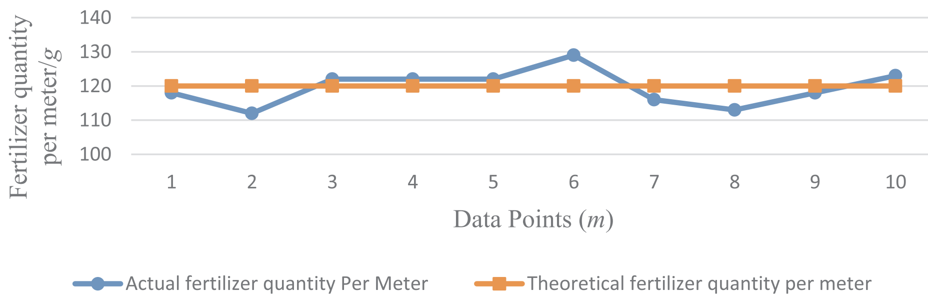

Fig. 19. Compare the actual fertilizer quantity with the theoretical fertilizer quantity (900 kg/hm^2).

construed as influencing the position presented in, or the review of, the manuscript entitled, "Design and Study on Lightweight Organic Fertilizer Distributor".

Acknowledgement

The author would like to thank the Southwest University Project [XDJK 2017D193; XDJK 2016E049] for funding this work. The author would also like to thank all participants for their cooperation in this study.

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