DESIGN AND TESTING OF A VARIABLE FERTILIZATION SYSTEM BASED ON SOIL NUTRIENT DETECTION

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基于土壤养分检测的变量施肥系统的设计与试验

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ABSTRACT

In order to solve the problems of low correlation between variable fertilizer application system and soil nutrient content detection and insufficient real-time performance, a variable fertilizer application system based on real-time soil nutrient content detection was developed. This paper describes the structure, working principle and design of key components of the soil information acquisition and fertilizer application system. It includes the simulation and analysis of fertilizer application using the discrete element method and the selection of curved blade fertilizer application discs. The system uses STM32F429IGT6 microcontroller and ROS higher-level computer for decision making. The device detects soil nutrients in real time, adjusts the fertilizer motor speed accordingly, and runs autonomously along the planned path. The decision coefficient R^2 between the fertilizer application rate and the speed of the fertilizer application wheel is not less than 0.97, and the relative error between the actual fertilizer application rate and the theoretical fertilizer application rate is up to 5.91%, with the maximum value of the coefficient of variation (CV) of 10.18%. The indoor bench test shows that the relative error between the actual fertilizer application rate and the target fertilizer application rate within a single operating grid is up to 6.2%, with the maximum value of CV being 6.64%. The field test in the orchard showed that the maximum relative error between the actual fertilizer application and the target fertilizer application in a single operation grid was 6.3%, and the maximum value of CV was 12.34%, and the fertilizer application was completed in the operation grid, which demonstrated that the device was able to realize real-time and accurate variable fertilizer application according to the soil nutrient information.

摘要

针对变量施肥系统与土壤养分含量检测之间的关联性程度低，实时性不足的问题，开发了一种基于土壤养分实时检测的变量施肥系统。本文介绍了土壤信息采集与施肥系统的结构、工作原理和关键部件的设计。其中包括利用离散元法对撒肥进行仿真和分析，以及对弯曲形叶片撒肥盘的选择。系统采用 STM32F429IGT6 微控制器和 ROS 上位机进行决策。装置能实时检测土壤养分，相应地调整施肥电机转速，并沿着规划的路径自主运行。排肥量与排肥轮转速之间决定系数 R^2 不小于 0.97，实际排肥量与理论排肥量相对误差最大为 5.91%，变异系数最大值为 10.18%，室内台架试验表明，单个作业栅格内的实际施肥量与目标施肥量的相对误差最大值为 6.2%，变异系数最大值为 6.64%。果园田间试验表明，单个作业栅格内的实际施肥量与目标施肥量的相对误差最大值为 6.3%，变异系数最大值为 12.34%，且施肥均在作业栅格中完成，试验表明，该装置能够根据土壤养分信息实现实时精准变量施肥。

INTRODUCTION

Fertilizer is an indispensable key factor in agricultural production, many orchards in China still use the traditional manual fertilization, which leads to inaccurate fertilizer application, leakage and the practice of inadequate and excessive fertilization is pervasive, resulting in environmental contamination and pollution. (*Liu et al., 2019*). So, how to achieve automation of precise variable fertilizer application is the current urgent need to solve the problem (*Xu et al., 2023*). Researchers at home and abroad have done a lot of research on the structural design of the fertiliser discharge device, the linkage between soil nutrient information and variable fertiliser application, and the integration of the control system (*Pawase et al., 2024*).

Bo Wang et al. addressed the problems of over-application of fertiliser and poor uniformity of fertiliser discharge in maize fertiliser planter (*Wang et al., 2022*). A set of precision sensing and control system for maize fertiliser planter was studied. In the study of variable rate fertiliser application based on working prescription charts, the 'SOILECTION' fertiliser system produced by Open Ag-chem Instrumentation Co., Ltd. in the United States, can be used for dry or liquid fertiliser application. It adjusts the application rates of nitrogen, phosphate and potash according to the fertiliser prescription chart (*Poncet et al., 2018*). Bai Qiwei and other research for the orchard fruit tree fertiliser problem, developed a set of accurate variable automatic target fertiliser application device and its control system. The volume of the slot of the fertilizer discharge wheel can be automatically adjusted according to the target fertilization amount of fruit trees and the size of the canopy diameter, which can meet the requirements of precise and variable automatic fertilization of different sizes of fruit trees with different fertilizer requirements. (*Bai et al., 2021*).

Domestic and foreign variable fertilizer application equipment and control technology mainly relies on external information collection and offline analysis, fertilizer application often adopts the uniform fertilizer application method, and manual operation reduces the efficiency (*Zhang J., Liu G. et al., 2019; Przywara et al., 2015; Fan et al., 2024*). In view of the above problems, this paper explores a series of accurate variable fertilizer application equipment and control system based on soil nutrient detection. Soil-integrated sensors are used to detect the nutrient information in the soil grid, and the relationship between the target fertilizer requirement of plant growth in the grid and the variables such as the speed of the fertilizer wheel, the width of fertilizer application, the speed of the fertilizer wagon, and the actual fertilizer content in the soil, and the control rules of the wheel speed, and add the path planning and navigation technology is implemented in the fertilizer application apparatus, enabling it to traverse, sample, and apply fertilizer along a designated route. This facilitates a more precise correlation between variable fertilizer application and soil nutrients, while also enhancing the intelligence of the fertilizer application device.

MATERIALS AND METHODS

Structure of the whole machine

The whole machine structure consists of a medium-size crawler robot chassis equipped with soil information collecting device, fertilizer discharging device and control system. The soil information collection device consists of drilling mechanism, coupling, soil collection sensor, electric actuator, fixed frame, etc.; the fertilizer discharge device consists of fertilizer discharge box, fertilizer discharge wheel, fertilizer discharge pipe, fertilizer spreading wheel, fertilizer spreading belt, fixed frame, etc.; the control system consists of STM32F429IGT6 microcontroller, decision making host computer based on the development of ROS (Robot Operating System) system, VCU of the crawler chassis, motor driver, Hall sensor, GNSS (Global Navigation Satellite System), etc.. The structure of the whole device is shown in Figure 1.

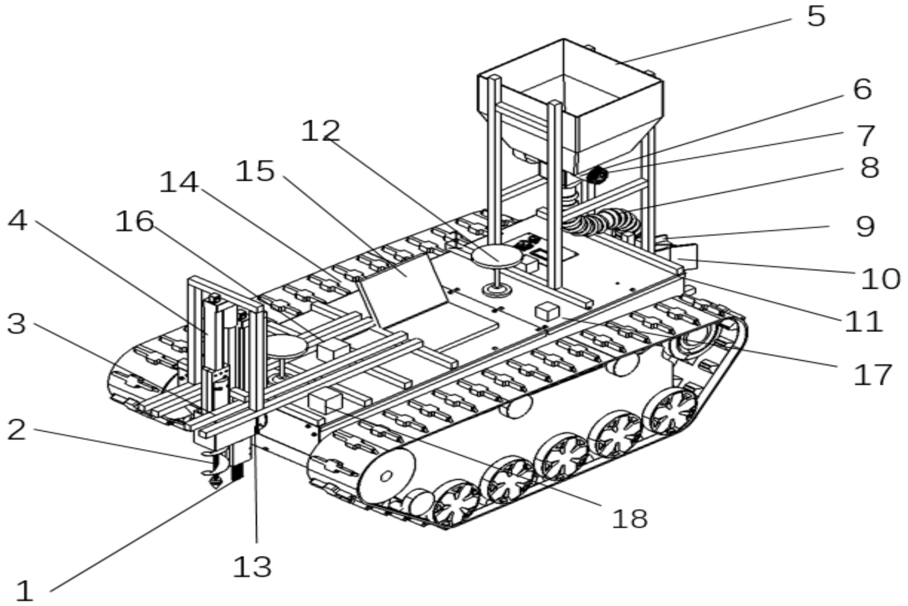


Fig. 1 - Structure of variable fertilization device based on soil nutrient detection

1. Soil integrated sensor; 2. Driller; 3. Coupler; 4. Linear actuator; 5. Compost Bin; 6. Fertilizer motor; 7. Hall encoder; 8. Fertilizer pipe; 9. Spinner fertilizer spreader; 10. Protecting band driller; 11. Fertilizer moto; 12. Dual Antenna GNSS-RTK; 13. Mounting; 14. Caterpillar traveling chassis; 15.ROS upper computer; 16. 24V DC power supply; 17. 12V DC power supply; 18. Control box

Working Principle

Before the operation of the machine, the GNSS carried by the chassis is first used to locate the sampling points in the operation area and control the whole machine to move according to the pre-planned path. During the operation of the machine, the RTK_GNSS receiver will acquire the latitude and longitude information of the current position of the whole machine in real time, and upload the data to the ROS host computer mounted on the vehicle through the RS232 serial port. The vehicle speed of the fertilizer application operation of the device is controlled within the range of 0-2 meters per second, starting from the head of the vineyard rows and moving forward, while the speed of the fertilizer application vehicle is monitored by the Hall sensor in real time. The schematic diagram of the control system of this device is shown in Figure 2.

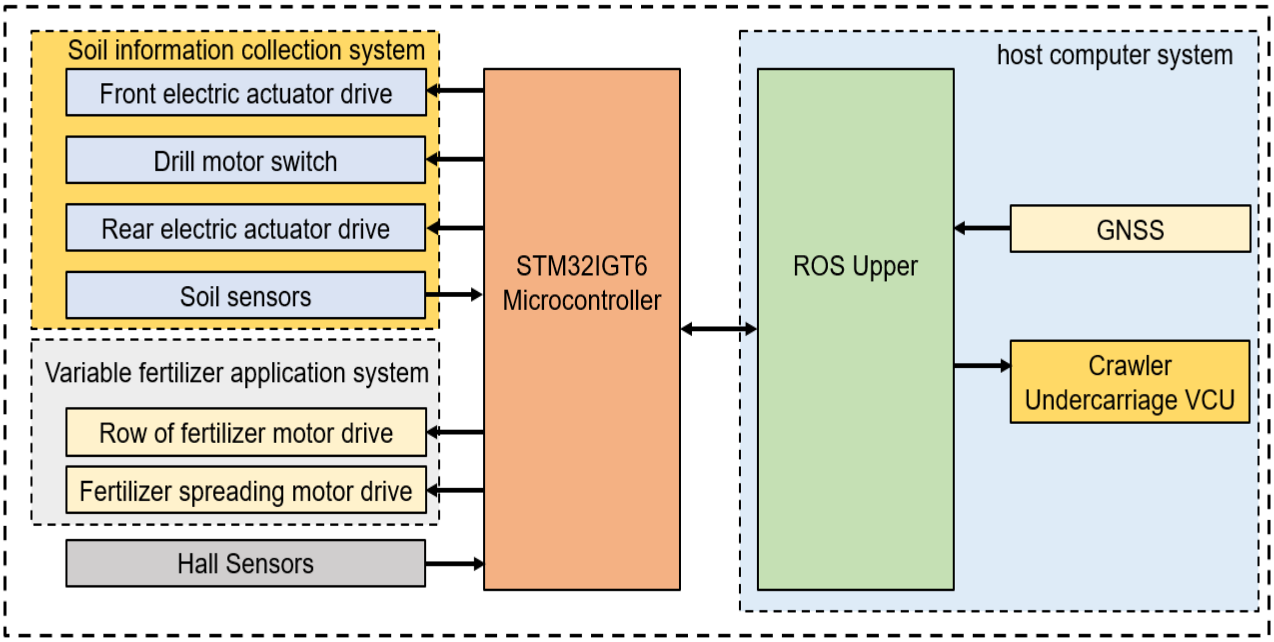
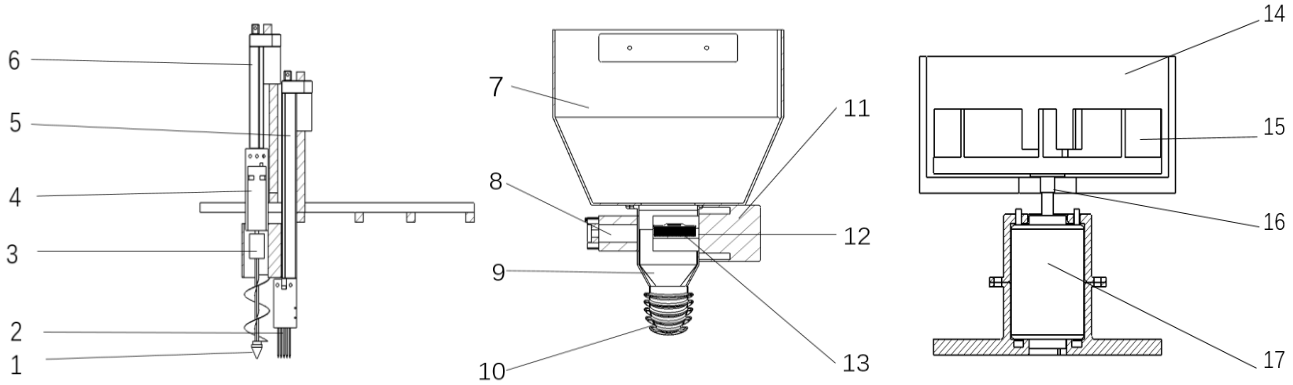


Fig. 2 - Schematic diagram of control system of variable fertilization device based on soil nutrient detection

When the instrument arrives at the specified sampling point, the travel speed is reduced to 0 m/s. At this time, the host computer sends acquisition instructions to the microcontroller, instructing the soil sampler to begin acquiring soil information. The size of the sampling grid is set according to the actual soil structure (taking into account the differences in row spacing of different crops, e.g. row spacing is 3.5-5 m for apples, 1.5-2.5 m for peaches and 1-2 m for vines) (*Walton J.C. et al., 2009*).

The soil nutrient detection structure consists of two electric actuators: the front electric actuator fixes the 42GP-775 24V planetary gear motor (torque 28 kg.cm), which is connected to the auger to form a soil loosening device; the rear electric actuator is connected to the soil synthesis sensor through the sensor fixing piece to form a collecting device. The structure of the soil sampling device is shown in Figure 3(a). During soil sampling, the loosening device first loosens the soil, and then the collecting device starts working to collect soil information. The microcontroller uploads the soil data read by the sensor to the host computer control system through serial communication, and the control system sends control instructions to the microcontroller according to the fertilizer requirement of fruit trees, fertilizer truck speed, fertilizer spreading width and soil nutrient information collected, so as to automatically adjust the rotational speed of the fertilizer discharge motor (20-60 rpm).

Fertilizer device consists of fertilizer discharging mechanism and fertilizer spreading mechanism, in which fertilizer discharging mechanism adopts external grooved wheel structure, fertilizer discharging mechanism consists of fertilizer box and 12V DC motor with deceleration device, which is connected to fan blade spindle by coupling, with fertilizer brush set in fertilizer outlet slot, and fertilizer discharge pipe connected to outlet of slot. The fertilizer spreading device consists of a 12V DC motor and a fertilizer spreading disc connected to the motor rotation axis by a flange. The construction principle of fertilizer spreader is shown in Figure 3(b,c). By changing the rotational speed of the fertilizer discharge motor, the amount of fertilizer discharged will change, and the fertilizer will be transported to the fertilizer spreading disc for spreading through the fertilizer discharge pipe.



(a) Soil nutrient testing organizations (b) Manure spreader (c) Fertilizer spreader

Fig. 3 Schematic diagram of soil information collection mechanism and fertilizer application mechanism

1. Drill; 2. Soil acquisition sensor; 3. Coupling; 4. Planetary gear reduction motor; 5. Rear electric push rod; 6. Front electric push rod; 7. Fat box; 8. Outer wheel; 9. Manure box; 10. Fertilizer can; 11. Fertilizer discharge motor; 12. Fertilizer fan leaf; 13. Fertilizer brush; 14. protected zone; 15. Manure spreader; 16. Ring flange; 17. Fertilizer motor

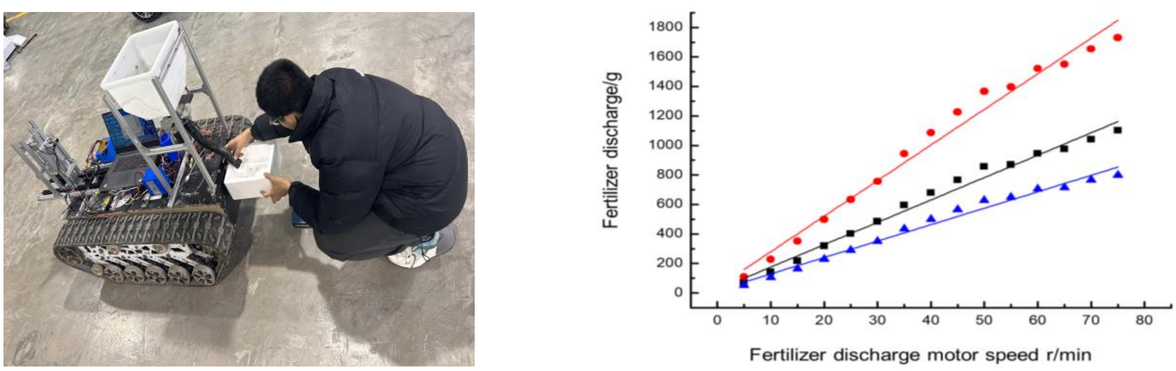
Calibration of the effect of fertilizer discharge device and fertilizer spreader

The volume of fertilizer discharged per revolution of the external chute wheel type fertilizer discharger is the total mass of fertilizer particles in the forced and driven layers, and the theoretical volume of fertilizer discharged per revolution can be calculated according to formula (1) (.

$$q = q_1 + q_2 = \pi dls\gamma(\frac{\alpha(n) f}{t} + c(n)) \tag{1}$$

q for the fertilizer discharge per turn of the fertilizer discharge, g/r; q_1 is the amount of fertilizer discharged from the forced layer per revolution of the fertilizer discharger, g; q_2 for each revolution of the fertilizer discharger is driven out of the fertilizer, g; d for the diameter of the grooved wheel, cm; l for the working length of the grooved wheel, cm; s for the grooved wheel grooves of the end area, cm^2; γ is the density of fertilizer, g/cm^2; $\alpha(n)$ is the filling coefficient of fertilizer to the groove of the grooved wheel; t is the pitch between the groove teeth of the grooved wheel, cm; f is the cross-sectional area of the groove of the grooved wheel, cm^2; $c(n)$ is the characteristic coefficient of the driving layer (calculated thickness), cm. The test was conducted with the three different granular fertilizers with the bulk density of 750 kg/m^3 urea, 850 kg/m^3 calcium superphosphate and 880 kg/m^3 potassium nitrate as test materials, and the density of the granular fertilizers was calculated by the method of (1). Fertilizers as test materials, by (1) formula were calculated to obtain the theoretical per-rotation discharge of granular fertilizers urea for 16.56 g, calcium superphosphate for 26.46 g, potassium nitrate for 12.17 g.

The fertilizer discharger discharges the fertilizer at 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75 r/min discharging speed for 1 minute, the fertilizer collection box collects the discharged fertilizer, and the electronic scale weighs the mass of the discharged fertilizer. Each fertilizer was subjected to the above experimental procedure 10 times at different rotational speeds and the average of the 10 discharges was calculated. The test platform was set up indoors as shown in Fig. 4(a), and the relationship between the rotational speed of the discharge wheel and the actual amount of fertilizer discharged by the three kinds of granular fertilizer is shown in Figure 4(b).



(a) Indoor test platform (b) Fertilizer Displacement versus RPM

Fig. 4 - Fertilizer discharge calibration test

In Fig. 4(b), with the increase of the rotational speed of the fertilizer discharge wheel, the amount of fertilizer discharged increases, and the fertilizer discharge amount and the rotational speed of the fertilizer discharge wheel are subjected to one-way linear regression analysis, resulting in a one-way linear regression model between the two as (2).

$$q = kn_{\tau} + b \tag{2}$$

Where n_{τ} is the rotational speed of the fertiliser wheel, r/min; q is the volume of fertiliser discharged by the fertiliser discharger, g; k, b are the coefficients and constants of the univariate linear regression model, respectively, and the values of k, b are different under the conditions of different fertilisers, and the results of the significance test of each regression model are shown in Table 1.

Table 1

Regression results and significance test

Fertilizer type	k	b	R^2	P-value
urea (NH2)2CO	0.9685	15.481	0.98	0.0071
calcium superphosphate (Ca(OH)2)	0.9729	16.841	0.98	0.0045
potassium nitrate	0.9556	17.668	0.97	0.0069

As can be seen from Table 1, the values of the coefficients of determination R2 of the univariate linear regression models established for different granular fertilizers in terms of rotational speed and fertilizer discharge were not less than 0.97, and the P values were all less than 0.01, and the univariate linear regression equations between the fertilizer discharge volume of the three granular fertilizers and the rotational speed of the fertilizer discharge wheels were all particularly significant and with high degree of fit, which had practical significance. In Figure 4(b), the same type of fertilizer from the speed 5-75 r/min, the amount of fertilizer discharged is a gradient of rising. If the rotational speed of the fertilizer discharge wheel is less than 20 rpm, the fertilizer discharge mechanism of the outer groove wheel will shake severely and the amount of fertilizer discharged will be low. When the rotating speed of the fertilizer discharge wheel is higher than 60 r/min, the rotating speed of the outer groove wheel is too fast, and the fertilizer cannot be filled into the fertilizer cavity by gravity in time, and the amount of fertilizer discharged is also seriously low, based on the above situation. The rotational speed of the fertilizer discharge wheel and the amount of fertilizer discharged cannot satisfy the linear relationship, so the rotational speed of the fertilizer discharge wheel is limited to the range of 20-60 rpm to meet the needs of different fertilizer discharge amounts in the operation grid area. The rotational speed of the fertilizer wheel is limited to 20-60 rpm to meet the needs of different fertilizer discharges in the working grid area. The calibration results of three kinds of fertilizer under each speed are shown in Table 2-4. From Table 2-4, it can be seen that in the range of 20-60 rpm, the relative error between the actual fertilizer discharge and the theoretical fertilizer discharge is within 6%, and the accuracy of fertilizer discharge meets the requirements, which can be further used for precise variable fertilization.

Table 2

Fertiliser Discharger Rotation Speed and Fertiliser Discharge of Urea Granular Fertiliser

Motor speed (r/min)	Mean value / g	Theoretical value / g	Relative Error / g	Coefficient of variation / %
20	318.98	331.2	3.69	6.49
30	484.43	496.8	2.49	8.69
40	679.22	662.4	2.54	7.46
50	855.99	828	3.38	6.67
60	946.30	993.6	4.76	7.01

Table 3

Rotational speed of fertiliser discharger and fertiliser discharge of calcium superphosphate granular fertiliser

Motor speed (r/min)	Mean value / g	Theoretical value / g	Relative Error / g	Coefficient of variation / %
20	499.19	559.7	5.67	8.21
30	756.09	793.8	4.75	13.78
40	1085.81	1058.4	2.59	10.68
50	1365.60	1323	3.22	9.89
60	1521.87	1587.6	4.14	8.65

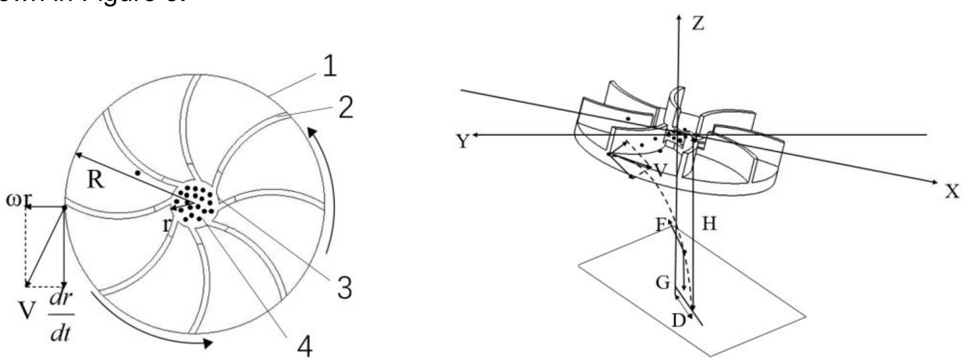
Table 4

Rotational speed of fertiliser discharger and discharge rate of potassium nitrate granular fertiliser

Motor speed (r/min)	Mean value / g	Theoretical value / g	Relative Error / g	Coefficient of variation / %
20	229.02	243.4	5.91	9.33
30	349.80	365.1	4.19	10.18
40	499.16	486.8	2.54	9.57
50	627.67	608.5	3.15	9.16
60	704.50	730.2	3.52	7.36

Calibration of the spreading effect of fertiliser discs

In this paper, a reasonable balanced fertilisation was carried out according to the law of fertiliser demand of grapes, taking into account the spreading width of fertilisers, and three kinds of spreading disc rotation speeds were selected for verification. Firstly, by analysing the movement and force of the fertiliser particles in the spreading disc and in the air, ignoring the bouncing between the fertilisers and the spreading disc and the interaction force between the fertilisers, it was found that the speed of the granular fertilisers when they left the discs was mainly related to the rotational speed of the discs, v, and the calibre R of the discs (*Gou Y., Li H. et al., 2022*). The speed of granular fertiliser when leaving the disc is mainly related to the rotational speed v of the disc and the diameter R of the disc, while the spreading width is mainly related to the spreading height H under the condition of a certain rotational speed (*Liu C. et al., 2017*). The force analysis of the granular fertiliser movement is shown in Figure 5.



a) **b)**

Fig. 5 - Motion analysis of granular fertilizer

1. Fertilizer spreading disc; 2. Blade; 3. Fertilizer falling area; 4. Granular fertilizer; 5. r is the radius of the fertilizer falling area; 6. R fertilizer disc radius; 7. v is the speed of the granular fertilizer when it leaves the disc at the moment of t; 8. is the angular speed of the fertilizer spreading disc rotation; 9. G is the gravitational force of the movement in air; 10. F is the resistance during the movement in the air; 11. X is the width of the fertilizer spreading width; 12. H is the height of the fertilizer spreading; 13. D the width of fertiliser spreading.

Fertilizer spreading disc is a key component of the fertilizer spreading device, its operational performance is excellent or not directly affects the accuracy and stability of fertilizer spreading, therefore, EDEM was used to build the simulation model of the fertilizer spreading disc, analyse the impact of changes in the parameters of the spreading disc on the accuracy and stability of fertilizer spreading, and select the optimal spreading structure. Fertilizer contact area of the spreading device model is PLA material and 3D printed, using SolidWorks in accordance with the ratio of 1:1 to build and import the model into the EDEM software, combined with the literature to determine the model parameters as shown in Table 5 (*Dun et al., 2016; Xin et al., 2023; Liu et al., 2021*).

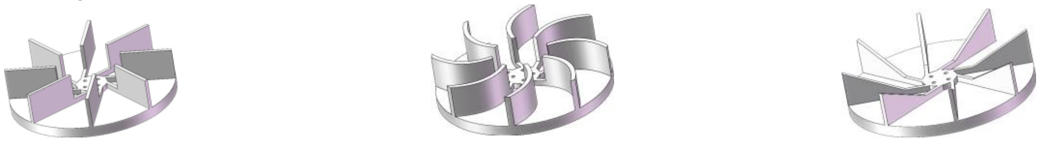
Table 5

Pre-treatment parameters setting

Items	Parameters	Numerical value
	Poisson's ratio	0.25
Granular Fertilizer	modulus of rigidity / Pa	1.1×10^8
	Densities / kg/m^3	750
	Poisson's ratio	0.42
PLA Consumables	modulus of rigidity / Pa	2.6×10^9
	Densities / kg/m^3	1260
Pellet-Pellet	Crash factor	0.3

Items	Parameters	Numerical value
	Static Friction Coefficient	0.34
	Dynamic friction factor	0.16
	Crash factor	0.324
Pellet-PLA consumables	Static Friction Coefficient	0.104
	dynamic friction factor	0.01

Considering the structure and mechanism of centrifugal disc fertilizer spreader, the influence of key parameters such as fertilizer spreading height, blade position angle and fertilizer falling position angle on the uniformity of centrifugal disc fertilizer spreader is analysed. In this paper, it is found that the uniformity of fertilizer spreading is better when the number of blades is 8. Based on this, this paper designs three kinds of fertilizer spreading discs with the number of blades of 8 and the diameter of 170 mm, as shown in Figure 6.



(a) Linear blades *(b) Curved blades* *(c) Wedge-shaped blade*

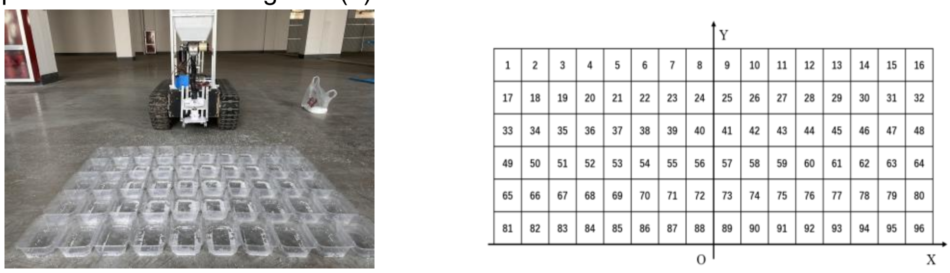
Fig. 6 - Fertilizer Spreading Discs with Different Blades

The vertical height of the fertilizer spreading disc from the ground is 300-500 mm, and the rotational speed of the fertilizer spreading disc is 200 r/min. The effect of the fertilizer spreading blade on the distribution of fertilizer spreading is investigated by the discrete element simulation test, as shown in Figure 7, the granular fertilizers, under the action of centrifugal force of the fertilizer spreading disc, are thrown according to a certain trajectory of movement, and the three kinds of fertilizer spreading discs are thrown in the same parameter settings for the simulation, and the results show that the curved-type blade spreads fertilizer in a wider width, and the fertilizer spreads in a better uniform manner.

(a) Straight blade *(b) Curved blade* *(c) Wedge blade* *(d) Side view trajectory*

Fig. 7 - Fertilizer throwing motion trajectory

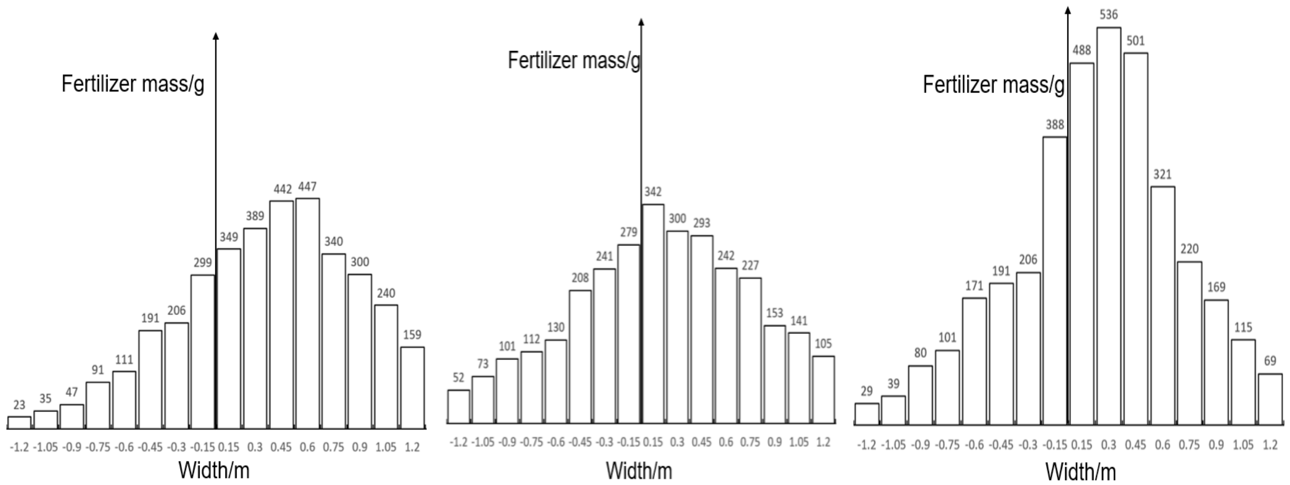
Granular calcium superphosphate fertilizer was selected as the test object, and three different types of fertilizer spreading discs were subjected to static tests. In the test, the distance between the falling point of the fertilizer on the spreading disc and the centre of the disc was 80 mm, the height of the disc from the ground was 450 mm, the rotation speed was set to 200 r/min, and the disc was rotated counterclockwise for spreading, and the granular fertilizers were collected and weighed, and the average value was taken after repeating the test for three times. The collection area was selected as a rectangular area of 1560mm x 2400mm (width x length), and 96 fertilizer collection boxes with the dimensions of 260mm x 150mm x 50mm were used for collection. The fertilizer boxes were numbered from 1-96 and the mass of granular fertilizer in each column of 6 fertilizer collection boxes was taken as the concentration of particles in the fertilizer spreading disc in the spreading area along the width direction (*Yang Li et al.,2019*). Taking 5 kg of fertilizer in the fertilizer collection box at a constant speed falling on three different fertilizer spreading discs, after the end of spreading the fertilizer was collected in each rectangular area and weighed using electronic scales to measure the record, the test process is shown in Figure 8(a).



(a)Indoor bench test *(b) Sampling area delineation*

Fig. 8 - Spreading fertilizer static test

As shown in Figure 8(b), the y-axis direction is the fertilizer spreading direction, the origin O is the centre of the fertilizer spreading width, the right side of the fertilizer spreading disc takes the value of the positive direction of the x-axis as positive, and the negative direction of the x-axis takes the value of the negative direction, and the collecting area is divided into a single-column fertilizer collecting matrix with a width of 100 mm, and the quality of fertilizer particles of the six fertilizer collecting boxes in the single-column collecting matrix represents the concentration of the particles of the fertilizers scattered along the spreading width after the fertilizer spreader passes through the collecting matrix (*Liu et al., 2022*). The quality of the fertilizer particles in each single column collection matrix is shown in Figure 9. By comparing the fertilizer spreading results of three different blade structures with the same parameters, it can be seen that the three-blade fertilizer spreading discs are more concentrated when they are close to the y-axis, and the quality of granular fertilizer of the three kinds of blades is obviously asymmetric about the y-axis, and the spreading area of linear and wedge blades is to the right of the whole with respect to that of curved blades, while the curved blades are close to the centre of fertilizer spreading. The spreading area of the linear blade and wedge-shaped blade is to the right of that of the curved blade, while the granular fertilizer quality of the curved blade is more concentrated near the centre of fertilizer spreading, and the overall change is smoother.



(a) Straight blades *(b) Curved blades* *(c) Wedge-shaped blades*

Fig. 9 - Histogram of fertilizer spreading distribution

Fertiliser application control model and control system design

In this study, the relationship between the nutrient content estimation points x_i and the sampling points x_a in the sampling grid area was calculated using the radial basis function method and combined with statistical laws. From equation (3), the nutrient content values $Z(x_i)$ were calculated for the four estimation points of (4) (*Rastgou M. et al., 2022*).

$$Z(x_i) = \sum_{j=1}^{5} w_i e^{-\frac{1}{2\sigma^2}(\|x_i - x_a\|)^2} \tag{3}$$

where$||x_i - x_a||$ is the Euclidean distance between the estimated point x_i and the point to be measured x_i, σ is the standard deviation of the Gaussian function. ω_i is the weight of the known point x_a.

$$Z(x_1)、Z(x_2)、Z(x_3)、Z(x_4) \tag{4}$$

The soil nutrient content values of the four estimation points and one sampling point within the sampling grid described above, totalling five points, were each assigned a different weight δ_i in equation (5) to derive the mean soil nutrient distribution value S_v in the operational grid (*Daou L. et al., 2021*).

$$S_v = \frac{\sum_{i=1}^{5} Z(x_i)\delta_i}{\sum_{i=1}^{5} \delta_i} \tag{5}$$

When fertiliser is applied according to a given target fertiliser application rate for fruit trees, common methods for determining the target fertiliser application rate include the geotechnical zoning (level) allocation method, the target yield allocation method and the soil effective nutrient correction coefficient method. Combined with the actual situation, this paper adopts the soil effective nutrient correction coefficient method, and equation (6) is used to calculate the target fertiliser application rate in the sampling grid.

$$y_i = \frac{N_a T - 0.15 S_v \mu_N}{\omega_f \eta_{Nf}} \tag{6}$$

where 0.15 is the soil quick-acting nutrient coefficient, y_i is the amount of fertiliser applied, g; N_a is the nutrient uptake per unit of crop yield, g; T is the target yield, g; S_v is the soil test value, mg/kg μ_N is the soil effective nutrient correction coefficients for N, P and K of 0.65, 0.5 and 0.80 respectively, and ω_f is the nutrient content in the fertiliser, % and η_{Nf} is the fertiliser utilisation rate, %.

The fertiliser is applied according to the target fertiliser quantity required for the growth of the fruit trees in the collection grid, and the relationship between the target fertiliser quantity y_i, g; the fertiliser application wheel speed n_τ, m/s; the fertiliser vehicle speed v, m/s; the fertiliser application width β, m; and the fertiliser application rate q, g; in a single collection grid is as follows Formula (7).

$$y_i = \frac{10000\, q n_\tau}{v\, \beta} \tag{7}$$

Substituting equation (2) into equation (7) and simplifying yields:

$$10000 k n_\tau^2 + b n_\tau - y_i v \beta = 0 \tag{8}$$

In the orchard fertilization test, the chassis moves forward according to the set speed, and when the positioning system detects that the fertilization device arrives at the sampling grid, the host computer sends the acquisition command to the STM32F429IGT6 microcontroller, thus controlling the acquisition device to perform soil sampling and according to the acquisition of various soil parameters, so as to realize the automatic and accurate variable fertilization of fruit trees.

Solving for n_τ in equation (8) gives.

$$n_{\tau 1} = \frac{-b + \sqrt{b^2 + 40000 k y_i v \beta}}{20000k} \tag{9}$$

$$n_{\tau 2} = \frac{-b - \sqrt{b^2 + 40000 k y_i v \beta}}{20000k} \tag{10}$$

Analysis of (9) (10) formula can be seen, if y_i, v, β any one of the three values of 0, the device does not need to apply fertilizer, fertilizer wheel rotation speed is 0, $n_{\tau 1}$ in accordance with the actual situation, $n_{\tau 2}$ is not 0, the device discharges fertilizer, not in accordance with the actual situation; so to sum up, the formula (9) will be used as a fertilizer discharge system to obtain the control rules, imported into the device control system on the fertilizer wheel rotation speed for automatic control.

After the system is turned on and reset, the vehicle travels from the ground at a constant speed according to the set vehicle travel path, the positioning system detects that the implement arrives at the first working grid when the implement stops, the STM32F429IGT6 controls the soil information collecting device to collect soil parameters, the soil integrated sensor uploads the collected information to the ROS host computer decision system through the serial port, and the decision system quickly derives the rotational speed of the fertilizer discharger according to equation (9), generates an adjustable duty cycle pulse waveform PWM wave, and sends the instruction to the STM32F429IGT6 through the serial port, the decision system quickly derives the rotational speed of the fertilizer discharging device, generates an adjustable duty cycle pulse waveform PWM wave, and sends the instruction to STM32F429IGT6 through the serial port, and the microcontroller controls the rotation of the fertilizer discharging motor, which drives the fertilizer discharging wheels to apply the fertilizer, and before the device performs the operation, the rotational speed of the universal spreading device spreads the fertilizer according to the actual required fertilizer spreading width set in the decision system. During the fertilizer application period, the traveling machine moves forward at a speed of 1 m/s until it reaches the next working area, and during the soil information sampling period, the fertilizer spreading motor stops rotating and no fertilizer is applied. The hardware wiring diagram is shown in Figure 10.

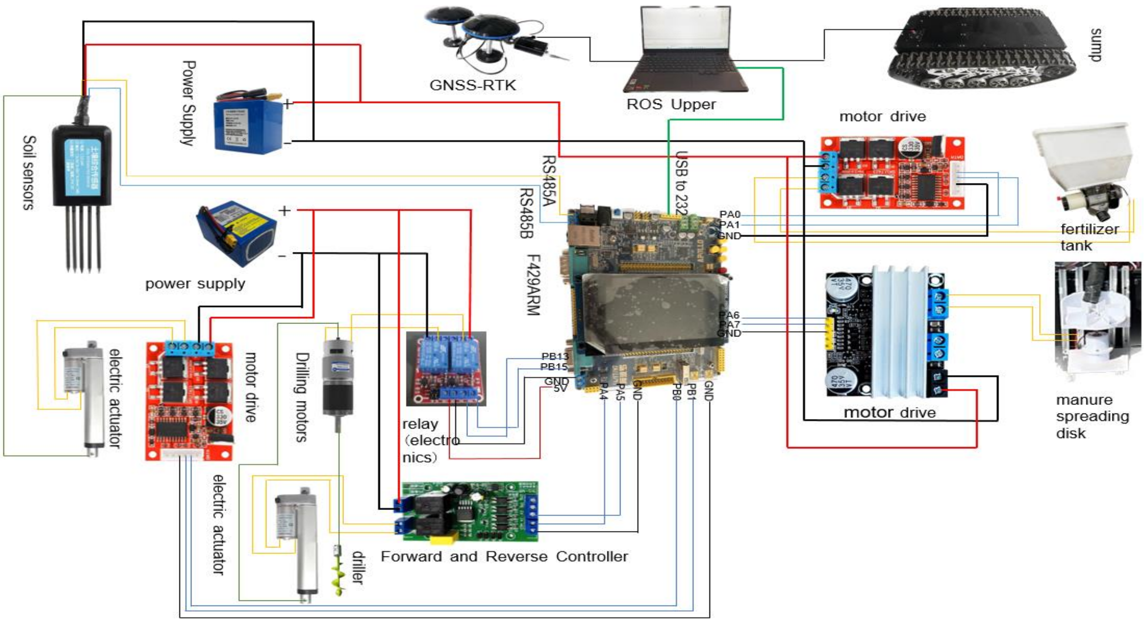


Fig. 10 - System hardware wiring diagram

The control system of this fertilizer device uses STM32F429IGT6 type microcontroller as the core of the lower computer control, and the upper computer developed by ROS system is responsible for deciding the target fertilizer discharge. According to the established fertilizer control model, the variable fertilizer control program based on soil parameter information is written in C language, and its main process is shown in Fig.11.

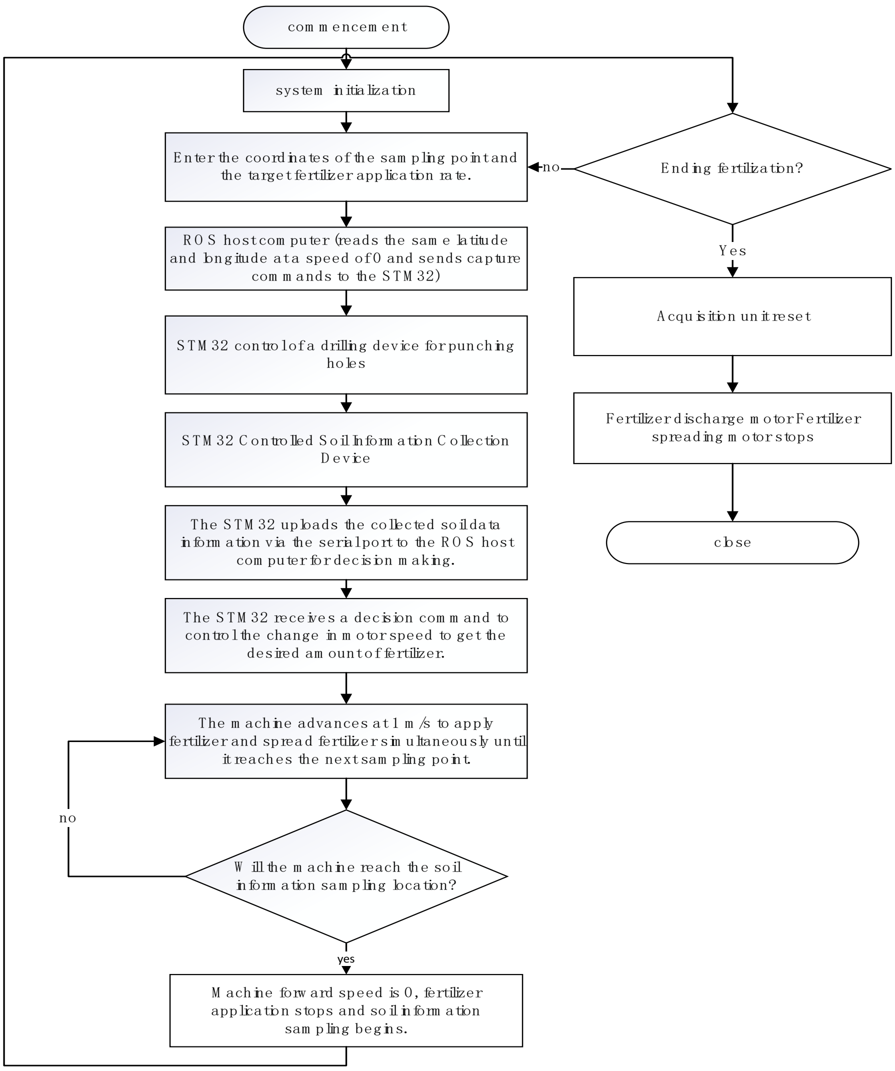


Fig. 11 - Flow chart of variable fertilization control based on soil nutrient content detection

Test condition

In order to verify whether the range of fertilizer application rate of the experimental device and the control system meets the requirements of fruit trees for different granular fertilizers in different growth periods, as well as the match between the width of fertilizer application and the width of fruit trees between rows, indoor experiments and field tests for soil information acquisition and variable fertilization, respectively, were conducted using grapevines as an example.

Grapes in China are mainly grown on the plains in areas with fertile soil and good irrigation conditions. Cultivation methods in vineyards mainly include hedgerow and trellis cultivation. The row spacing of grapes varies according to the cultivar and environment, usually ranging from 0.6 m to 1.5 m and 2.5 m to 3.5 m. Fertilization is usually a combination of organic and chemical fertilizers. Depending on the stage of growth of the fruit trees, grapes need to be fertilized several times during the year. Fertilizers are applied according to the nutrient content of the soil and the nutritional needs of the fruit trees. Indoor simulated variable fertilization trials are usually conducted in vineyards with row spacing of 1.5 m × 1.5 m, while variable fertilization trials based on soil nutrient content detection are conducted in mature vineyards with row spacing of approximately 1.5 m × 2 m.

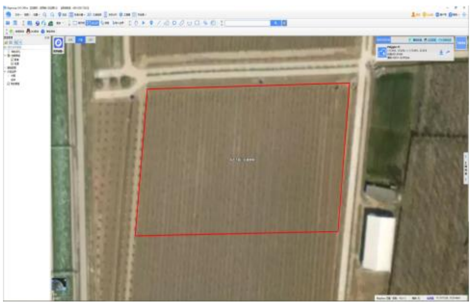
Indoor simulated variable fertilization trials

This system uses an STM32F429IGT6 type microcontroller to control the fertilizer application motor and fertilizer spreading motor. The simulated collected nutrient content of the raster soil was input to the ROS higher-level computer decision system, and the ROS higher-level computer quickly calculated the required rotational speed of the fertilizer discharge wheel according to equation (9) and sent commands to the STM32F429IGT6, which then controlled the rotational speeds of the fertilizer discharge motor and the fertilizer spreading motor. The indoor simulated variable fertilizer application test is shown in Figure 5(a) and Figure 9(a).

In the experiment, the planting distance was set at 1.5m×1.5m row spacing, and the selected test soil grid was 1.5m×0.5m. 6,800 plants could be planted per hectare, and the selected nitrogen content of urea was 46.6%, the phosphorus content of calcium superphosphate was 45.59%, and the potassium content of potassium nitrate was 38.6%. 100 kg of calcium superphosphate and 50 kg of potassium nitrate were applied per 667 square meters. The fertilizer requirement of each vine is different at each stage of the growing period, and the nitrogen requirement of a single fruit tree throughout the year is 200-600 g, phosphorus is 150-300 g and potassium is 200-400 g. Setting the target fertilizer application in the fertilizer grid is 50, 100, 150, 200, 300 g granular urea, 100, 200, 300 g granular calcium superphosphate and 400, 500 g granular potassium nitrate. 80, 120, 180, 250, 300 g of granular potassium nitrate were applied, and the fertilization test was carried out sequentially. According to the size of the fertilizer grid and the target speed of fertilizer application, the maximum driving speed of the simulated fertilizer truck was controlled to be from 1 m/s to 1.5 m/s. For the same target fertilizer application, the operation was repeated three times, and the mass of fertilizer after application was weighed by an electronic scale to obtain the actual amount of fertilizer applied, and the average value of the three trials and the coefficient of variation of the amount of fertilizer applied were calculated.

Field trials

The soil sampling device and fertilizer application device were mounted on an unmanned sports chassis, and the experiment was conducted at the foot of 1,000 mu vineyard in Huantai County, Zibo City, Shandong Province (N37.07420°, E117.91777°). The ambient temperature at that time was 19°C to 27°C and the relative humidity was 13%, and the exact location is shown in Figure 12.

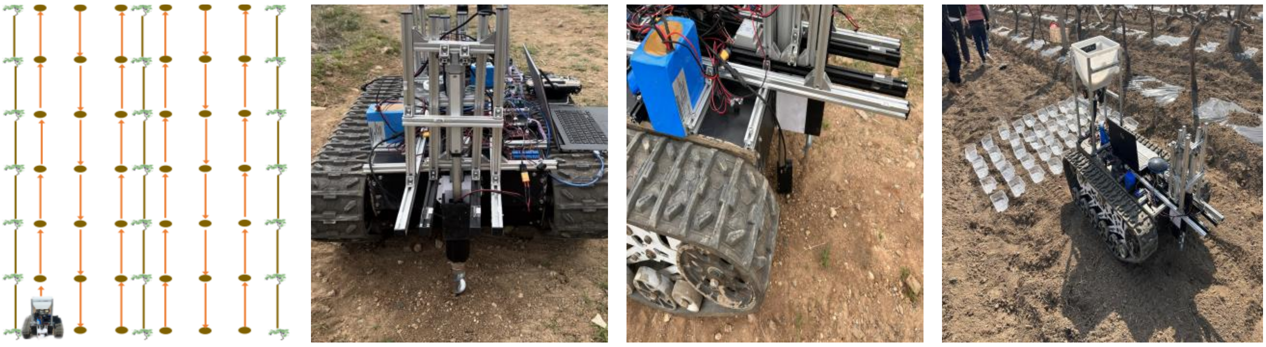


(a)Vineyard Map

(b) Vineyard field scenes

Fig. 12 - Test site

The test procedure is shown in Figure 13.



(a)Operational schematic (b) Soil loosening (c) Soil information collection (d) variable fertilizer application

Fig. 13 - Field trial of variable rate fertilization based on soil nutrient testing

According to the actual nutrient content of the soil in the fertilization area and the target fertilizer requirement for grape growth, the developed soil information collection and fertilization device and control system were used to fertilize a 50m×1.5m orchard area. Granular fertilizer urea 30, 60, 90 g, calcium superphosphate 130, 160, 200 g, potassium nitrate 40, 70, 100 g were applied, and nine fertilizer spreading grids of 1.5m×0.5m each were selected for the sampling and fertilization test. In the test process, according to the actual collection of soil nutrient content and fruit tree growth fertilizer requirement, the fertilizer application vehicle speed is set to 1 m/s, and the soil sampling device automatically collects soil data for on-demand fertilization. For the same target fertilizer application amount, 3 trials were conducted, the collection box was placed in the fertilizer spreading area, and the mass of fertilizer in the collection box was weighed to determine the actual amount of fertilizer discharged and to evaluate the uniformity of fertilizer spreading width. Finally, the average of the 3 trials and the coefficient of variation of the fertilizer application rate were calculated.

RESULTS AND ANALYSIS

The results of the indoor simulated variable fertilization test are shown in Table 6; the results of the orchard variable fertilization test are shown in Table 7.

Table 6

Results of indoor simulated variable fertilization experiment

Type of fertiliser	Vehicle speed (m/s)	Element Type	Soil nutrient content (mg/kg)	Target fertiliser application rate/(g)	Average fertiliser application/(g)	Relative error/(%)	Coefficient of variation/(%)
urea (NH2)2CO	1m/s	N	15	50	53.1	6.20	5.21
			16	100	102.7	2.70	6.34
			17	150	145.6	2.93	5.98
			18	200	194.9	2.55	2.21
			20	300	290.2	3.27	3.41
calcium superphosphate (Ca(OH)2)	1.5m/s	P	16	100	103.1	3.10	4.23
			18	200	193.4	3.30	5.45
			20	300	296.5	1.17	6.64
			22	400	390.7	2.33	2.27
			24	500	489.8	2.04	5.65
potassium nitrate	1m/s	K	54	80	78.3	2.13	3.36
			56	120	124.4	3.67	2.39
			59	180	188.1	4.50	1.83
			51	250	259.0	3.60	5.82
			50	300	311.3	3.77	5.52

The indoor simulation experiments in Table 6 show that the maximum relative error between the actual amount of urea fertiliser applied to the grapes in the grid and the target amount of fertiliser is 6.2%, the maximum relative error in the amount of calcium superphosphate applied is 3.3%, the maximum relative error in the amount of potassium nitrate applied is 4.5%, and the maximum value of the coefficient of variation of the amount of fertiliser applied is 10.52%.

The width of the spread from the edge of the fertiliser grid is the maximum distance of -0.17 m, and the locations of the fertiliser drops are all within the area of the fertiliser grid. The locations were all within the range of the fertiliser grid.

Table 7

Table 7 Precision variable fertilization in orchard field

Type of fertiliser	Vehicle speed m/s	Element type	Soil nutrient content mg/kg	Target fertiliser application rate/g	Average fertiliser application/g	Relative error/%	Coefficient of variation/%
urea (NH2)2CO	1m/s	N	9	30	31.8	6	10.83
			10	60	63.8	6.3	11.26
			11	90	87.2	3.1	9.32
calcium superphosphate (Ca(OH)2)	1m/s	P	13	130	133.9	3	7.41
			14	160	154.7	3.3	12.34
			16	200	209.3	4.6	10.43
potassium nitrate	1m/s	K	50	40	38.6	3.5	7.33
			52	70	74.3	6.5	8.2
			54	100	105.0	5	9.61

The coefficient of variation within a single fertilizer grid in the vineyard test was generally higher than that in the indoor simulation experiment, mainly due to the fact that the rotational speed of the fertilizer wheels was not stable enough when the fertilizer applicator was operating in the orchard, especially in the rough conditions along the roadside. However, based on the target fertilizer application rate of the vines in the grid, the actual soil nutrient content, the fertilizer application width, and the vehicle speed of the fertilizer application device, the system could automatically adjust the rotational speed of the fertilizer discharge wheel, which resulted in the relative error of the fertilizer application rate of a single vine being less than 6.5%, with a maximum coefficient of variation of 12.34%. Through the real-time detection of the actual soil nutrient content in the fertilizer grid based on the built-in soil nutrient sensor, it ensures that the fertilizer drop locations are all within the fertilizer grid. Therefore, the fertilizer application device combines the collection device and the control system to realize the precise variable fertilization of different fruit trees in the grid for different granular fertilizer needs.

In addition, the orchard validation experiments of this device and control system were conducted in vineyards with the same ridge spacing and the same selected grape variety. However, the ridge spacing of different grape varieties varies greatly, so when sampling and fertilizing a large area in vineyards with different planting densities, it is necessary to improve the structure of the soil nutrient detection device again to improve the detection efficiency and accuracy. In addition, the device was mainly tested for three kinds of granular fertilizers, namely urea, calcium superphosphate and potassium nitrate, and further experimental studies are needed to investigate the application effects of powder and liquid fertilizers.

CONCLUSIONS

(1) Using unmanned technology, the relationship between the target fertiliser application rate and the rotational speed of the fertiliser spreading wheel, the speed of the fertiliser spreading vehicle, the width of the fertiliser spreading width and the actual nutrient content of the soil, as well as the control rules of the rotational speed of the fertiliser spreading wheel were established according to the actual content of soil nutrients in the fertiliser spreading grid and the target fertiliser application rate of different fruit tree varieties.

(2) Through the comparative analyses of simulation test, indoor test and orchard test on three kinds of fertiliser spreading blades, the results showed that the curved blades were more uniform in spreading effect.

(3) The results of the indoor simulation test showed that when applying urea granular fertiliser, the maximum error of fertiliser application in a single grid was 6.2%, the maximum error of calcium superphosphate fertiliser application amount was 3.30% and the maximum error of potassium nitrate fertiliser application amount was 4.5%.

(4) The field test in the orchard showed that the integrated soil nutrient sensor could accurately detect the nutrient content in different farm grids and could meet the requirement of precise variable fertiliser application for fruit tree growth in the farm grids. The maximum relative error of fertiliser application within a single spacing was 6.5% and the maximum coefficient of variation was 12.43%.

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