Design of motor-driven precision seed-metering device with improved fuzzy PID controller for small peanut planters

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Abstract: Traditional passive ground wheel drive of peanut planters has displayed poor high-speed seeding performance and the slippage caused in case of sticky and wet soil. Given this, an integrated electric-driven precision seed metering device and controller were designed, which features the application of improved fuzzy PID algorithm. Based on a small peanut planter with one ridge width and duplicate rows, the servo motor drive is used to replace the traditional passive ground wheel. In addition, the satellite speed measurement is employed to complete the electric driving and controlling modification of the seed meter and precise seeding control. A working process mathematical model for the peanut metering device was established to conduct motor speed and field tests which aim at comparing performances between the conventional and the improved fuzzy PID controls. The motor speed trial shows that the average error of the actual speed of the improved fuzzy PID motor was ±1 rad/min, and the coefficient of variation was less than 1%. Against the conventional one, it can better suppress overshoot and improve the response speed. The stable output speed can still be obtained even in case of step changes. Field tests show that when working at medium and low speeds, the qualified rate of plant spacing was greater than 98%, and the rate of missed sowing is <2%; while working at high speed, the qualified rate was greater than 94%, and the rate of missed sowing was less than 4%. The average plant spacing qualification rate of the seed device increased by 6.72%; compared with other electric-driven peanut seed meters, the plant spacing qualification rate increased by 4% during high-speed sowing. In summary, this study has provided an effective technical reference for high-speed precision planting of peanuts.

Keywords: peanut planter, precision seeding, control system, improved fuzzy PID

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1 Introduction

Peanut has been an important economic and oil crop in China[1]. Its precision seeding can reduce seed input, increase yield and expand economic advantages[2,3]. Precision sowing operations require uniform and stable plant spacing, the design structure and driving method of the seeder are crucial, which is an important component to ensure uniform plant distance[4]. The continuous optimization of the mechanical structure of the current peanut seed metering device[5,6] can make sure that the seeder can complete the operation stably at a certain working speed[7-9]. However, the traditional seed metering device adopts ground-wheel-driven chain transmission for seeding, by which the high-speed seeding effect is unsatisfied, the ground wheel slippage and the chain jam are prone to occur, which seriously declines the performance of peanut mechanized sowing operations[10].

With the development and the progress of science and technology, electric motors came to be applied to seed metering devices[11-13] and have quickly become research objectives[14,15] in terms of their characteristics such as controllable power, stable operation, strong anti-interference ability, and easy monitoring of the working process[16-18].

Jiang[19] used a stepper motor to drive the rotation of the seed shaft with a chain drive and established a mathematical model to study the connections among the forward speed of the tractor and that of the stepper motor as well as the plant spacing. Among them, the speed of the seeding shaft is feedback-controlled by the forward speed of the tractor, which achieves the purpose of stepless speed regulation to adjust the sowing plant distance, and verifies that the pass rate of motor-driven row plant distance works greater than that of the ground wheel driving plant pitch. Yin.[20] designed a median filtering method to improve the accuracy of the encoder feedback value, so as to obtain a stable driving speed of the equipment to improve the seeding uniformity. In addition to improving the driving mode and the speed measurement method, the precise control of the working speed of the seed discharge plate is an important guarantee for achieving the precision seeding of the system[21]. While He et al.[22] and Ding et al.[23] proposed a PID closed-loop control method to harness the corn seed row, which proved that the seeding quality can be improved, but the following performance of the system obtained by this method is under expectation. Chen et al.[24] proposed a double closed-loop fuzzy PID method, which uses fuzzy PID algorithm to control the speed and current double loops. But this method is prone to produce a large number of overshoots when the speed appears a great deviation, which undermines the sowing uniformity. In view of the problems of large overshoot and long response time in the process of position PID control adjustment, Yang et al.[25] proposed

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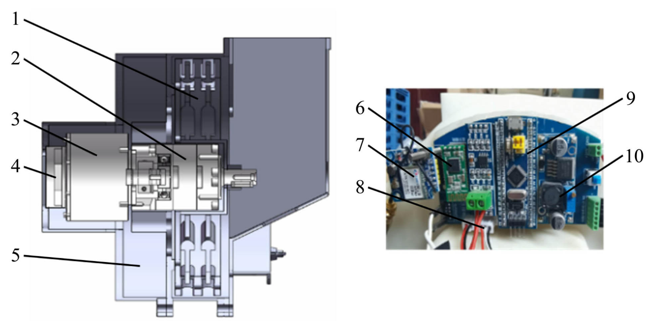
the idea of fuzzy PID control, adjusting different parameters at different speed stages to reduce overshoot and shorten response time. A larger speed step, however, will still produce a large number of overshoots while reseeding.

In view of the above problems, an electric-driven peanut precision seeder is planned, and the electric drive control system of the peanut precision seed meter is studied based on the improved fuzzy PID control algorithm. By employing DC motor as the driving unit, the satellite speed measuring module receives the signal to detect the driving speed of the planter, which improves the double-loop servo control system. The system will choose the conventional PID control when the target speed has a step. While, in case of stable speed, the fuzzy PID control will be applied to obtain a stable output. In this way, the precision gear reducer directly drives the seed plate to ensure uniform spacing and attain the precise seeding of peanuts.

2 Working principle and general design of the seed-metering device

The electric-driven seed-metering device is mainly composed of a seed rowing plate, a servo DC motor, a precision gear reducer, and a control system which includes an STM32 single-chip microcomputer, a satellite speed measurement module, a missed seeding detection module, and a Bluetooth communication module. The specific structure is shown in Figure 1. The seed rower integrates a DC drive motor, a precision gear reducer, and a control unit. The drive motor provides power for the seed-metering device and drives the seed plate to rotate; the precision gear reducer is directly connected to the drive motor and the seeding plate, reducing the output speed of the drive motor and amplifying the output torque; satellite speed measurement module, leakage detection sensor, Bluetooth communication module, and single-chip microcomputer form a control module to realize information collection and command judgment and sending.



1. Seed releasing plate 2. Precision gear reducer 3. DC drive motor 4. Encoder 5. Control box 6. Bluetooth module 7. Satellite speed measuring module 8. Miss seeding detection module 9. Single chip microcomputer 10. Power Regulator Module

Figure 1 Structure diagram of the peanut precision seeder

The satellite speed measurement module receives the satellite signal and obtains the instantaneous driving speed of the seeder by measuring the displacement between two points per unit of time, and feedback to the microcontroller. The leakage detection sensor is equipped for detecting the filling of each nest hole during the seeding operation. If there is no seed in the nest hole, it sends the missing seed instruction feedback to the microcontroller. Bluetooth module functions as a communication mode of human-computer interaction. It is, via a mobile phone Bluetooth APP or mini program as a human-computer interaction mode, responsible for sending the required plant distance setting information, displaying the speed of the planter, receiving alarm information, etc. The microcontroller receives the information on the travel speed of the planter and the lack of seed information detected by the satellite speed measurement module. It also realizes the output of different rotational speeds of the drive motor by outputting different frequency pulse width modulation (PWM) signals to complete the even planting distance and automatic reseeding. The work flow chart is shown in Figure 2.

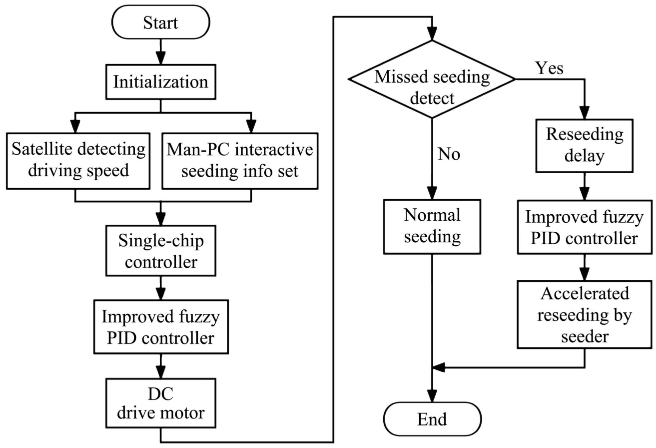


Figure 2 Operating flow chart

3 Design of electrically driven peanut seed disperser and control system

3.1 Drive motor selection

The selection of the drive motor, as the main working part of the seed rower, is extremely important. When choosing a drive motor, the main considerations are the type of drive motor, torque, speed, voltage, and other characteristics. The overall structure of the stepper motor is large and not convenient for close transmission with the seed rower, so the DC brushless motor was chosen. The test found that the maximum torque required to drive the seed rower was 20 N·m and the speed was below 60 rad/min. Because the DC motor cannot meet the required torque, so choose a 1:10 precision gear reducer to amplify the distortion, while the speed is expanded by 10 times, and finally choose a 60AIM25 model DC motor, working parameters such as Table 1. motor working voltage is 24 V, if choose the tractor comes with 12 V power supply to do boost processing, easy to cause voltage instability phenomenon affects the drive motor speed output, so choose 24 V power supply is directly supplied after voltage stabilization.

Table 1 Main operating parameters of the motor

Parameter	Value
Model	60AIM25
Type	DC motors
Voltage	24 V DC
Current	7 A
Torque	2 N·m
Rated speed	1000 r/min
Maximum speed	1500 r/min

3.2 Structure design

3.2.1 Transmission structure of seed metering plate

The seeding plate's structure of traditional peanut metering devices, as shown in Figure 3a, is driven by the ground wheel through the chain and sprocket drive, but it is likely to jump and jam teeth during high-speed operation. In order to solve this problem, the seeding plate is directly driven by the drive motor, and the structure of the plate is optimized to achieve the internal integrated drive motor. The seed metering plate structure is shown in Figure 3b.

a. Seed releasing plate structure of conventional seed-metering device b. Seed-metering device electric-driven seed-metering

Figure 3 Seed-metering Plate Structure

After optimization, the drive shaft of the seed metering plate protrudes towards the seed filling side. The motor and the reducer body are embedded inside the seed metering device, and the motor shaft that directly connects the flange drives the seeding plate to rotate.

3.2.2 Location selection of the missing seed detection sensor

According to the working principle of the internal filling seeder, the operating process is divided into four stages: seed filling, cleaning, retaining, and releasing. Peanut seeds enter the seeding nests in the seed filling area, removing excess seeds in the nests by seed cleaning to ensure single seeds. Then complete seed casting in the stage of seed protection in which the seeds in the nest hole are most stable. So the missing detection should be carried out in the seed protection stage, as shown in Figure 4.

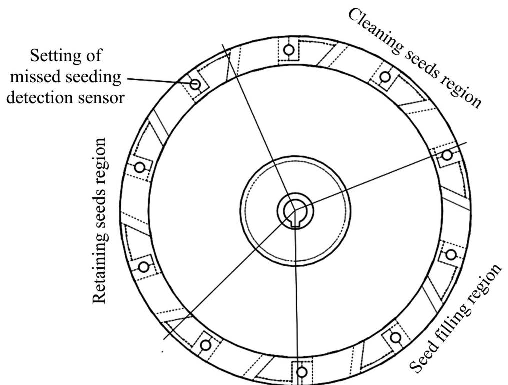


Figure 4 Installation position of the missed seed detection on the seed metering plate

3.3 Hardware design of the control system

3.3.1 Design of velocity measurement module

Peanut seeding occurs in spring and summer. As summer peanuts are planted in no-tillage[26] with previous crops on the surface of the arable land, which often leads to the slippage of traditional mechanical ground wheels, speed measurement errors cannot be avoided. Ding et al.[27] reported that the variation coefficient of satellite speed measurement is smaller than that of ground wheel. In addition, its seeding grain spacing qualification index and variation coefficient are less affected by operating speed. Therefore, the speed measurement by satellite was preferred.

The satellite speed measurement module is employed to detect the forward speed of the seeder and feed it back to the single-chip microcomputer, controlling the motor speed to ensure a certain plant distance. The satellite module uses SkyTraq's S1216F8-BD which features 167 channels, a tracking sensitivity of up to –165 dBm, with a measurement output frequency of up to 20 Hz, as well as real-time accurate speed measurement (Figure 5).

3.3.2 Design of missing broadcast detection module

For the missed-seeding detection module determines the success rate of missed-seeding and reseeding, which can be improved by enhancing detection accuracy and the timeliness of missed-seeding detection, a strong penetrating counter-sensitive photoelectric sensor is applied and placed in a dark environment for detection[28,29].

The transmitting end of a through-beam photoelectric sensor emits infrared rays, while its receiving end collects light signals. A signal is the output provided that an object blocks the beam path. The transmitting end continuously emits the light beam. When the peanut seeds are blocked in the middle, the electrical level is pulled down and transmitted to the single-chip microcomputer through the signal line. The sensor circuit diagram is shown in Figure 6.

3.3.3 Bluetooth Module Design

Bluetooth enjoys better convenience against mobile network for there is no need to build network, and it is suitable for field use[30]. This design adopts HC-05 Bluetooth serial communication module with a communication distance of 80 m, which supports cell phone APP and applet operation, sending required plant distance setting information, displaying seeder operation parameters and receiving alarm information, etc. The circuit diagram is shown in Figure 7.

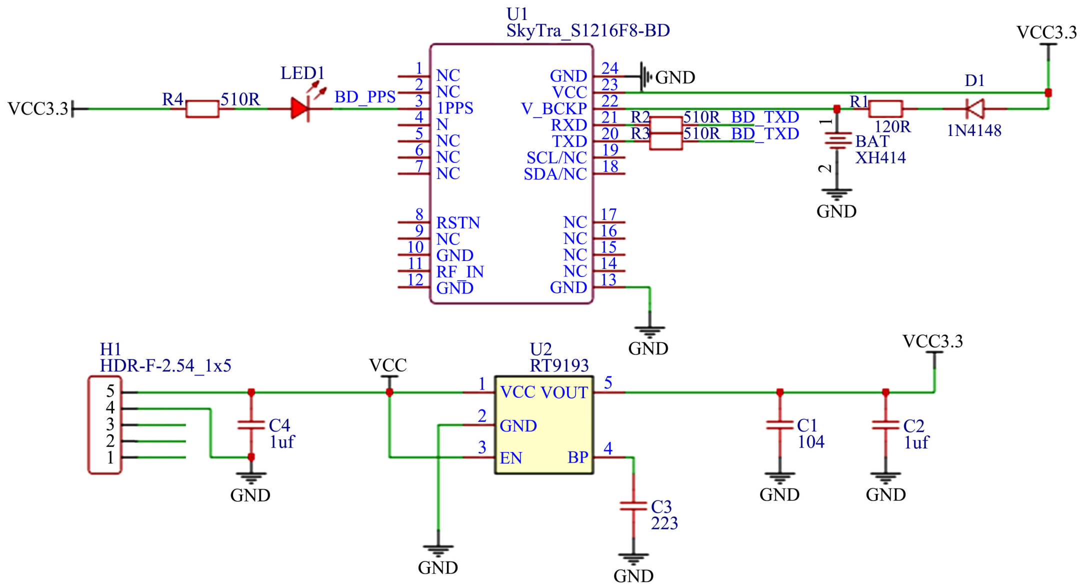


Figure 5 Circuit diagram of satellite speed measurement module

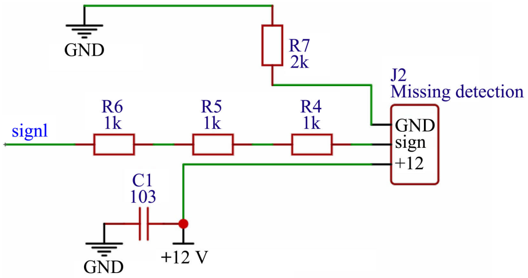


Figure 6 Circuit diagram of the through-beam photoelectric sensor

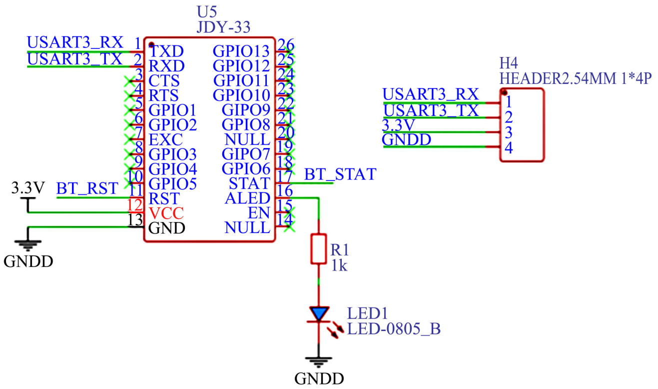


Figure 7 Bluetooth module circuit diagram

3.4 Software design of the control system

The control system is programmed by Keil software, which program flowchart is shown in Figure 8. After it starts, the seed-metering device control system completes the initialization of each module first, waiting for the host computer to send the setting information, and then for the satellite signal to be received to obtain the equipment's driving speed. It gets the theoretical output speed based on the mathematical relationship by the established working speed, seeder speed, and plant distance, configuring the microcontroller TIM3 timer to output the corresponding frequency PWM wave to drive the motor. After the motor is driven, it feedbacks and outputs real-time speed through the MODBUS485 protocol, by which the motor speed is dynamically adjusted. In case of missed sowing, the system calculates the delay time according to the mathematical model of missed sowing delay, and accelerates the motor to finish reseeding after a short postpone.

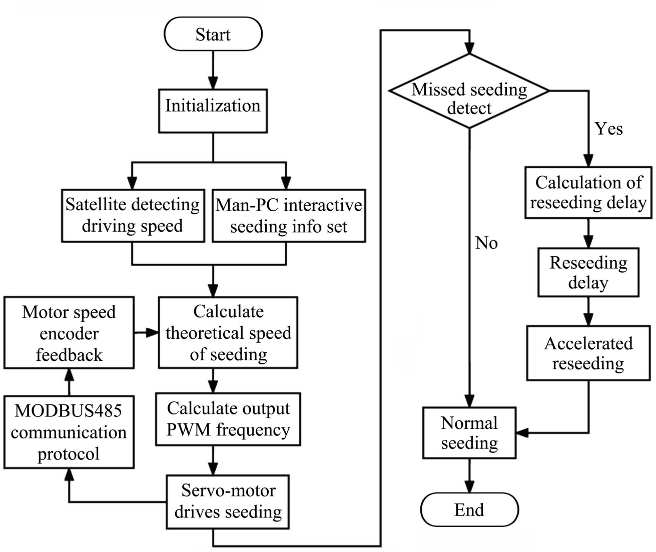


Figure 8 Software flow chart

4 Design of improved fuzzy PID controller

4.1 Mathematical modeling

As the speed of the driving motor directly affects the uniformity of seeding and plant spacing, it is particularly important to establish a mathematical model of the seeder's driving speed, plant spacing, and motor speed, to analyze the automatic replanting process, and clarify the speed control process. The speed control of the drive motor is divided into two categories. One is that there is no missed seeding, and the drive motor can work at a stable speed to ensure uniform plant spacing. The other is the occurrence of missed seeding. It is necessary to accelerate the motor to jump over the missing seed nest after a short delay to continuously ensure uniform plant spacing.

4.1.1 Mathematical model in the case of no missed seeding

Provided that no missed sowing occurs, the seeder only needs to work at a stable speed to achieve uniform plant spacing. Setting the working speed of the seeder to V_1, and the plant spacing to L. The time it takes for the seeder to pass a plant distance L is T_1. The radius of the seeding plate is R, and ten nests are evenly distributed. Then the arc length between the two nests is $\frac{1}{5}\pi R$, the rotation speed of the seed plate is n, and the time spent by the seeder to pass a plant distance L at the speed V_1 is T_1.

$$T_1=\frac{L}{V_1} \tag{1}$$

Similarly, the seed metering should rotate one nest within the time T_1, that is

$$T_1=\frac{\frac{1}{5}\pi R}{2\pi R\frac{n}{60}}=\frac{6}{n} \tag{2}$$

Therefore, the mathematical model of the seeder travel speed V_1, plant distance L, and seeder speed n is

$$n=\frac{6V_1}{L} \tag{3}$$

where, V_1 is the seeder travel speed, m/s; L is the plant distance, m; n is the seeder speed, rad/min.

The control mode of the DC motor is the encoder follow mode which changes the DC motor speed by adjusting the PWM output frequency of the microcontroller. The relation between the motor speed n and the pulse frequency f is as follows:

$$f=\frac{n}{60}\times 8192 \tag{4}$$

where, 8192 is the number of pulses for one revolution of the motor.

4.1.2 Mathematical model in case of missed seeding

The reseeding method designed in this paper is to detect the missing seed during the work of the seeder and skip the empty seed nest by acceleration[31]. After the missed seeding detection sensor detects a missing one, with a short delay, the seeder accelerates to skip the empty seed nest and achieves automatic replanting.

According to the working principle of accelerated skipping reseeding, the time for delaying the reseeding, for the required reseeding speed, and for acceleration time can be obtained by calculation when the missed seeding is detected. The distance from the missed seeding detection port to the seed releasing port is three nests. The motor should accelerate to pass the seeding port one nest before the empty seed nest, that is, the motor should increase the speed after T_2 time and T_2 is calculated as follows:

$$T_2 = \frac{\frac{2}{5}\pi R}{2\pi \frac{n}{60} R} = \frac{12}{n} \quad (5)$$

To ensure consistent spacing between seeds, the motor should speed up to jump over each empty seed nest by time T_1 at the speed of n_a, as following equation:

$$2\pi R \frac{n_a}{60} = \frac{\frac{2}{5}\pi R}{\frac{6}{n}} \quad (6)$$

Simplified as:

$$n_a = 2n \quad (7)$$

So, the motor should jump over the empty nest at the speed of n_a.

Similarly, if two consecutive nests are empty, the reseeding time is delayed at $T_2' = \frac{6}{n}$ and the replanting speed is delayed at n'_a=3n.

If three or more seeds are missed, a warning will be sent to the operator to remind him of replanting.

4.2 Design of improved fuzzy PID dual-loop control system

In order to improve the seeding accuracy and stability, the double-loop servo control system is improved based on the self-tuning fuzzy PID control algorithm[32]. But the fuzzy PID control algorithm would overshoot when the target speed occurs step. So conventional PID control is adopted when steps take place, otherwise, fuzzy PID control would be optioned in case of stable speed. In addition, the driving motor speed adjustment is achieved by outputting different frequency PWM signals, and the control flow chart is shown in Figure 9.

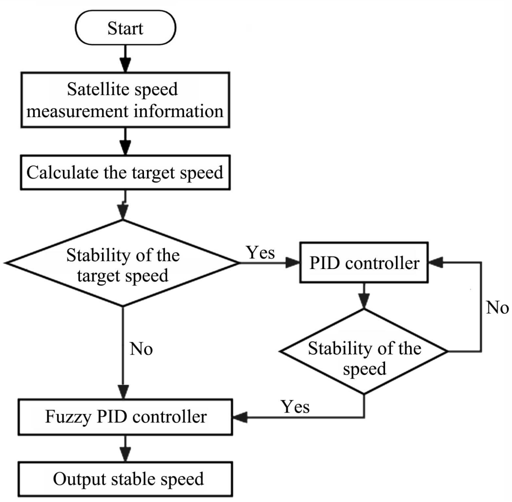


Figure 9 Flow chart of the fuzzy PID control process

4.2.1 Design of fuzzy PID control system

The fuzzy PID control system model is shown in Figure 10. The speed given value is compared with the feedback value of the speed measuring encoder. The error e and error change rate e_c are used as input quantities. And the PID parameters are adjusted by the fuzzy PID controller outputs K_p, K_i, and K_d to correct the PWM generation frequency, controlling the DC motor speed, which can effectively suppress the speed fluctuation, improving the anti-interference ability during operation and ensuring the quality of operation[33,34]. As the inner loop, the current loop uses the speed loop as output, while the current information feedback and commutation information as inputs to offset load rotation and power supply fluctuations to ensure stable motor dynamic performance[35].

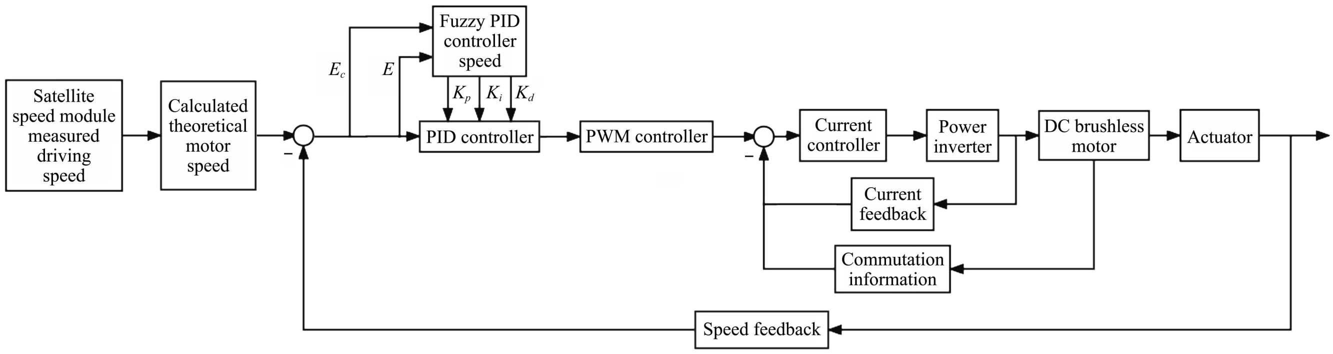


Figure 10 Fuzzy PID control system model

The difference e between the target speed n and the feedback speed n_f and the difference change rate e_c are the input quantities of the fuzzy controller. Both e and e_c are precise quantities. After being fuzzified, the fuzzy quantities E and E_c are obtained. The correction parameters ΔK_p, ΔK_i, and ΔK_d are acquired after reasoning and defuzzification. The three correction parameters are automatically and optimally adjusted in real-time according to the running state of the motor, so as to fulfill the self-tuning of PID control parameters.

The PID parameters of the system are confirmed by the trial and error method. The peanut planting distance in Shandong is generally between 15-27 cm, with a maximum working speed of 5 km/h. From Equation (3), it can be known that the speed range of the seeding plate is 0-55.56 rad/min, that is, the driving motor output speed range is 0-555.6 rad/min. Through multiple experiments and adjustment of the PID parameters, the fuzzy set e and the fuzzy set e_c are both {NB, NM, NS, Z, PS, PM, PB}, with the domain of {–5, 5}; and K_p is {NB, NM, NS, Z, PS, PM, PB} with the domain of {9.7, 10.3}; K_i is {NB, NM, NS, Z, PS, PM, PB}, with the domain of {0.3, 0.9}; K_d is {NB, NM, NS, Z, PS, PM, PB}, with the domain of {0.07, 0.13}. The self-tuning PID parameters ΔK_p, ΔK_i, ΔK_d are utilized to confirm the relation between the input $e(t)$ and the output $u(t)$ as follows:

$$u(t) = \Delta K_p e(t) + \Delta K_i \int_0^t e(t)\mathrm{d}t + \Delta K_d \frac{\mathrm{d}e(t)}{\mathrm{d}t} \quad (8)$$

As shown in Figure 11, the control system shows good speed following performance and can output the desired speed stably with an average error of about 2.4 rad/min. But when the target speed increases, the error accumulation is likely to produce an overshoot, resulting in a sudden increase in output speed, which causes an average error of about 25 rad/min. PID control is utilized in the speed loop when the target speed step occurs, while fuzzy PID control is chosen when the speed is stable, which effectively eliminates the large overshoot generated by the error accumulation of fuzzy PID when the step of target speed occurs.

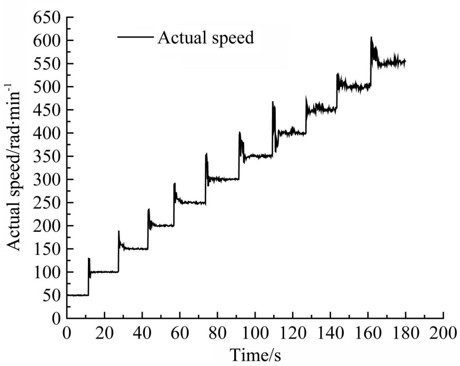


Figure 11 Real-time dynamic response performance under fuzzy PID control

4.2.2 Design of conventional PID control system

The conventional PID control system model, shown in Figure 12 processes the received host computer setting information and equipment travel speed, obtaining the motor target speed n by Equation (3). The speed feedback information is the motor speed n_f measured by the absolute encoder. Taking the difference e between the target speed n and the speed feedback value n_f as the input, the relation between the input e and the output u is determined as follows:

$$u = K_p e + K_i \int e\mathrm{d}t + K_d \frac{\mathrm{d}e}{\mathrm{d}t} \tag{9}$$

where, K_p is the proportional coefficient of the system; K_i is the integration coefficient; K_d is the differential coefficient.

Also through the trial-and-error method, the PID parameters were adjusted. The proportional coefficient K_p was finally determined to be 2, the integral coefficient K_i to be 2, and the differential coefficient K_d to be 0.1 as well. The actual output speed under the PID controller compared with the theoretical speed curve is shown in Figure 13, the response is rapid, the steady state error is 10 rad/min, and is susceptible to external disturbances resulting in large speed steps, so the conventional PID running time should be reduced.

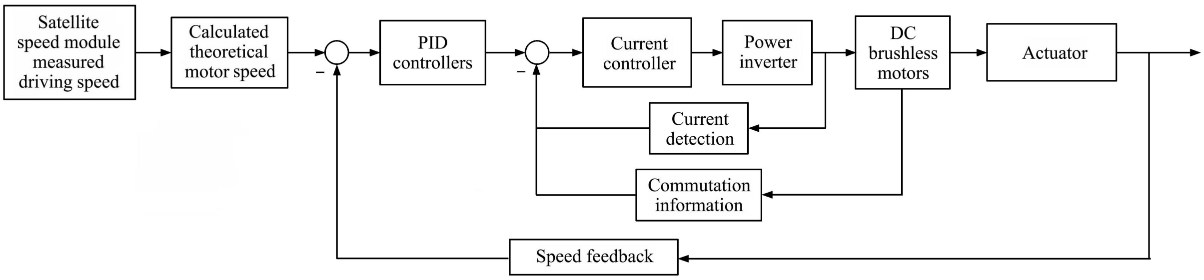


Figure 12 Conventional PID control system model

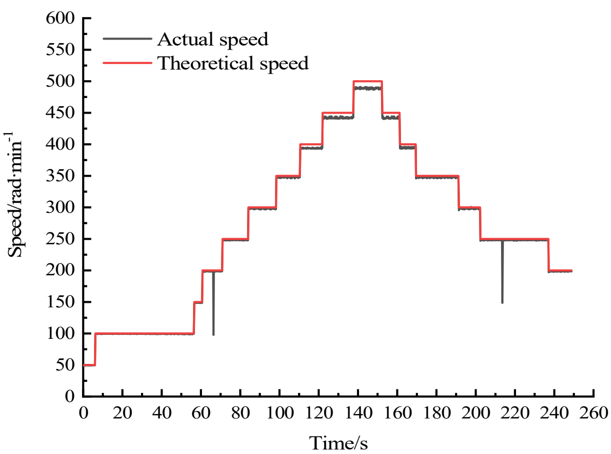


Figure 13 Comparison curve of actual output speed and theoretical speed under PID controller

4.2.3 Confirmation of interval length of conventional PID controller

In the peanut sowing operation, the target speed change that causes error accumulation only occurs in three phases the start-stop, acceleration, and deceleration as well as the leakage sowing. So the fuzzy PID double-loop control system is designed in order to stabilize the output speed. The system regulates that output speed is controlled by the conventional PID controller when the target speed step occurs and by the fuzzy PID controller when the output speed is stable. To ensure that the output speed has been stabilized, we need to determine the length of the working interval of the conventional PID controller, which can be achieved by defining a queue $H(\cdot)$ in the control system, with the elements of the queue denoted $H[i]$, holding the ground wheel speed data, and the queue length of N. Each element of the queue corresponds to a current velocity value. That is, $H[0]$, $H[1]$, $H[2]$, $H[3]$, …, $H[N-n+1]$, …, $H[N-1]$, $H[N]$. The actual output speed is judged to be stable by averaging the error of the N values at the end of the $H(\cdot)$ queue, and the test results are shown in Figure 14.

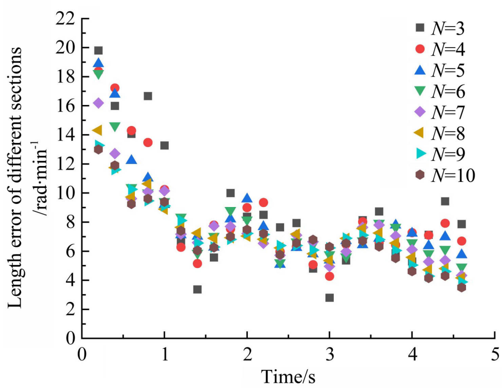


Figure 14 Average error of output speed of conventional PID controller under different interval lengths

As can be seen from Figure 14, the speed gradually stabilizes under the control of conventional PID controller, but there is still an error of about 0.5 rad/min. The interval length N is negatively correlated with the error, that is the larger the interval length N, the better to ensure the stability of the output speed. However, when N≥8, the error stabilization difference is about 0.2 rad/min, and the error does not decrease significantly with the increase of N. In order to end the PID control as soon as possible to ensure the output speed stability, the conventional PID controller interval length N=8 is set.

4.2.4 Verification

The motor speed accuracy test is conducted, with the average speed and coefficient of variation used as evaluation indicators. By collecting the actual speed n_{zF} of the driving motor output through LABVIWE serial data acquisition system for a repetition of 5 times (n_{zF1} to n_{zF5}), the motor speed coefficient of variation can be calculated.

As can be seen from Table 2, the control accuracy of this DC motor control system is positive, and the average output speed error ranges between ±1 rad/min at the theoretical speed of 50-550 rad/min, while the coefficients of variation are all below 1%.

Improved fuzzy PID double-loop servo control system of seed-metering device performance response graph is shown in Figure 15, the method has strong speed following performance, avoiding a large number of overshoots out of error accumulation when the target speed changes, featuring rapid response and the average error in 0.016 rad/min. The method effectively improves the output speed accuracy, providing a strong basis for precision seeding.

Table 2 Test results of speed control accuracy

No.	Theoretical speed/rad·min^{-1}	Real speed/rad·min^{-1}					Variation coefficient/%	Maximum error/rad·min^{-1}
		n_{zF1}	n_{zF2}	n_{zF3}	n_{zF4}	n_{zF5}		
1	50	49.87	50.02	49.91	49.83	49.84	0.84	1.3
2	100	99.32	99.33	99.35	99.41	99.38	0.96	2.5
3	150	150.23	150.21	150.20	150.26	15014	0.55	2.6
4	200	200.23	200.75	200.25	200.54	200.61	0.54	3.0
5	250	250.19	250.29	250.31	250.05	250.15	0.50	4.1
6	300	300.09	300.21	300.04	300.17	300.15	0.39	3.2
7	350	350.01	349.97	350.02	350.15	349.84	0.43	4.9
8	400	399.43	399.12	398.77	399.45	399.24	0.49	5.2
9	450	449.21	449.84	449.15	449.52	449.73	0.45	5.5
10	500	500.14	499.54	499.35	500.01	500.37	0.52	5.7
11	550	549.88	549.24	550.31	551.10	549.72	0.49	5.6

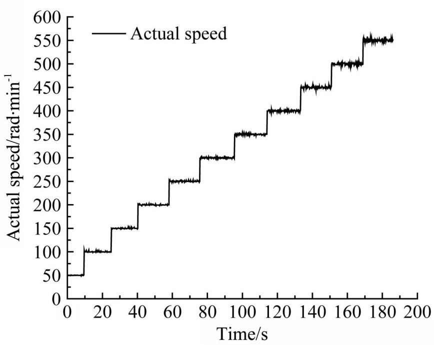


Figure 15 Real-time dynamic response performance of seed releasing section speed

5 Field tests

In the attempt to verify the working performance of the electric-driven peanut precision seed-metering device, the 2MB-1/2 peanut spreading and sowing machine of Qingdao Wannonda Peanut Machinery Co., Ltd. was chosen to carry out field sowing tests with the seed-metering device, as shown in Figure 16. For the peanut seed type, Luhua peanut was selected and the trial was conducted in Laixi City, Qingdao. The land was rototilled before the trial to ensure that the soil was loose and soft. In order to apply more accurate comparison tests, the designed electric-driven precision peanut seed-metering device was installed on the left side of the peanut seeder, and the ordinary ground wheel-driven peanut seeder was installed on its right side. And the mulching device was removed to avoid missing sowing caused by human factors.

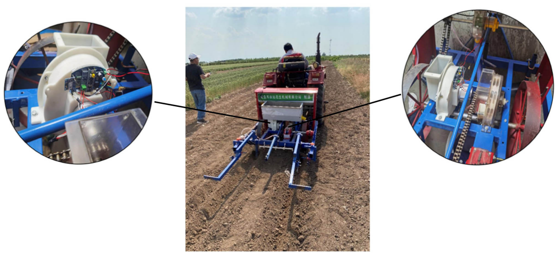


Figure 16 Field sowing test with the seed-metering deviece

Based on GB-T6973-2005 "Testing Methods of single seed drills (precision drills)"[36], tests were applied to clarify the effects of seeding speed on plant spacing stability, seeding driving mode effects on plant spacing stability and regularity, the qualified rate of plant spacing, missed seeding rate and reseeding rate.

The test parameters were set with reference to the peanut sowing standard in Shandong, the plant spacing is generally 15-27 cm, with a general working speed of 2-5 km/h. So, with reference to the mechanical plant spacing set on the peanut seeder, three levels of test seed-metering spacing were set at 16 cm, 21 cm, and 27 cm, with the respective seeding speed of 2-3 km/h, 3-4 km/h, and 4-5 km/h.

5.1 Test method

1) Test the effect of seeding speed on plant spacing stability

In order to investigate the effect of sowing speed on the stability of plant spacing, a single test was conducted to continuously measure the spacing of 250 seed rows under various sowing distances, which was repeated three times, with seeder operating speeds of 2-3 km/h, 3-4 km/h, and 4-5 km/h, respectively.

2) The effect of seeding driving mode on plant spacing stability and regular tests

The ground wheel-driven seeding, stepper motor-driven seeding, and DC motor-driven seeding were selected for comparison tests to explore the influence of different seeding drive methods on the stability of the plant spacing and its regularity. Then the seeding plant spacing was set at 16 cm, 21 cm, and 27 cm with a repetition of three times. The seeder operating speed was set to 2-3 km/h, 3-4 km/h, and 4-5 km/h, and a single test was performed to continuously measure the plant spacing of 250 seeds.

3) Measurement of plant spacing qualification, missed seeding, and reseeding rates

According to GB-T6973-2005, the sowing distance between ±0.5 times the set sowing distance shall be regarded as qualified sowing, more than 1.5 times shall be regarded as missed sowing, and less than 0.5 times shall be regarded as reseeding. In order to test the performance of this seed-metering device, the seeder was set to drive at normal operating speed (≤5 km/h), and field tests were conducted with the seeding spacing set at 16 cm, 21 cm, and 27 cm. 250 sets of data were collected after each test to obtain such field test results as the average value of actual seeding spacing $\overline{L}$ (m), the spacing conformity index L_q (%), the rate of missed seeding M (%), and reseeding rate R (%), calculated as follows:

$$\begin{cases} \overline{L} = \dfrac{\sum_{i=1}^{250} L_i}{N_z} \\ L_q = \dfrac{N_L}{N_z} \times 100\% \\ M = \dfrac{N_m}{N_z} \times 100\% \\ R = \dfrac{N_r}{N_z} \times 100\% \end{cases} \tag{10}$$

where, $\overline{L}$ is the average value of actual seeding spacing, m; L_q is the spacing conformity index, %; M the rate of missed seeding, %; R is reseeding rate, %; Nz is the total number of measurements, Nz=250 in this test; L_i is the actually measured plant spacing, m; N_L is the number of qualified plant spacing; N_m is the total number of missed seeds; N_r is the number of re-seeded seeds.

5.2 Test results and analysis

1) Test results and analysis of the effect of seeding speed on plant spacing stability

The test results proving the effect of seeding speed on plant spacing stability are shown in Table 3. The sowing plant spacing is regarded as qualified within ±0.5 times of the set one. As can be seen from the table, the sowing performance of 16cm and 21 cm spacing is better and less influenced by the operating speed, and the pass rate of spacing is about 98%. The pass rate, however, is negatively correlated with the operating speed when the spacing is 27 cm. Positively, the pass rate still remains above 95%.

Table 3 Test results of the effect of seeding speed on plant spacing stability

Working speed /km·h^{-1}	Set spacing /cm	Actual average spacing/cm			Qualified spacing rate/%		
		1	2	3	1	2	3
2-3	16	16.28	16.03	16.47	98.78	98.22	99.04
	21	21.47	21.22	21.31	97.95	98.14	97.45
	27	28.68	26.92	27.98	97.87	98.37	98.27
3-4	16	15.74	16.12	15.84	98.96	98.25	98.59
	21	21.63	20.92	21.23	98.54	98.87	98.32
	27	28.77	28.32	28.88	97.27	96.92	96.87
4-5	16	16.57	16.07	16.42	98.57	98.89	98.71
	21	22.59	22.36	22.28	97.52	97.21	97.05
	27	27.51	27.63	27.86	95.54	95.78	96.04

2) Test results and analysis of the effect of seed-metering driving method on the plant spacing stability and the regularity

As shown in Table 4, the seeding conformity rate of the three driving methods was above 97% at low speeds (2-3 km/h) with plant spacing set at 16 cm and 21 cm. while with the increase of operating speed and seeding distance, the rate of plant spacing of the ground wheel driving method obviously showed a decreasing momentum (98.19%-84.21%), and the two motor driving methods proved less influence from the operating speed and seeding distance. Comparing the two driving methods of stepper motor and DC motor, the qualified rate of DC motor plant spacing is higher than that of stepper motor plant spacing by about 4% in high speed sowing (4-5 km/h) and is less affected by the sowing distance.

(3) Test results and analysis of the qualified rate of plant spacing, missed sowing rate, and reseeding rate of seed-metering device

As shown in Table 5, the average qualified rate was 97.85% at the three set plant spacing as well as the operating speed, and the average missing rate was 1.42%. The seed-metering device had no obvious effect on the qualified rate of plant spacing when operating at low and medium speeds (2-3 km/h, 3-4 km/h), which were all around 98%. While at high speed (4-5 km/h), the qualified rate of plant spacing decreased as the set plant spacing increased. However, the spacing qualification rate was still about 95%. From the results of all field trials, it concludes that the seed-metering device can better complete the precision seed releasing operation of peanuts and is more suitable for the operation of peanut dense planting at precision low and medium speed.

Table 4 Effects of seed-metering driving method on the plant spacing stability test results

Working speed /km·h^{-1}	Set spacing /cm	Actual average spacing/cm			Qualified spacing rate/%		
		Ground wheel	Stepper motor	DC motor	Ground wheel	Stepper motor	DC motor
2-3	16	16.62	16.82	16.47	97.19	97.33	98.68
	21	20.51	21.55	21.31	96.61	97.92	97.85
	27	28.46	28.01	27.98	86.24	96.80	98.17
3-4	16	16.35	16.32	15.84	95.04	98.02	98.60
	21	21.50	21.75	21.23	90.53	98.80	98.58
	27	29.02	28.92	28.88	85.21	97.90	97.02
4-5	16	16.47	16.15	16.42	93.33	92.71	98.72
	21	19.92	22.68	22.28	91.78	94.48	97.26
	27	25.31	28.04	27.86	84.21	93.10	95.79

Table 5 Field test performance of seed-metering device

Working speed/m·h^{-1}	Seed spacing/cm	Actual spacing/cm	Qualification rate/%	Miss-seeding rate/%	Reseeding rate/%
2-3	16	16.47	98.68	0.72	0.6
	21	21.31	97.85	1.20	0.95
	27	27.98	98.17	1.12	0.71
3-4	16	15.84	98.60	0.92	0.48
	21	21.23	98.58	1.11	0.31
	27	28.88	97.02	2.07	0.91
4-5	16	16.42	98.72	0.95	0.33
	21	22.28	97.26	1.35	1.39
	27	27.86	95.79	3.33	0.88

6 Conclusions

1) Based on a small peanut seeder with one ridge width and duplicate rows, a servo motor drive is applied to replace the traditional passive ground wheel one. In addition, satellite speed measurement is adopted to complete the electric drive and electric control modification of the seed-metering device and precision seeding control.

2) The improved fuzzy PID control algorithm avoids a large number of errors caused by the acceleration of the seeder and the target speed step during replanting. The test proves that the speed of the system has a strong follow-up ability, with an average speed error of ±1 rad/min, and a coefficient of variation of about 1%. Combined with the field test, it proved that the maximum error of the system has a minor effect on the qualified rate of plant spacing, which is within the error range permitted.

3) Field tests proved that the motor-driven method increased the average seeding spacing pass rate by 6.72%, compared with the traditional ground wheel-driven seed-metering device. For the comparison with other electric-driven ones, there was no significant difference in the operation at low and medium speeds,

but the spacing pass rate increased by about 4% at high speed sowing, and negative effects caused by sowing distance were significantly reduced.

4) The field tests showed that the plant spacing qualification rate was greater than 98% and missed seeding rate was less than 2% in operation at medium and low speeds. The plant spacing qualification rate was not significantly related to the set plant spacing. When operating at high speed, the plant spacing qualification rate was greater than 94% and the omission rate is less than 4%. The former is negatively correlated with the set plant spacing.

In this study, precision seeding of peanuts and uniform seeding can be achieved when the working speed is limited to 5 km/h. anyway, there are many other factors affecting field operation, such as sowing height, seeder vibration, peanut variety, etc. The influence of the interaction between the above factors on the performance of seed releasing operation remains an occupation of our research.

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