Electronic control seed-metering system for precision seeding maize based on fuzzy PID

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Abstract: Aiming at the problem of poor uniformity of maize sowing caused by ground wheel slip, an electronic control seed-metering system (ECSMS) for maize single seed precision sowing was designed and a mathematical model for motor control of the ECSMS was determined. The PID parameters were set by Z-N method and fuzzy control. The fuzzy PID control design and Simulink simulation were completed by MATLAB, which reduced response time of the system by 0.23 s and improved the control accuracy. Experiments on the JPS-12 test bench show that the qualification index (QI) of maize seed-metering device with the ECSMS increases by 4.47%, the multiples index (MI) decreases by 1.96%, the miss index (MIX) decreases by 2.81%, and the coefficient of variation (CV) of qualified seed spacing decreases by 5.06%, and the sowing uniformity has been greatly improved. Test results of the soil-tank test bench show that the system has good sowing uniformity and stability. And the QI is 96.74%, the MI is 2.15%, the MIX is 1.10%, and the CV of qualified seed spacing is 16.24%. Under different setting seed spacing and different sowing operation speed, the change range of seeding quality index was within 10%. The results of field sowing test show that the QI was 84.21%, the MI was 2.63%, the MIX was 7.89%, and the CV of qualified seed spacing was 22.15%, which meet the requirements of JB/T 10293-2013 'Specification for single seed planters (precision planters)' and the agronomic requirements for maize precision sowing. The system runs stably and reliably in practical operation and has good operation performance.
Keywords: maize, seed-metering system, electronic control, precision sowing, parameters tuning, fuzzy PID control, simulink simulation
DOI: 10.25165/j.ijabe.20241704.8247

Citation: Zhao X S, Zhao H P, Wang Z H, Li J C, Yu H L, Yan Q. Electronic control seed-metering system for precision seeding maize based on fuzzy PID. Int J Agric & Biol Eng, 2024; 17(4): 217–226.

1 Introduction

Intelligent precision sowing technology is the inevitable trend of the development of precision agriculture in the future[1,2], but at present, the domestic planter is still mainly mechanical. The seed-metering device, the core component of the planter, is driven by the ground wheel through the chain to sow. Due to the complex field operation environment, the ground wheel will slip frequently[3-7], resulting in a decrease in sowing uniformity. The ECSMS uses the motor to drive the sowing device, which can greatly improve the sowing uniformity. Zhang et al.[8] studied the control realization of a DC brushless motor using PWM speed regulation mode and PID parameter tuning based on a genetic algorithm. Ding et al.[9,10] designed an electronic control system for a maize planter based on a PID control algorithm and GPS velocity measurement. He et al.[11] developed an automatic operation system for rice transplanters by using a PID speed control algorithm and joint navigation technology. Ding et al.[12] designed a navigation controller for rape planters that is based on the Immune PID control algorithm and uses the Beidou Navigation Satellite System and an electronic compass to realize navigation control for rape planters. Yang et al.[13] designed an electric seed-metering system based on the segmented PID control method, which used CAN bus communication to realize system signal transmission. Fu et al.[14] designed a set of sowing depth control systems composed of a profiling mechanism, a hydraulic system, and an electric control system on the maize sowing unit. Cheng et al.[15] developed an electric control system for wheat plot sowing based on a STM32 single-chip microcomputer. The system can set the parameters of plot sowing by operators and control the rotation speed of the vertebral grid and seed separator by controlling the stepping motor and DC motor. The sowing and fertilization machinery produced abroad is equipped with advanced control and monitoring systems, and the degree of automation and intelligence in sowing and fertilization is high. Kamgar et al.[16] developed a seeding controller for realization in the grain planter. Jafari et al.[17] designed and constructed a closed-loop control system based on a DC motor. Kim et al.[18] designed a pneumatic variable particle fertilizer applicator. In a word, the research on the PID control algorithm and intelligent precision sowing technology of ECSMS is an inevitable trend for the development of precision agriculture in the future, and the research on seed-metering systems is extensive[19-25], but the control accuracy and stability of ECSMS need to be further improved.

In view of the above problems, an ECSMS for maize precision sowing based on fuzzy PID was designed to further improve the sowing uniformity and the operating performance of the system.

Received date: 2024-03-12 **Accepted date:** 2024-06-25
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2 Materials and methods

2.1 System structure and working principle

The ECSMS is mainly composed of the STC89C52RC microcontroller, DC brushless motor, motor driver, rotary encoder, and LCD display, as shown in Figure 1. During the sowing operation, the user sets the sowing operation parameters, and the system detects the sowing operation speed and motor speed in real time through the rotary encoder installed on the speed measuring wheel. The theoretical speed of the motor is calculated by the single chip microcomputer, and a certain frequency PWM signal is sent to the motor driver to drive the motor to operate. In this process, the motor speed is compared with the theoretical speed through the fuzzy PID control algorithm, and the PWM signal frequency is adjusted until the speed reaches the theoretical speed to complete the sowing operation.

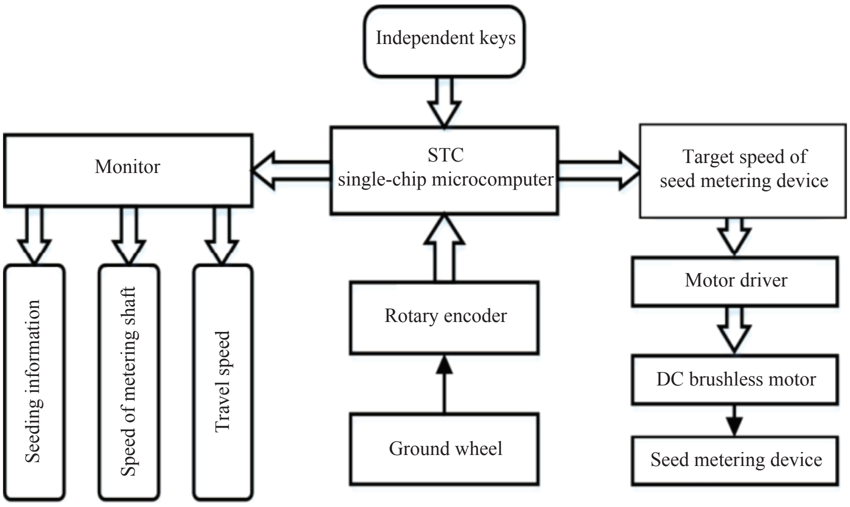


Figure 1 Block diagram of the electronic control seed-metering system

2.2 System design

2.2.1 System hardware circuit design

The hardware design of ECSMS mainly includes single-chip microcomputer system circuit design, power circuit design, RS485 communication circuit design, key display circuit design, and DC brushless motor control circuit design. The motor control circuit of the system is shown in Figure 2: U3 is the motor driver, and DC+ and DC– are respectively connected to the positive pole and negative pole of a 24V DC power supply to supply power to the motor driver. W, V, U, Hw, Hv, Hu, REF+, and REF– are connected to the DC motor, respectively, which provides power for the motor and realizes signal transmission. COM, EN, and BRK grounded together and control the motor positive rotation without using the brake control function. SV is connected to the P3.4 port of the MCU through a filter circuit composed of capacitance and resistance to complete the transmission of the PWM signal. SPEED is connected to the P3.2 port of the single-chip microcomputer through the filter circuit to realize the transmission of the motor speed signal. The single-chip microcomputer obtains the pulse signal and calculates the motor speed.

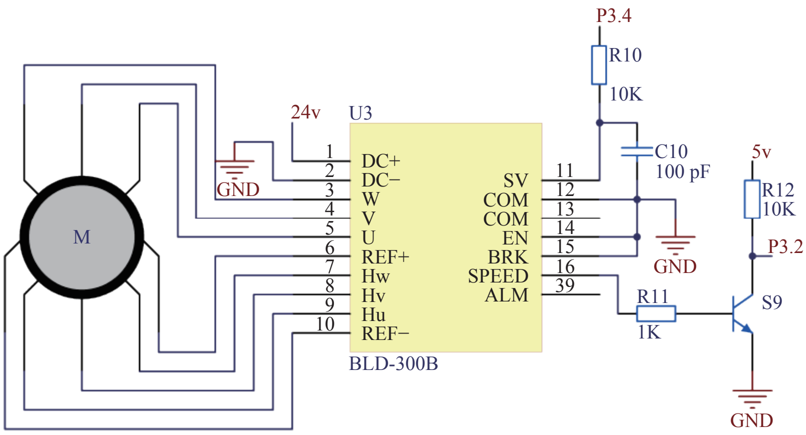


Figure 2 Control circuit of motor

2.2.2 System software design

System software development environment is Keil μVision4, which is C language and modular programming. The system is powered on. After the program is initialized, the user needs to select the sowing mode, input the sowing information, and start the motor in turn. Then the system detects the speed information through the rotary encoder and detects and controls the motor speed in real time. When it is necessary to stop the sowing, the tractor driver presses the key to stop. The overall process of the system is shown in Figure 3.

2.3 Fuzzy PID control principle

In the sowing operation, the speed of the machine changes in real time, and the use of a set of fixed PID parameters have poor adaptability and low control stability. In order to improve the stability and accuracy of the sowing control, the fuzzy PID control method[26,27] is used to realize the adaptive adjustment of PID

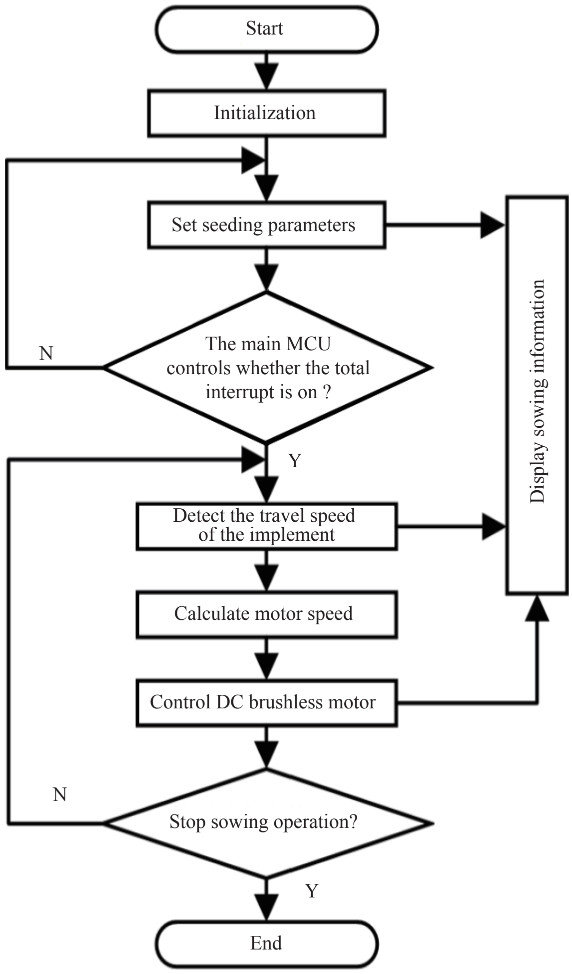


Figure 3 Flow chart of seed-metering system

parameters.

The basic process of fuzzy control is to fuzzify the change first, then perform fuzzy reasoning, and finally defuzzify to obtain the control quantity. The knowledge base (including the database and rule base) is needed in the process. The principle of fuzzy PID control is to use the fuzzy controller to complete the tuning of PID parameters. The control strategy structure is shown in Figure 4.

2.4 Mathematical model of the control system

To complete the programming, the mathematical relationship model between the sowing operation speed, the rotation speed of the sowing shaft, and the sowing operation information should be established. Taking the single maize seed-metering device as the research object, the falling time interval of two adjacent seeds will be

$$\Delta t=\frac{60}{nm} \tag{1}$$

where, Δt is the falling time interval of two adjacent seeds, s; n is the rotation speed of the seed-metering plate, r/min; m is the number of seeds.

The seed spacing is

$$Z=277.8v\Delta t=\frac{1.67\times10^4 v}{nm} \tag{2}$$

where, Z is the set seed spacing, mm; v is the machine operation speed, km/h. The rotation speed of the seed-metering plate (n) can be obtained from Equation (2).

$$n=\frac{1.67\times10^4 v}{Zm} \tag{3}$$

The radius of the measured wheel (the ground wheel) is R (mm). Equation (3) can be expressed as

$$n=\frac{2\pi R}{Zm}n_1 \tag{4}$$

where, n_1 is the rotation speed of the ground wheel, r/min.

2.5 Incremental PID control

The PID control principle is the deviation of the proportion, integral and differential through a linear combination of control variables to control the controlled object, including position PID and incremental PID two[28-31]. The general equation for PID control is.

$$u(t)=K_p\left[e(t)+\frac{1}{T_i}\int_0^t e(t)\mathrm{d}t+T_d\frac{\mathrm{d}e(t)}{\mathrm{d}t}\right]+u_0 \tag{5}$$

where, K_p is proportional coefficient; T_i is integral time constant; T_d is differential time constant; $e(t)$ is the deviation between the given value and the actual output value; u_0 is the initial value of the control; t is time, s. Applying PID control to single-chip microcomputer control system requires the discretization of Equation (5).

$$u(k)=K_pe(k)+K_i\sum_{j=0}^{k}e_j+K_d(e(k)-e(k-1))+u_0 \tag{6}$$

where, K_p = K_p; K_i = $K_p(T/T_i)$; K_d = $K_p(T_d/T)$; T is the sampling period; k is the sampling moment.

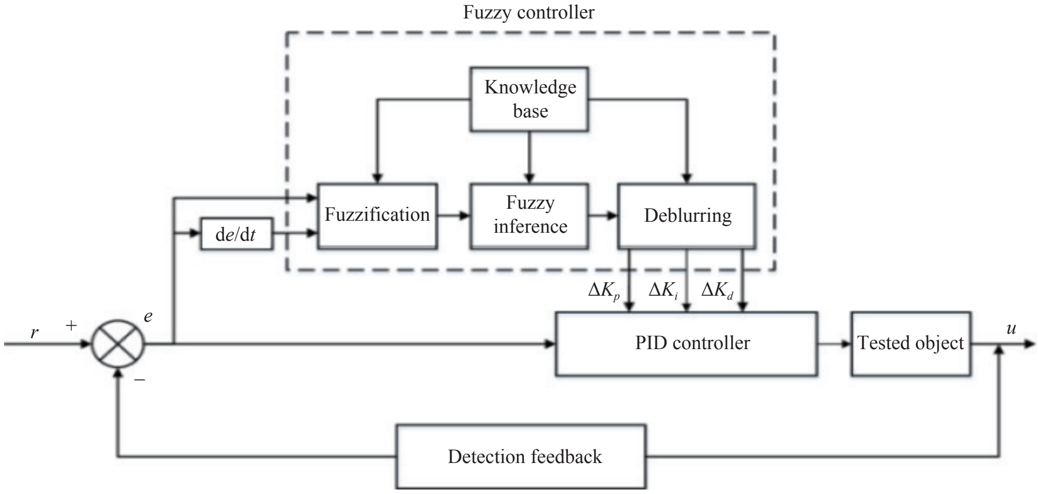


Figure 4 Structure diagram of fuzzy PID controller

The output values at k–1 sampling moment obtained by Equation (6).

$$u(k-1)=K_p e(k-1)+K_i\sum_{j=0}^{k-1}e_j+K_d(e(k-1)-e(k-2))+u_0 \quad (7)$$

The incremental PID control algorithm equation can be obtained by subtracting Equation (7) from Equation (6).

$$\Delta u(k)=K_p(e(k)-e(k-1))+K_i e(k)+K_d(e(k)-2e(k-1)+e(k-2)) \quad (8)$$

The incremental PID control algorithm does not need cumulative calculation in the single-chip microcomputer system and reduces the operation time. When the system is disturbed and leads to a large error, the method of logical judgment can be used to judge and eliminate the error.

2.6 Critical oscillation method (Z-N method) to set PID parameters

2.6.1 Simulink simulation

As a component of MATLAB, Simulink can model, simulate and comprehensively analyze the dynamic system. The core of the ECSMS is to realize the control of the DC brushless motor. The establishment of Simulink simulation requires the transfer function of the control system, that is, the transfer function of the DC brushless motor. According to the principles of electromotology, the differential equation of the DC brushless motor is as following[7].

$$T_d T_m\frac{d^2n_1}{dt^2}+T_m\frac{dn_1}{dt}+n_1=\frac{1}{C_e}U_0 \quad (9)$$

where, T_d is the electromagnetic time constant; T_m is the electromechanical time constant; n_1 is the speed of the motor; C_e is the motor counter electromotive fore coefficient; U_0 is the armature voltage. The transfer function obtained by the Laplace transform of Equation (9) is

$$G(s)=\frac{\frac{1}{C_e}}{T_mT_ds^2+T_ms+1} \quad (10)$$

The motor selected for the system is 80BL02 DC brushless motor, and the relevant parameters are: T_d = 0.01 s, T_m = 0.978 s, C_e = 0.075 V/(rad/s), and substituting these parameters into Equation (10) can get:

$$G(s)=\frac{13.3}{0.009\,78s^2+0.978s+1} \quad (11)$$

The Simulink model of the ECSMS is shown in Figure 5. The input is the speed of the machine, and the output is the speed of the motor. In the model, K_P, K_I and K_D represent K_p, K_i and K_d in the incremental PID control algorithm Equation (8), respectively.

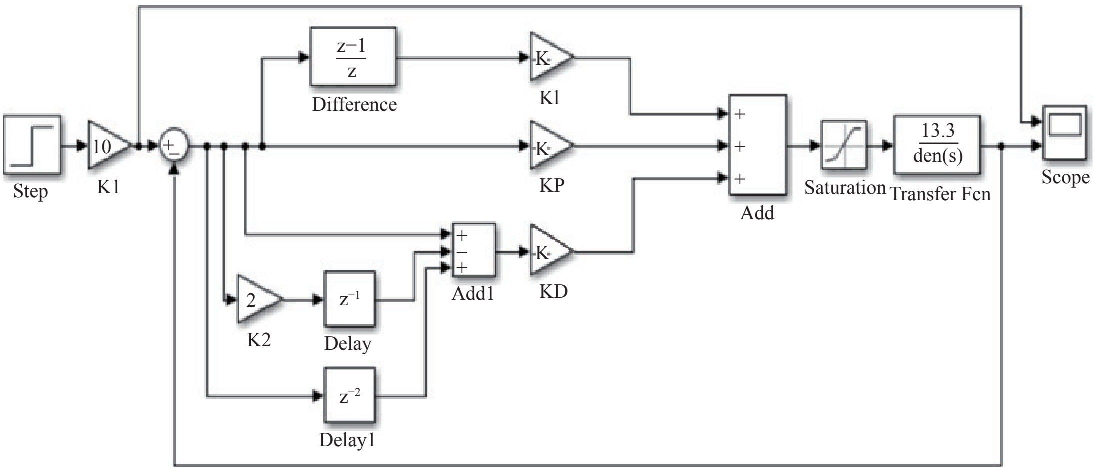


Figure 5 Simulink model

2.6.2 PID parameter tuning

The traditional PID parameter tuning method can obtain a set of fixed optimal parameters, but in practical application, the optimal parameters of PID control often change with the operation of the system, and the fixed parameters cannot meet the requirements of control precision. Therefore, this paper uses the critical oscillation method, namely the Ziegler-Nichols (Z-N) method, to obtain a set of PID parameters as the initial value, and realizes the self-tuning of PID parameters through fuzzy control, so as to improve the performance of the control system.

The parameter tuning steps of the Z-N method are as follows: Firstly, the K_I and K_D are set to zero, and the K_P is adjusted to make the system oscillate. Secondly, adjust the K_P until the system begins to exhibit equal amplitude oscillation, find the critical oscillation point, record K_P critical value K_{pcrit} and oscillation period T_{crit}; the values of K_I and K_D are calculated according to the Z-N equation. As shown in Table 1, T_i and T_d represent the integral time constant and the differential time constant respectively. Finally, K_P, K_I and K_D were appropriately adjusted.

Table 1 Parameters calculation equation based on the Z-N method

Controller type	K_P	T_i	T_d	K_I	K_D
P	$0.5{\cdot}K_{pcrit}$				
PD	$0.8{\cdot}K_{pcrit}$		$0.12{\cdot}T_{citr}$		$K_P{\cdot}T_d$
PI	$0.45{\cdot}K_{pcrit}$	$0.85{\cdot}T_{citr}$		K_P/T_i	
PID	$0.6{\cdot}K_{pcrit}$	$0.5{\cdot}T_{citr}$	$0.12{\cdot}T_{citr}$	K_P/T_i	$K_P{\cdot}T_d$

The K_P is adjusted from large to small, and the response curve is observed. When K_{pcrit} = 25, the response curve of the system has an equal amplitude oscillation, and the oscillation period T_{crit} = 0.2 s is shown in Figure 6. The system uses a PID controller. According to the corresponding equation of the PID controller in Table 1, K_P = 15, K_I = 150, and K_D = 0.36 can be obtained, and input into the Simulink model to simulate. The system response curve is shown in Figure 7.

The response time of the system obtained by using the PID parameters adjusted by the Z-N method is 0.45 s, but there is still overshoot in the system. In order to further shorten the response time, reduce the overshoot and improve the stability of the system, the PID parameters are adjusted on the basis of the Z-N method. Finally, a set of parameters is obtained: $K_P = 19$, $K_I = 115$, $K_D = 0.15$. The corresponding system response curve is shown in Figure 8, and the system response time is 0.38 s, with no overshoot.

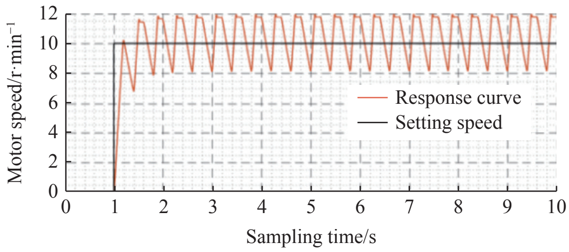


Figure 6 Constant amplitude response curve

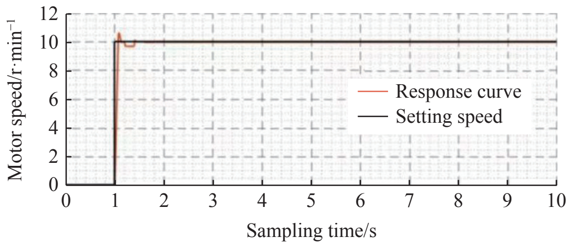


Figure 7 Response curve after parameter tuning based on the *Z-N* method

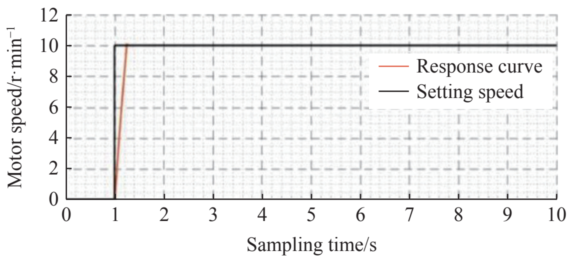


Figure 8 Response curve after adjusting PID parameters

2.7 Realization of a fuzzy PID control strategy

The input of the fuzzy PID controller is error e and error change rate e_c. In the fuzzification process, the input variables need to correspond to the variable universe through the quantization factor. According to the quantization results and the fuzzy subset, the membership degree of the input to the subset is obtained. The fuzzy subset is the same as the fuzzy subset of the output variables ΔK_p, ΔK_i and ΔK_d, which are

{NB,NM,MS,Z0,PS,PM,PB}

The domain of each variable is selected as [–6,6], and the quantization factor is

$$K_e = \frac{n_e}{e_{\max}}, \quad K_{e_c} = \frac{n_{e_c}}{e_{c\max}} \tag{12}$$

where, n_e and n_{ec} are fuzzy series, e_{max} and e_{cmax} are the maximum values of variables e and e_c. The defuzzification process needs to pass the scale factor, and the fuzzy quantity is transformed into the accurate quantity, and the scale factor is

$$K_{K_p} = \frac{K_{p\max}}{L}, \quad K_{K_i} = \frac{K_{i\max}}{L}, \quad K_{K_d} = \frac{K_{d\max}}{L} \tag{13}$$

K_{pmax}, K_{imax} and K_{dmax} are the maximum values of PID parameters, respectively, and L is the fuzzy series of output. Both fuzzification and defuzzification need to obtain the membership degree of variables in the fuzzy subset. The membership function curve can be obtained by using MATLAB software. For example, the membership function of input e is shown in Figure 9.

According to the fuzzy rules of K_p, K_i and K_d, and the defuzzification process, the fuzzy quantity is transformed into an accurate quantity, and the fuzzy control query tables of ΔK_p, ΔK_i and ΔK_d are obtained, respectively. The query table for ΔK_p is listed in Table 2. Through Simulink simulation, the system response time of fuzzy PID control is 0.15 s. The system response curve obtained is shown in Figure 10. Compared to the traditional PID control method mentioned above, the system response time has been shortened by 0.23 s.

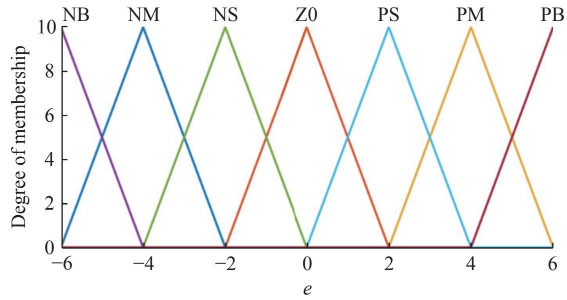


Figure 9 Membership function curve

Table 2 The fuzzy lookup table of ΔK_p

ΔK_p		Deviation change rate e_c												
		–6	–5	–4	–3	–2	–1	0	1	2	3	4	5	6
	–6	0	0	0	4	4	4	4	3	2	1	0	0	0
	–5	0	0	0	4	4	3	3	3	2	1	0	0	0
	–4	0	0	0	4	4	3	2	2	2	1	0	0	0
	–3	4	4	4	4	4	3	2	1	1	0	–1	–1	0
	–2	4	4	4	4	4	3	2	1	0	–1	–2	–2	0
	–1	4	4	4	3	3	2	1	0	–1	–2	–3	–3	0
Deviation e	0	4	4	4	3	2	1	0	–1	–2	–3	–4	–4	0
	1	3	3	3	2	1	0	–1	–1	–2	–3	–4	–4	0
	2	2	2	2	1	0	–1	–2	–2	–2	–3	–4	–4	0
	3	2	1	1	0	–1	–2	–3	–3	–3	–4	–4	–4	0
	4	2	1	0	–1	–2	–3	–4	–4	–4	–4	–4	–4	0
	5	2	1	0	–1	–2	–3	–4	–4	–4	–4	–4	–4	0
	6	0	0	0	0	0	0	0	0	0	0	0	0	0

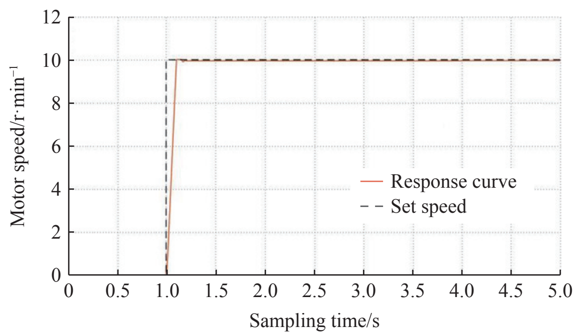


Figure 10 Response curve of the fuzzy PID control system

To further analyze the effectiveness of fuzzy PID control, both traditional PID control and fuzzy PID control were compared through simulation. The simulation inputs used were step signals and continuous pulse signals, as shown in Figure 11. When the simulation input was a step signal, the response time of the fuzzy PID control system was shorter and the response speed was faster. As shown in Figure 12, when the simulated input is a pulse signal, the following process of calculating the speed can be simulated.

When the speed continuously changes, fuzzy PID control has better following performance and faster response speed. The response speed of traditional PID control is slow and generates certain disturbances, resulting in poor performance. Through simulation analysis, it can be concluded that the control performance and accuracy of the fuzzy PID control system are superior to traditional PID control.

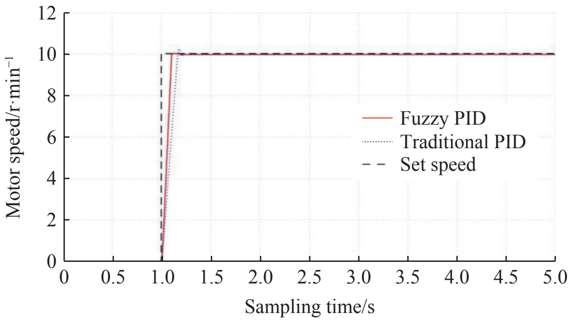


Figure 11 Response curve of the comparative simulation system for the input step signal

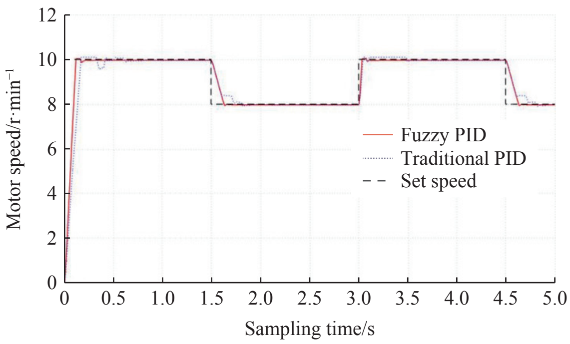


Figure 12 Response curve of a comparative simulation system for an input pulse signal

2.8 Testing of the ECSMS

2.8.1 Test design of the seed-metering device test bench

The maize seeds of 'Zhengdan 958' were used as the research objection, and the maize single seed precision sowing experiment was carried out. The test equipment included one set of ECSMS, one 80BL02 DC brushless motor, one BLD-300B motor driver, one HN3806-AB-400N rotary encoder, one 12 V DC battery, one 220 V transfer 24 V power supply module, and one unit of scoop-wheel maize seed-metering device. According to GB/T6973-2005 'Testing methods of single seed planters (precision planters)', the QI, MI, MIX and CV were selected as evaluation indexes.

The seed-metering system test based on the JPS-12 seed-metering device test bench is shown in Figure 13. The seedbed speed of 3 km/h, 6 km/h and 9 km/h was set to simulate the working speed of the machine, and the seed metering experiments with 100 mm, 150 mm, 200 mm, 250 mm and 300 mm seed spacing were carried out at each speed. The experiments were repeated three times in each group. The maize seed-metering device unit with and without ECSMS was used to test. The test results are listed in Tables 3 and 4.

According to GB/T 6973-2005 'Testing methods of single seed planters (precision planters)' , the test methods and data processing methods for single seed precision sowing are specified:

Divide into sections at intervals of $0.1X_{ref}$ (X_{ref} is the theoretical seed spacing), and the variables for each section are:

$$X_i = \frac{x_i}{X_{ref}} \tag{14}$$

where, x_i is the median value of the section. Process the particle size data into X_i and calculate the value of n_i according to regulations, n'_1 is the number of X_i within the corresponding range.

$$\begin{cases} n'_1 = \sum n_i(X_i \in \{0 \sim 0.5\}) \\ n'_2 = \sum n_i(X_i \in \{> 0.5 \sim\leq 1.5\}) \\ n'_3 = \sum n_i(X_i \in \{> 1.5 \sim\leq 2.5\}) \\ n'_4 = \sum n_i(X_i \in \{> 2.5 \sim\leq 3.5\}) \\ n'_5 = \sum n_i(X_i \in \{> 3.5 \sim +\infty\}) \end{cases} \tag{15}$$

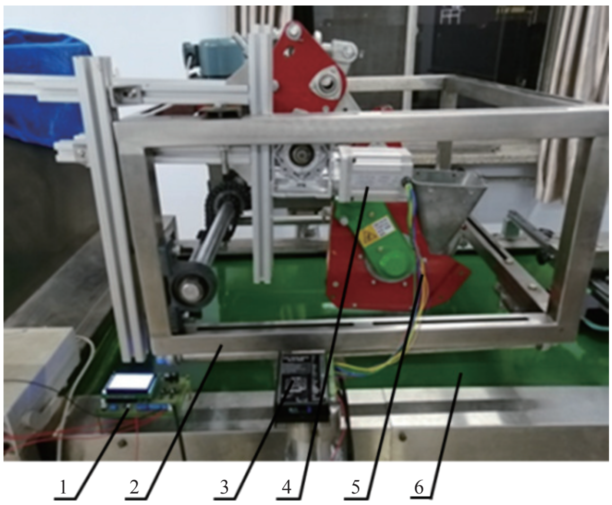
$$\begin{cases} N = n'_1 + n'_2 + n'_3 + n'_4 + n'_5 \\ n_2 = n'_1 \\ n_1 = N - 2n_2 \\ n_0 = n'_3 + 2n'_4 + 3n'_5 \\ N' = n'_2 + 2n'_3 + 3n'_4 + 4n'_5 \\ \bar{X} = \dfrac{\sum n_i X_i}{n_2} \end{cases} \tag{16}$$

where, N is the number of seeds measured in the experiment; n_2 is the number of replays; n_1 is the qualified quantity; n_0 is the number of missed broadcasts; N' is the interval number; X is the average qualified seed spacing; $X_i \in \{>0.5\text{-}1.5\}$.

The evaluation indicators specified in the national standard include

$$\begin{cases} A = \dfrac{n_1}{N'} \times 100 \\ D = \dfrac{n_2}{N'} \times 100 \\ M = \dfrac{n_0}{N'} \times 100 \\ \sigma = \sqrt{\dfrac{\sum n_i X_i^2}{n'_2} - \bar{X}^2} X_i \in \{> 0.5 \sim\leq 1.5\} \\ C = \sigma \times 100 \end{cases} \tag{17}$$

where, A is the qualification index (QI); D is the multiples index (MI); M is the miss index (MIX); $\sum$ is the standard deviation; C is the coefficient of variation (CV).



1. SCM control system 2. Seed-metering device holder 3. Motor driver 4. Brushless DC motor 5. Maize seed-metering device 6. Conveyor belt

Figure 13 JPS-12 seed-metering device test bench sowing test

Table 3 Test results of maize seed-metering device with ECSMS

Setting plant spacing/mm	Performance/%	Sowing operation conditions			
		3 km/h	6 km/h	9 km/h	Variable speed operation
100	QI	95.24	100.00	98.01	96.64
	MI	3.40	0.00	0.66	2.01
	MIX	1.36	0.00	1.32	1.34
	CV	20.38	17.03	17.6	17.61
150	QI	98.68	98.04	100.00	100.00
	MI	0.00	0.00	0.00	0.00
	MIX	1.32	1.96	0.00	0.00
	CV	13.48	15.63	11.28	12.07
200	QI	100.00	100.00	98.66	100.00
	MI	0.00	0.00	0.67	0.00
	MIX	0.00	0.00	0.67	0.00
	CV	10.71	10.31	11.34	12.65
250	QI	99.33	98.66	100.00	100.00
	MI	0.67	0.67	0.00	0.00
	MIX	0.00	0.67	0.00	0.00
	CV	12.44	11.76	12.36	12.07
300	QI	100.00	100.00	100.00	100
	MI	0.00	0.00	0.00	0.00
	MIX	0.00	0.00	0.00	0.00
	CV	13.00	12.51	10.05	16.17

Table 4 Test results of maize seed-metering device without ECSMS

Setting plant spacing/mm	Performance/%	Sowing operation conditions			
		3 km/h	6 km/h	9 km/h	Variable speed operation
100	QI	94.12	93.40	92.75	90.02
	MI	2.84	3.02	2.10	3.91
	MIX	3.04	3.58	5.15	6.07
	CV	19.68	20.32	21.42	23.83
150	QI	93.64	92.06	91.52	95.43
	MI	2.53	3.61	3.05	2.56
	MIX	3.83	4.33	5.43	2.01
	CV	18.72	19.93	18.62	24.24
200	QI	95.36	96.34	95.62	92.70
	MI	3.17	2.49	0.72	2.15
	MIX	1.47	1.17	3.66	5.15
	CV	15.85	14.63	17.74	19.32
250	QI	96.82	97.21	93.48	92.94
	MI	1.49	1.54	2.77	3.54
	MIX	1.69	1.55	3.75	3.52
	CV	15.76	17.90	15.66	19.57
300	QI	97.40	96.12	97.35	93.57
	MI	1.15	0.79.	1.32	2.64
	MIX	1.45	3.09	1.33	3.79
	CV	14.35	15.83	19.81	18.72

2.8.2 Test design of a soil-tank test bench

(1) Test purpose

In order to further verify the working performance of the ECSMS, the seeding test was carried out on the soil-tank test bench which was closer to the field.

(2) Test equipment and materials

The test equipment mainly includes a soil-tank test bench and related equipment, a 80BL02 DC brushless motor, a BLD-300B motor driver, a DC brushless motor reducer (reduction ratio of 1:20), a HN3806-AB-400N rotary encoder, a single-chip microcomputer controller, a 12 V DC battery, a 220 V transfer 24 V power module, and a spoon wheel maize seed-metering device monomer. The maize grain variety used in the sowing test was 'Zhengdan 958'.

(3) Test method

The seeding operation speed was set to be 3 km/h, 6 km/h and 9 km/h respectively. The seeding experiments with plant spacings of 100 mm, 150 mm, 200 mm, 250 mm and 300 mm were carried out at each speed. Each group of experiments recorded 250 adjacent grain spacing values and repeated three times. The installation of soil trough sowing test equipment is shown in Figure 14, the test results are listed in Table 4.

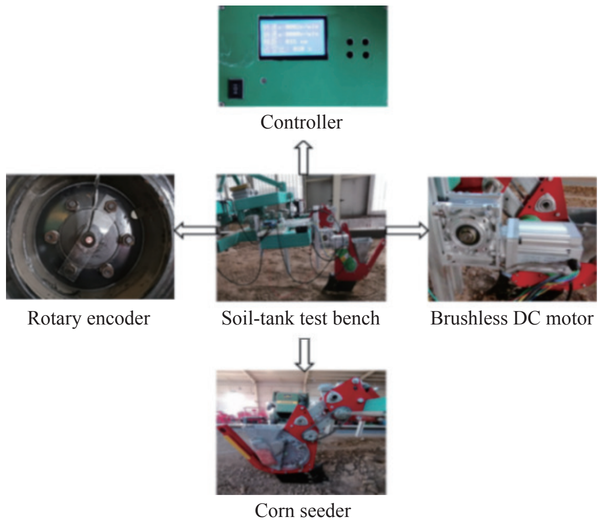


Figure 14 Test equipment installation pictures on the soil-tank test bench

2.8.3 Field test design

(1) Time and place

In order to verify the actual operation performance of the ECSMS, the sowing test was completed in Mazhang Village, Xinji City on June 27, 2023. On July 12, 2023, the seedlings were checked and the plant spacing was measured.

(2) Test conditions and test equipment

The main equipment and materials used in the sowing test include: a Dongfanghong LX950 tractor, a 4-row maize precision planter, a ECSMS, and some 'Zhengdan 958' maize seeds.

(3) Test method

The sowing mode of wide row 800 mm and narrow row 400 mm was adopted, the plant spacing was set to 250 mm, and the sowing speed was 6 km/h, and the maize sowing test was carried out. In the seedling check test, the position information of maize seedlings within 1000 mm was recorded, and the plant spacing value was obtained. The test was repeated three times. The field test site of the maize precision planter with the ECSMS is shown in Figure 15. The test site for maize emergence is shown in Figure 16.

3 Results and discussion

3.1 Test results and analysis of the seed-metering device test bench

The sowing test results of the ECSMS were recorded and analyzed. It can be seen from Table 3 that the QI was 99.16%, the MI was 0.40%, the MIX was 0.43%, and the CV was 13.52%. The results all met the technical conditions of JB/T 10293-2013 'Specification for single seed planters (precision planters)'.

Figure 15 Field test picture of the maize precision planter

Figure 16 Test picture of maize emergence

As shown in Figure 17, under different setting grain spacing, the variation of each sowing quality evaluation index is not more than 5%. With the increase of setting grain spacing, the CV of qualified grain spacing, MI and MIX show a decreasing trend, the QI increases, and the row quality improves. As shown in Figure 18, under different sowing speeds, the sowing quality of variable speed operation is slightly lower than that of constant sowing speed, but the difference of each sowing quality evaluation index is within 5%, and the sowing effect is good.

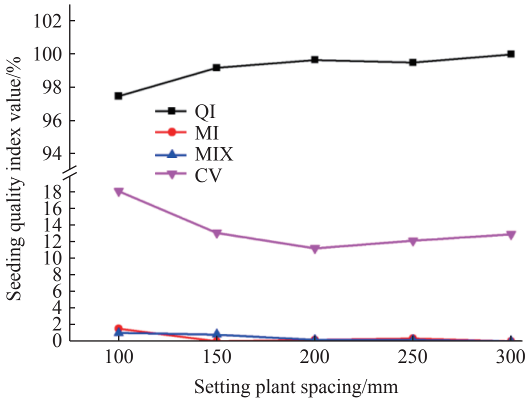


Figure 17 Seed-metering quality indexes under different plant spacing on the seed-metering device test bench

It can be seen from Table 4 that the seed metering qualification index obtained from the test of the maize seed-metering device without the ECSMS is 94.39%, the MI is 2.36%, the MIX is 3.24%, and the CV is 18.58%. Compared with the traditional mechanical maize seed-metering device, the electric control seed-metering system increases the seed-metering QI by 4.47%, the MI decreases by 1.96%, the MIX decreases by 2.81%, and the CV decreases by 5.06%. The ECSMS has a better seed-metering effect.

3.2 Test results and analysis of the soil-tank test bench

It can be seen from Table 5 that the QI, MI, MIX and CV test on the soil-tank test bench were 96.74%, 2.15%, 1.10% and 16.24%, respectively. As shown in Figures 19 and 20, the variation of QI is less than 10% under different setting seed spacing and different sowing speed. When the setting seed spacing is 250 mm, the minimum variation CV is 15.03%, and the maximum QI is 97.89%, and the sowing effect is the best. When the seed spacing is 300 mm, the maximum variation CV is 17.43, and the uniformity of sowing is poor. When the sowing speed is 6 km/h, the minimum variation CV is 15.68%, and the sowing uniformity is the best. The highest CV is 16.79% under variable speed operation, and the test results meet the national standard requirements. Through the soil-tank test bench with closer sowing conditions, it has been further verified that the system has better metering control performance and better metering uniformity.

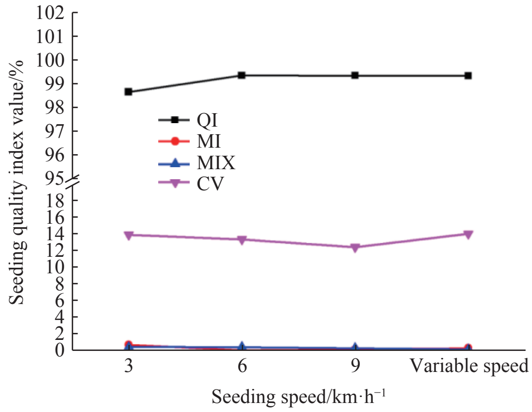


Figure 18 Seed-metering quality indexes under different operating speed on the seed-metering device test bench

Table 5 Test results of the system on the soil-tank test bench

Setting plant spacing/mm	Performance/%	Sowing operation conditions			
		3 km/h	6 km/h	9 km/h	Variable speed operation
100	QI	97.96	93.62	91.67	97.96
	MI	2.04	6.38	6.25	2.04
	MIX	0.00	0.00	2.08	0.00
	CV	16.65	15.21	18.35	16.78
150	QI	100.00	96.00	96.00	94.12
	MI	0.00	2.00	2.00	1.96
	MIX	0.00	2.00	2.00	3.92
	CV	18.25	15.83	10.61	15.80
200	QI	98.04	97.96	97.96	98.04
	MI	0.00	2.04	2.04	0.00
	MIX	1.96	0.00	0.00	1.96
	CV	15.41	19.05	14.69	18.40
250	QI	97.69	100.00	95.83	98.04
	MI	2.04	0.00	4.17	0.00
	MIX	0.00	0.00	0.00	1.96
	CV	16.65	16.16	15.51	11.81
300	QI	93.88	96.00	96.00	97.96
	MI	4.08	2.00	2.00	2.04
	MIX	2.04	2.00	2.00	0.00
	CV	12.86	16.43	19.23	21.18

3.3 Field test results and analysis

The plant spacing measurement results are listed in Table 6, and the data are analyzed according to the national standard requirements. The QI of field sowing operation is 84.21%, the MI is 2.63%, the MIX is 7.89%, and the CV is 22.15%. The sowing indexes meet the national standard requirements. The results of the field sowing test showed that the ECSMS system had good stability and operation performance.

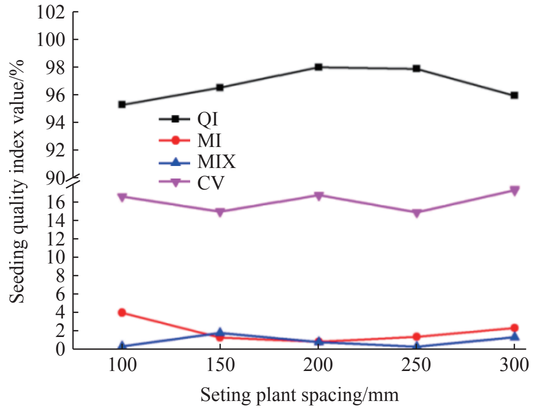


Figure 19 Seed-metering quality indexes under different plant spacing on the soil-tank test bench

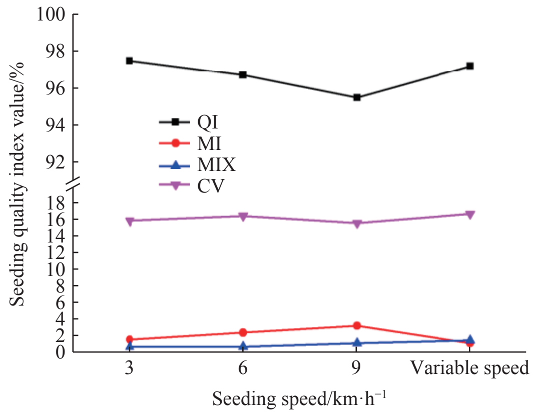


Figure 20 Seed-metering quality indexes under different operating speed on the soil-tank test bench

Table 6 Field sowing test data

Serial No.	Plant spacing/mm					
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
1	240	352	502	220	460	259
2	170	196	404	317	288	295
3	3	356	229	240	374	273
4	321	216	316	288	135	228
5	217	191	204	258	318	246
6	244	319	265	307	266	277

4 Conclusions

(1) In view of the problem that the sowing quality of the traditional maize planter is reduced due to the sliding of the ground wheel, an ECSMS is designed to realize the single-grain precision sowing of maize. The self-tuning of PID parameters is realized by the combination of the Z-N method and fuzzy control, and the mathematical model of the DC motor is established. The PID control algorithm is used to control the motor speed. The fuzzy PID control is designed by MATLAB and simulated by Simulink, which shortens the response time of the system by 0.23 s and improves the control accuracy.

(2) The test of the seed-metering device test bench showed that the QI of the maize seed-metering device equipped with ECSMS increased by 4.47%, the MI decreased by 1.96%, the MIX decreased by 2.81%, and the CV decreased by 5.06%. The ECSMS had a better seed metering effect.

(3) The soil-tank test bench test further verifies that the ECSMS has better seed-metering control performance. Under different setting seed spacing and different sowing speeds, the change of sowing quality index is within 10%, and the ECSMS has better seed-metering uniformity and stability.

(4) The field experiment showed that the QI of sowing operation was 84.21%, the MI was 2.63%, the MIX was 7.89%, and the CV was 22.15%. All the indexes meet the requirements of JB/T 10293-2013 'Specification for single seed planters (precision planters)', and have good operation performance in actual field operation, which could be popularized and applied.

Acknowledgements

This work was financially supported by Hebei Agriculture Research System (HBCT2024020205); The State Key Laboratory of North China Crop Improvement and Regulation (Grant No. NCCIR2024ZZ-12); The Sci-Tech Program of Hebei (Grant No. 23567601H); The Central Government Guides Local Funds for Scientific and Technological Development (Grant No. 236Z7202G).

[References]

[1] Zhao X S, Bai W J, Li J C, Yu H L, Zhao D W, Yin B Z. Study on positive-negative pressure seed metering device for wide-seedling-strip-seeding. Int J Agric & Biol Eng, 2022; 15(6): 124–133.

[2] Liu K, Yi S J. Design and experiment of seeding performance monitoring system for suction corn planter. Int J Agric & Biol Eng, 2019; 12(4): 97–103.

[3] Zhao X S, Ran W J, Hao J J, Bai W J, Yang X L. Design and experiment of the double-seed hole seeding precision seed metering device for peanuts. Int J Agric & Biol Eng, 2022; 15(3): 107–114.

[4] Yuan Y W, Bai H J, Fang X F, et al. Research progress on maize seeding and its measurement and control technology. Transactions of the CSAM, 2018; 49(9): 1–18. (in Chinese)

[5] Lei X L, Hu H J, Yang W H, Liu L Y, Liao Q X, Ren W J. Seeding performance of air-assisted centralized seed-metering device for rapeseed. Int J Agric & Biol Eng, 2021; 14(5): 79–87.

[6] Liu J X, Wang Q J, Li H W, He J, Lu C Y. Design and seed suction performance of pinhole-tube wheat precision seeding device. Transactions of the CSAE, 2019; 35(11): 10–18. (in Chinese)

[7] Jin X, Li Q W, Yuan Y W, Qiu Z M, Zhou L M, He Z T. Design and test of 2BFJ-24 type variable fertilizer and wheat precision seed sowing machine. Transactions of the CSAM, 2018; 49(5): 84–92. (in Chinese)

[8] Lai Q H, Sun K, Yu Q X, Qin W. Design and experiment of a six-row air-blowing centralized precision seed-metering device for Panax notoginseng. Int J Agric & Biol Eng, 2020; 13(2): 111–122.

[9] Ding Y Q, Yang L, Zhang D X, Cui T, He X T, Zhong X J. Design of row-unit driver for maize variable rate planter. Transactions of the CSAE, 2019; 35(11): 1–9. (in Chinese)

[10] Cheng X P, Li H W, He J, Wang Q J, Lu C Y, Wang Y B. Optimization of operating parameters of seeding device in plot drill with seeding control system. Int J Agric & Biol Eng, 2021; 14(3): 83–91.

[11] He J, Zhu J G, Zhang Z G, Luo X W, Gao Y, Hu L. Design and experiment of automatic operation system for rice transplanter. Transactions of the CSAM, 2019; 50(3): 17–24. (in Chinese)

[12] Ding Y C, He Z B, Xia Z Z, Peng J Y, Wu T H. Design of navigation immune controller of small crawler-type rape seeder. Transactions of the CSAE, 2019; 35(7): 12–20. (in Chinese)

[13] Yang S, Wang X, Gao Y Y, Zhao X G, Dou H J, Zhao C J. Design and experiment of motor driving bus control system for corn vacuum seed meter. Transactions of the CSAM, 2019; 50(2): 57–67. (in Chinese)

[14] Kang J M, Peng Q J, Zhang C Y, Zhang N N, Fang H M. Design and testing of a punching-on-film precision hole seeder for peanuts. Transactions of the ASABE, 2020; 63(6): 1685–1696.

[15] Cheng X P, Li H W, Wang Q J, He J, Lu C Y, Yang W. Design and experiment of wheat seeding control system in plot seeder. Transactions of the CSAM, 2019; 50(7): 30–38. (in Chinese)

[16] Kamgar S, Noei-Khodabadi F, Shafaei S M. Design development and field assessment of a controlled seed metering unit to be used in grain drills for direct seeding of whea. Information Processing in Agriculture, 2015; 2(3-4): 169–176.

[17] Jafari M, Hemmat A, Sadeghi M. Development and performance assessment of a DC electric variable-rate controller for use on grain drills. Computers and Electronics in Agriculture, 2010; 73(1): 56–65.

[18] Kim Y J, Kim H J, Ryu K H, Rhee J Y. Fertiliser application performance of a variable-rate pneumatic granular applicator for rice production. Biosystems Engineering, 2008; 100(4): 498–510.

[19] Zhou X H, Li D L, Zhang L, Duan Q L. Application of an adaptive PID controller enhanced by a differential evolution algorithm for precise control of dissolved oxygen in recirculating aquaculture systems. Biosystems Engineering, 2021; 208: 186–198.

[20] Wang Y Z, Zhang H W, Wang L, Li G Y, Zhang Y, Liu X M. Development of control system for cotton picking test bench based on fuzzy PID control. Transactions of the CSAE, 2018; 34(23): 23–32. (in Chinese)

[21] Han B, Yang Y N, Wang H W, Fan W. Design of PID automatic control system for depth into earth of intra-row weeding components and its bench experiment. Transactions of the CSAE, 2018; 34(11): 68–77. (in Chinese)

[22] Yao J F, Lu J, Zheng Y L, Wang X F, Zhao Y D, Chen X C, et al. DC motor speed control of annual-ring measuring instrument based on variable universe fuzzy control algorithm. Transactions of the CSAE, 2019; 35(14): 57–63. (in Chinese)

[23] Zhou X H, Wang J P, Huang L, Li D L, Duan Q L. Modelling and controlling dissolved oxygen in recirculating aquaculture systems based on mechanism analysis and an adaptive PID controller. Computers and Electronics in Agriculture, 2021; 192: 0168–1699.

[24] Cheng Z, Lu Z. Research on the PID control of the ESP system of tractor based on improved AFSA and improved SA. Computers and Electronics in Agriculture, 2018; 148: 142–147.

[25] Elebaid J I, Liao Q X, Wang L, Liao Y T, Yao L. Design and experiment of multi-row pneumatic precision metering device for rapeseed. Int J Agric & Biol Eng, 2018; 11(5): 116–123.

[26] Cao F Y, Li H D, Yan X H, Xu L Y. Hydro-mechanical compound transmission constant rotational speed output control method under step input based on double feedforward and fuzzy PID. Transactions of the CSAE, 2019; 35(1): 72–82. (in Chinese)

[27] Goodchild M S, Jenkins M D, Whalley W R, Watts C W. A novel dielectric tensiometer enabling precision PID-based irrigation control of polytunnel-grown strawberries in coir. Biosystems Engineering, 2018; 165: 70–76.

[28] Chen L Q, Xie B B, Li Z D, Yang L, Chen Y X. Design of control system of maize precision seeding based on double closed loop PID fuzzy algorithm. Transactions of the CSAE, 2018; 34(9): 33–41. (in Chinese)

[29] Ding Y C, Yang J Q, Zhang L L, Zhu K. Design and experiment on variable reseeding system for rapeseed precision metering device. Transactions of the CSAE, 2018; 34(16): 27–36. (in Chinese)

[30] Yang L, Yan B X, Cui T, Yu Y M, He X T, Liu Q W. Global overview of research progress and development of precision maize planters. Int J Agric & Biol Eng, 2016; 9(1): 9–26.

[31] Zhao X S, Zhao D W, Chi D D, Huo Q, Bai W J, Ran W J. Design and test of precision electronic metering system for wheat wide seedling belt based on EDEM-Fluent coupling simulation. Journal of Hebei Agricultural University, 2022; 45(1): 105–114, 120.