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DESIGN AND FIELD TEST OF CORN SEEDING SYSTEM BASE ON FUZZY PID CONTROL METHOD COMBINE WITH PSO

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KEYWORDS

corn seeder, particle swarm optimization, fuzzy PID control algorithm, control strategy.

ABSTRACT

Current corn sowing equipment shows relatively low levels of automation and intelligent response. Issues such as wheel slipping and chain jumping occur in seeders driven by wheels and chains, leading to a decrease in the seeding qualification rate. To solve the problems of wheel slipping and low control strategy accuracy, an electric control sowing system has been designed. This system uses radar to collect the locomotive speed and automatically adjusts the motor speed. To improve the control accuracy of the electric control system, a dual closed-loop control method is employed, and the proportional-integral-derivative (PID) controller parameters are optimized by combining the particle swarm optimization (PSO) algorithm and the fuzzy algorithm. Control accuracy tests and field tests are conducted for both the traditional PID control system and the fuzzy PID control system based on the PSO algorithm. The average error of this system is 0.622%, which is 1.6% lower than that for the traditional method. Field tests show that in operation, the sowing system achieves the average seeding qualification index of 93.99%, which is 3.19% higher than that for the traditional PID control method. The fuzzy PID control system shows improved sowing effectiveness compared to the traditional PID control method.

INTRODUCTION

Currently, the precision planting of corn is gradually advancing toward automation. Precision planting technology is a crucial means of production, and the integration of intelligent technologies such as precise control, information collection, and smart navigation has significantly advanced the development of precision planting technology (Zhai et al., 2016; Ma et al., 2016; Wang et al., 2019).

The occurrence of problems such as wheel slippage and chain jumping in the seed planter driven by wheels and chains leads to a decrease in the seeding accuracy. Additionally, the precision of the existing controller control strategies is low, resulting in uneven spacing between the seeds during planting (Zhang et al., 2010; Fu et al., 2016; Staggenborg et al., 2004). The seed planter is evolving from traditional wheel-driven to motor-driven. The electrically-driven seed dispenser offers higher control precision and promotes more stable operation (He et al., 2017; Yang et al., 2015). To address issues such as wheel slippage and chain jumping, Precision Planting (Precision Planting 2018) has developed a system that utilizes a DC motor and speed radar to monitor the speed of the locomotive. Based on real-time speed detection, the system adjusts the rotational speed of the planter. Although this electronic control system has been widely adopted commercially, its control efficiency is not optimal. Yao et al. (Yao, 2022) developed a seeding unit based on fuzzy PID. This unit utilizes a Hall sensor to collect the forward speed of the locomotive. However, due to uneven field surfaces, it is difficult to completely eliminate the impact of wheel slippage on seeding quality. To address this issue comprehensively, Xie et al. and Ding et al. (Ding et al., 2018; Xie, 2018) developed a planting system based on GPS speed measurement that determines the rotational speed of the planter using an encoder. Although the GPS speed measurement effectively solves the problem of the measurement errors caused by wheel slip, it is affected by various factors, such as satellite clock error, atmospheric refraction error, receiver clock error, and cloud thickness (Cay et al., 2018a; Cay et al., 2018b), resulting in unstable signals and reduced speed measurement accuracy.

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Utilization of proportional-integral-derivative (PID) control algorithms is currently predominant approach in the field of agricultural machinery control. However, the use of traditional PID algorithms often leads to issues such as excessive overshooting, slow system response, and prolonged adjustment time. Moreover, when facing external environmental influences, significant deviations can easily occur, impacting the quality of sowing (Liu et al., 2021; Chen & Cao, 2021; Zhi et al., 2018; Khan & Rahman, 2008). To enhance the precision and responsiveness of the system control, Wang et al. (Wang et al., 2021) employed closed-loop control and utilized a genetic algorithm to determine and optimize the PID parameters in the seeding system. This system demonstrates significant robustness. However, genetic algorithms encounter challenges such as slow and convergence, and limited accuracy. Zhang et al. and Yan et al., (Yan, 2020; Zhang et al., 2017) have utilized a combination of the Ziegler-Nichols (Z-N) phase response method and genetic algorithm to optimize the PID parameters, resulting in the improved response speed and accuracy of the system. Although traditional optimization methods such as the Z-N method are simple, there is still significant room for improvement of the accuracy and response rate. To enhance the quality of seeding, further optimization of the control strategy is still necessary.

This article presents a precision seeding control system based on a radar speedometer designed to address the aforementioned issues. The system utilizes a microcontroller as the core control unit and adopts a dual-closed-loop control system. By combining the particle swarm algorithm with the fuzzy algorithm, the PID parameters are optimized through self-tuning, resulting in improved system response time and accuracy. The radar-collected locomotive speed effectively avoids the impact of wheel slippage, thereby reducing occurrences of missed or repeated seeding, enhancing seeding quality, and increasing crop yield.

Overall design of the electronic control system

Figure 1 shows a diagram illustrating the principle of the electronic control system. The system utilizes a radar speedometer to evaluate the planting speed, and the keyboard is used to input the set spacing, which is then fed back to the controller. The controller calculates the theoretical speed of the planter and outputs the corresponding PWM pulse width modulation ratio. This, in turn, changes the average voltage at both ends of the motor, achieving motor speed control. The real-time speed of the planter is detected and fed back through a Hall sensor. To reduce the difference between the theoretical and actual speeds of the planter, the PID parameters are optimized using a particle swarm algorithm. Additionally, the fuzzy algorithm is employed for self-tuning optimization. Dual-loop control is adopted to improve the precision and response speed of the motor, thereby enhancing planting efficiency and production quality.

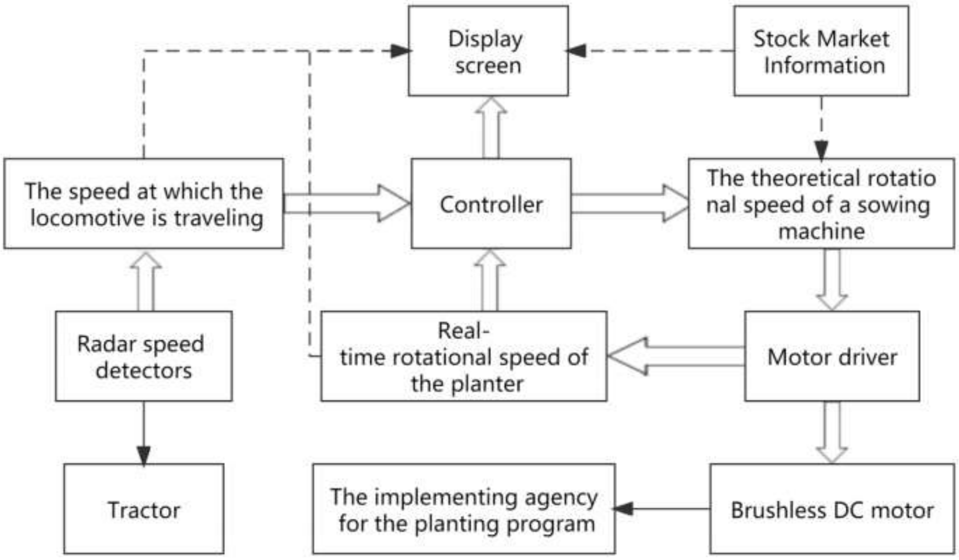

FIGURE 1. Block diagram of the electronic control system.

Relationship between the sowing speed and the speed of the seeder

The falling time intervals of two adjacent seeds under ideal conditions are calculated according to [eq. (1)].

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

Where:

Δt is the time difference between the landing of two adjacent seeds;

n is the speed of the seeder, r min^{-1}, and

m is the number of holes.

The plant spacing is given by [eq. (2)].

$$S = 277.78v\Delta t = \frac{1.67\times10^{4}v}{nm} \tag{2}$$

Where:

S is the corn plant spacing, mm, and

v is the tractor walking speed, km h^{-1}.

In this study, m = 24 was substituted into eqs. (1) and (2), and then n was obtained according to [eq. (3)].

$$n = \frac{695.83v}{S} \tag{3}$$

Speed regulation characteristics of brushless DC motors

Motor speed control plays a key role in this system. It was realized by using PWM signals to adjust the pulse width to alter the average voltage supplied to the motor, thus modifying the motor speed. The speed control characteristics of a brushless DC motor refer to the relationship between the motor speed and the direct current input voltage when the motor is in a stable operating state.

The speed of a DC motor is related to the back electromotive force as expressed in [eq. (4)].

$$E = Ce \times n \tag{4}$$

Where:

E is the back electromotive force in a stable operating state of an electric motor;

Ce is the coefficient of the back electromotive force, and

N is the motor speed.

Based on the equivalent model of a brushless DC motor and Kirchhoff's voltage law, it can be inferred that:

$$E = U - IR - \Delta U \tag{5}$$

Where:

U is the input voltage of the direct current;

I is the electrical current flowing through the armature;

R is the equivalent total resistance in an electrical circuit, and

ΔU is the voltage drop across the saturation region of the power devices.

The mathematical expression for the motor speed can be obtained by combining eqs. (4) and (5):

$$n = \frac{U - IR - \Delta U^{\circ}}{Ce} \tag{6}$$

It can be inferred from [eq. (6)] that there exists a linear relationship between the rotational speed (n) and the direct current input voltage of a brushless DC motor when it is operating in a stable condition.

Transfer function of the motor speed control system

The rotational speed of the sowing system is primarily controlled by the motor. Assuming that the motor is operating under ideal conditions, the differential equation for the motor can be derived using motor theory (Fu et al., 2012):

$$T_d T_m \frac{d^2 n_1}{dt^2} + T_m \frac{dn_1}{dt} + n_1 = \frac{1}{K_e} U_0 \tag{7}$$

Where:

T_d is the electromagnetic time constant;

T_m is the electromechanical time constant;

n_1 is the motor speed;

K_e is the coefficient of the back electromotive force of an electric motor, and

U_0 is the voltage at the armature.

By applying the Laplace transform to the above equation, the transfer function of the motor can be obtained.

$$G(s) = \frac{1/K_e}{T_m T_d s^2 + T_m s + 1} \tag{8}$$

In this design, a brushless DC motor is chosen, with the following main parameters: Z = 0.0254H, R = 2.513 Ω, J = 0.003 kg.m^2, and K_e = 0.075 Vs/rad. Substituting these values into [eq. (9)] yields the desired result.

$$G(s) = \frac{13.3}{0.01354s^2 + 1.35s + 1} \tag{9}$$

Controller control policy

Optimization of the PID parameter based on the particle swarm algorithm

Although traditional optimization methods such as the Z-N method are simple, they lack precision and are only suitable for slow dynamic industrial processes with large time constants (Nie et al., 2022; Liu & Cai, 2023). PSO is a relatively simple and more practical parameter tuning method that significantly improves the optimization of the three parameters of PID. The performance indicators of the control system including control precision, response speed, stability, and disturbance rejection, have been significantly improved through the application of PSO in the PID parameter optimization process (Hu et al., 2019; Zhou et al., 2021).

The particle swarm optimization (PSO) algorithm based on the process of birds foraging and searching for the optimal foraging area. As an intelligent algorithm, PSO simulates the process of making optimal decisions. Each bird's initial position is random and the location of the best foraging point is unknown. Additionally, the flying direction of each bird is also random. In the early stages of foraging, the movement trajectory of the bird flock is chaotic. Over time, birds in random positions learn from each other and share foraging information within the group. In each foraging process, each bird estimates the value of the current position by combining its own experience and the information transmitted by its companions. This search method is called the particle swarm algorithm. The likelihood of finding food in a specific location can be characterized by the fitness value. Each bird can remember its foraging position and find the best position, which is considered the local optimum. The best positions of all individuals in the bird flock is considered to be the global optimum. It is clear that the overall foraging activity of the bird flock will move toward this global optimum foraging area. Through the continuous iteration of the bird flock's movement and update of the bird velocities, the bird flock gradually approaches this optimal position. Based on the above discussion, the core idea of the particle swarm algorithm is based on collective collaboration and information sharing. This algorithm simulates the characteristics of bird foraging behavior, where birds are compared to particles. Multiple particles search for a target on a plane, and as they approach the target, they share their information with other individuals. Through this behavior, the algorithm gradually finds the optimal solution (Yu et al., 2023).

In K-dimensional space, a particle swarm consisting of n massless particles is formed. Each particle is represented as a K-dimensional vector, with its spatial position denoted as $x_i=(x_{i1}, x_{i2}..., x_{iK})$, where i=1, 2..., n. The K-dimensional spatial position represents the potential solution to the problem at hand. By substituting it into the objective optimization function, the fitness value for each particle is calculated, evaluating the quality of x_i based on its fitness value. The velocity of the i-th particle is a K-dimensional vector, denoted as $vi=(v_{i1}, v_{i2}..., v_{iK})$. The position of the best fitness value achieved by the i-th particle during the iteration cycle is referred to as its historical best position and is denoted as $p_i=(p_{i1}, p_{i2}..., p_{iK})$. The best position reached by the entire particle swarm is known as the global historical best position, denoted as $p_g=(p_{g1}, p_{g2}..., p_{gK})$. The individual update iteration is described by:

$$v_{ij} = v_{ij}(t)+c_1r_1(t)(p_{ij}(t)-x_{ij}(t))+c_2r_2(t)(p_{gj}(t)-x_{ij}(t)) \qquad (10)$$

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t) \qquad (11)$$

Here, the subscript j represents the jth dimension, while the subscript i represents the ith particle. The constants c_1 and c_2 are acceleration constants, and *t* denotes the *t*th generation. The variables r_1 and r_2 are two independently distributed random numbers between 0 and 1 (Lv, 2022).

The obtained parameters are input into the MATLAB simulation model. The simulation results are illustrated in Figure 2, from the simulation results, it can be observed that the system response time is 0.36 s. The PID parameters tuned by the particle swarm algorithm show a large overshoot and slow response time. Therefore, it is still necessary to optimize the parameters. The fuzzy algorithm can fuzzify some difficult-to-quantify parameters and is relatively simple, and is particularly suitable for systems where expert experience plays a major role. This paper further optimizes and tunes the PID parameters using the fuzzy algorithm.

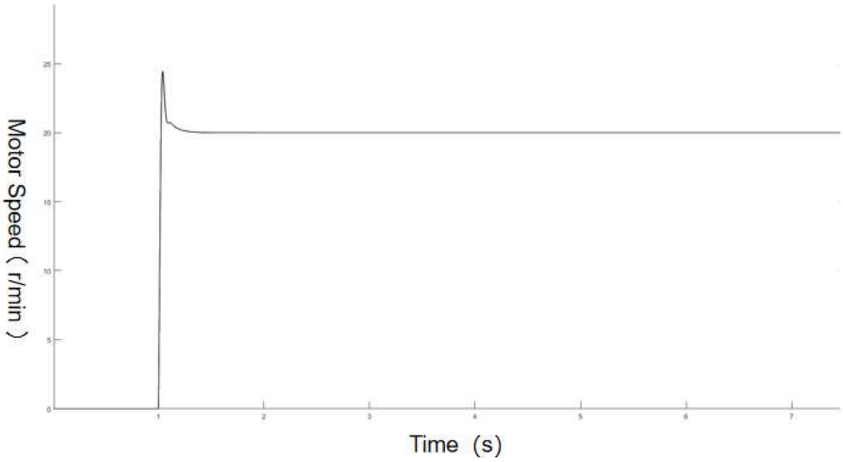

FIGURE 2. Simulation results of particle swarm optimization for PID parameters.

In the field of electronic control planting systems, the Z-N step response method is commonly used to tune PID parameters. To demonstrate the superiority of the particle swarm algorithm for the tuning of the PID parameters, the two algorithms were compared. It is observed from the simulation curve presented in Figure 3 that the response time when using the Ziegler-Nichols step response method to tune the PID parameters is 0.42 s, which is 0.08 s longer than the response time when using the PSO algorithm. Furthermore, the Z-N step response method resulted in a larger overshoot. Therefore, tuning the PID parameters using the PSO algorithm effectively improves the optimization of the three parameters, demonstrating its advantages of fast operation, easy implementation, and quick convergence.

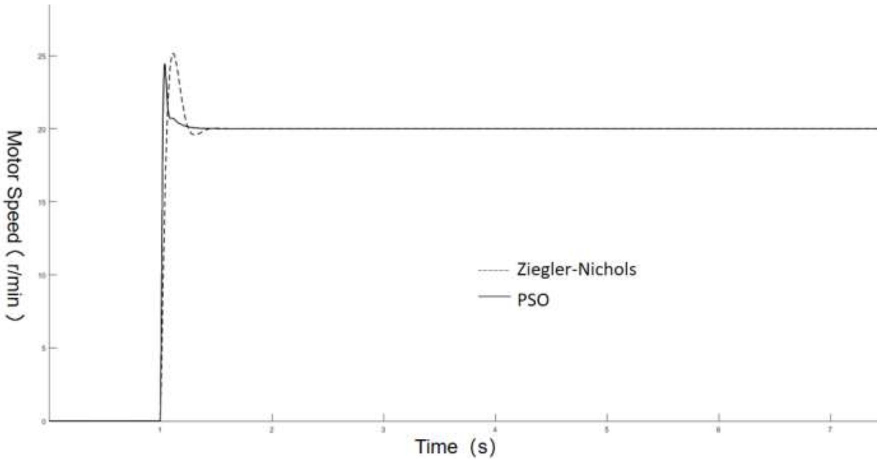

FIGURE 3. Comparison of simulation results (Z-N, PSO).

Optimizing and tuning the PID parameters of fuzzy algorithms

Fuzzy control is an intelligent control method based on fuzzy set theory, fuzzy linguistic variables, and fuzzy logical reasoning. It imitates the behavior of human fuzzy reasoning and decision-making processes. Fuzzy control allows for adaptive adjustment of the three parameters, Kp, Ki, and Kd. PID parameters are calculated using the PSO-obtained parameters as the baseline values. Then, using the fuzzy control method, the increment of the PID parameters is calculated based on the input deviation e and the deviation change rate ec. Finally, the increment value calculated by the fuzzy controller is added to the baseline PID values to obtain the final PID parameters.

This article presents a speed control system for a brushless DC motor based on fuzzy PID dual closed-loop control. The system consists of a control loop and a current loop. By using a radar speedometer, the seeding speed information is obtained, and the theoretical speed of the motor is calculated. The actual speed of the motor is detected using the built-in Hall sensor, and the speed deviation between the two is calculated. The PID parameters are dynamically adjusted in real time through fuzzy control. The reference current is outputted by the current regulator and input into the reference current calculation module to obtain the reference value of each current. The reference value and actual current value are input into the current hysteresis loop module, and the PWM control signal is output to drive the voltage inverter, thereby driving the motor and changing its speed.

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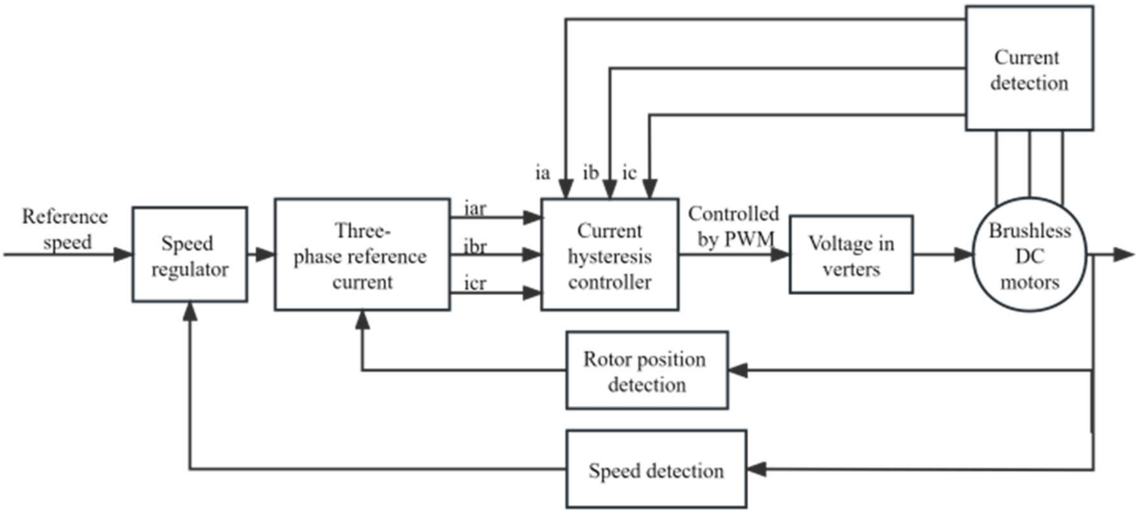

FIGURE 4. Diagram representing the dual closed-loop fuzzy PID control strategy.

The fuzzy PID control model was constructed as shown in Figure 4. The designed fuzzy controller in this design has two input variables, e and ec (deviation e and deviation change rate ec are formed by the feedback value of motor speed and the theoretical speed of the motor), as well as three output variables, which are the increments of Kp, Ki, and Kd. The fuzzy linguistic domain is set to [-3, 3]. According to fuzzy theory, fuzzy sets are defined as follows: negative large [NB], negative medium [NM], negative small [NS], zero [ZO], positive small [PS], positive medium [PM], and positive large [PB]. The linguistic domains of all inputs and outputs are designed as [-3, 3], and Gaussian membership functions are used. Triangular membership functions are used for the output variables. A fuzzy controller control rule (49 rules) is established. The proportional, integral, and derivative parameters are dynamically adjusted by adding the initial values and parameter increments of PID. Based on the designed fuzzy controller, the control model of the electronic seed planter is established through Simulink, as shown in Figure 5.

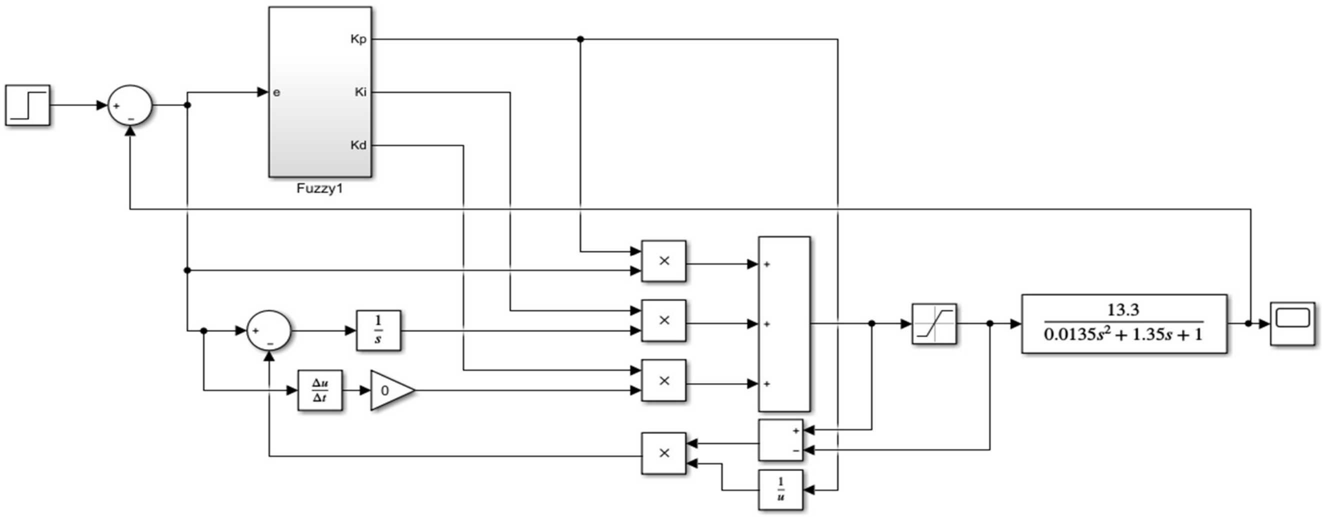

FIGURE 5. Simulation diagram of the fuzzy PID control model for a brushless DC motor.

The simulation results presented in Figure 6 demonstrate the use of PID parameters tuned with the PSO algorithm as the fundamental parameters. It is observed from the system response curve that the system exhibits virtually no overshoot and has a response time of 0.13 s.

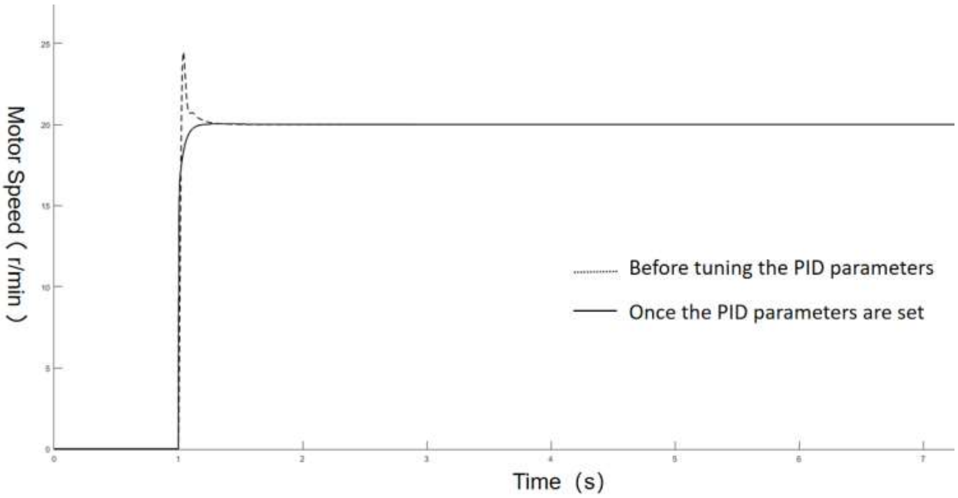

FIGURE 6. Blurred simulation results of PID.

Hardware design of control systems

The hardware modules in this design primarily consist of a tractor speed measurement module, motor drive module, alarm module, and human–machine interaction module. The physical representation is illustrated as shown in Figure 7. Since the motors operate at low speeds during planting operations, a gearbox with a speed ratio of 1:20 is installed to connect to the motors in this design. The motor speed is measured by sampling the pulses from the SPEED output pin on the driver, which is then input to the controller. The frequency of the pulses is used to calculate the motor speed using the speed calculation formula.

$$\text{Speed n} = \left(\frac{\text{The frequency of SPEED−OUT}}{6\times\text{Magnetic pole logarithm}}\right)\times 60/3 \tag{12}$$

The current actual rotational speed of the motor can be calculated.

FIGURE 7. The organization is responsible for implementing the planting program.

TABLE 1. Hardware and selection

Equipment Name	Model Number
Controller	AT89C52
Motor	BLD-300B BLDC motor
Motor Driver	80BL02
Sensor for monitoring crate condition	The E3Z-D61 through-beam photoelectric sensor is a light-sensitive sensor
Radar Chronograph	Rardar, a dominant device in the United States
Displayer	LCD12864

The system hardware and selection are illustrated in Table 1. The STC89C52 microcontroller model is chosen as the controller, operating at a voltage range of 3.3–5.5V. It has four built-in PWM outputs and three 16-bit timers/counters, fulfilling the requirements for planting operations. RS-485 communication is utilized to enable signal transmission between the master and slave microcontrollers. The relevant circuit diagrams are shown in Figures 8 and 9.

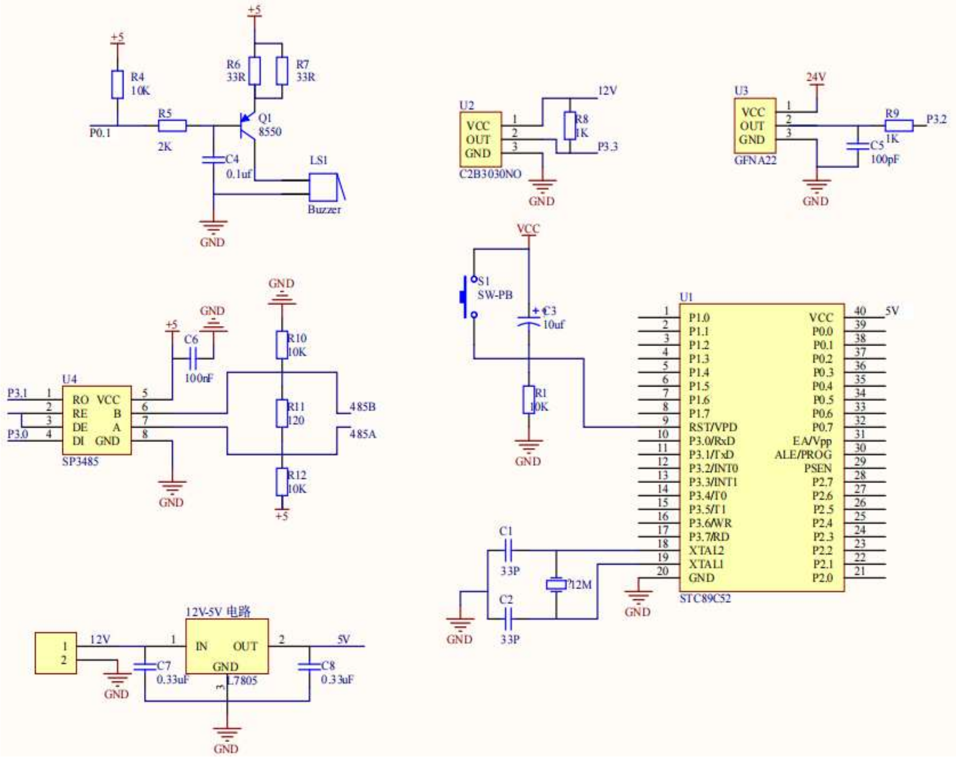

FIGURE 8. Main MCU system circuit.

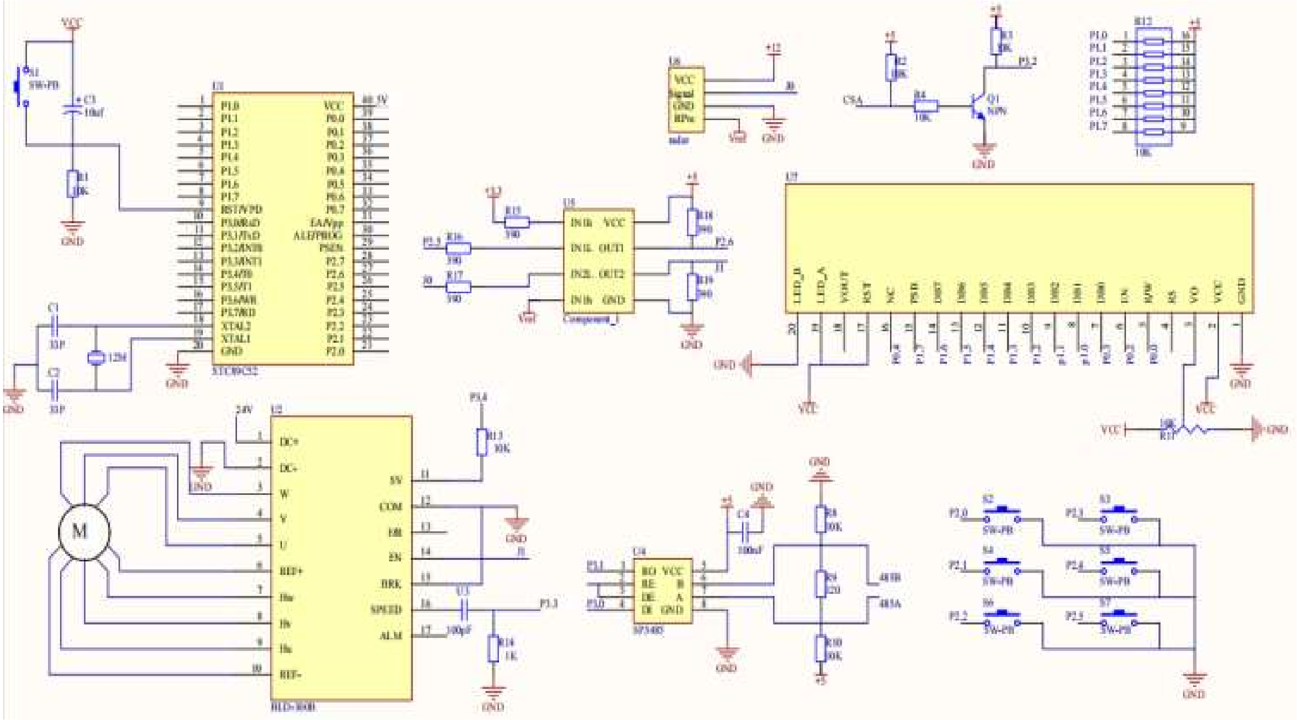

FIGURE 9. Circuitry of microcontrollers.

The main microcontroller is responsible for monitoring the seeding process, while the secondary microcontroller is responsible for the actual seeding operation. The communication between the two microcontrollers is facilitated by RS-485.

Software design

Keil µVision5 software is utilized in the development environment, where the programming is performed using the C language. The system flowchart is depicted in Figure 10.

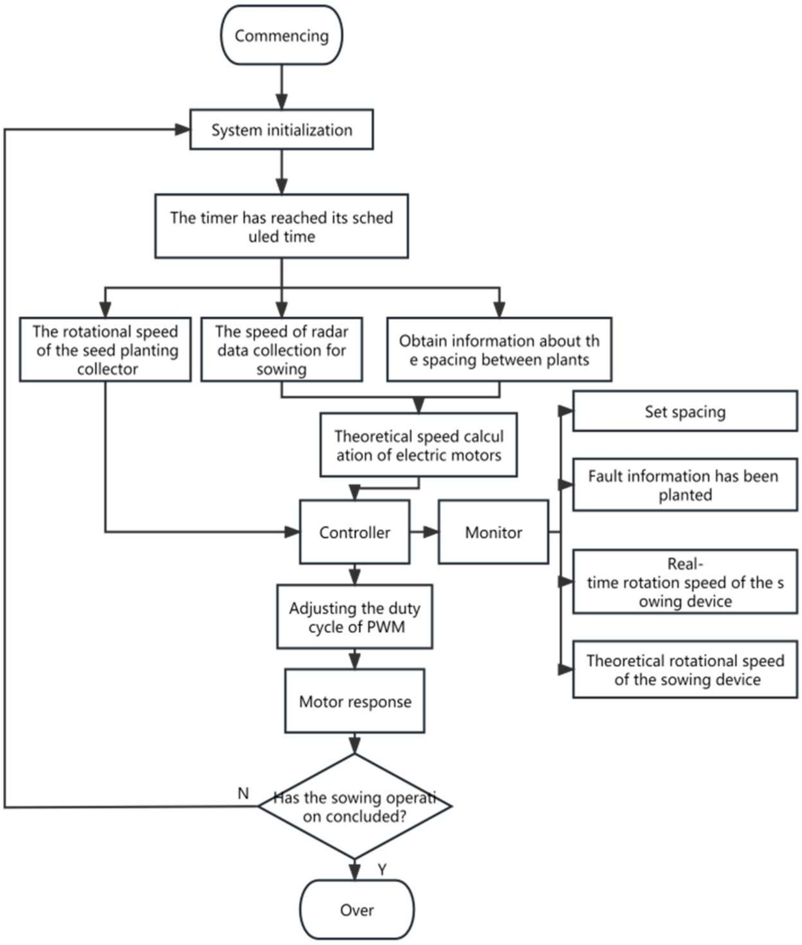

FIGURE 10. System flowchart.

RESULTS AND DISCUSSION

Control system accuracy test

Zhongdan 909 hybrid maize variety was used as the experimental material in this study. The locomotive speed was set at 3–12 km/h, with a row spacing of 20 mm. Ten sets of experiments were conducted, with each experiment repeated three times to calculate the average values. The theoretical motor speed was calculated using [eq. (3)], and the actual motor speed was calculated using [eq. (12)]. The motor control precision was tested for both traditional PID and fuzzy PID control methods. The experimental findings are illustrated in Figures 11 and 12. Analysis of the experimental results showed that using traditional PID control, the maximum obtained error was 4.98% with an average error of 2.223%. By contrast, using fuzzy PID control, the maximum obtained error was 1.94% with an average error of 0.622%. Therefore, the fuzzy PID control method demonstrated higher precision than the traditional PID control method.

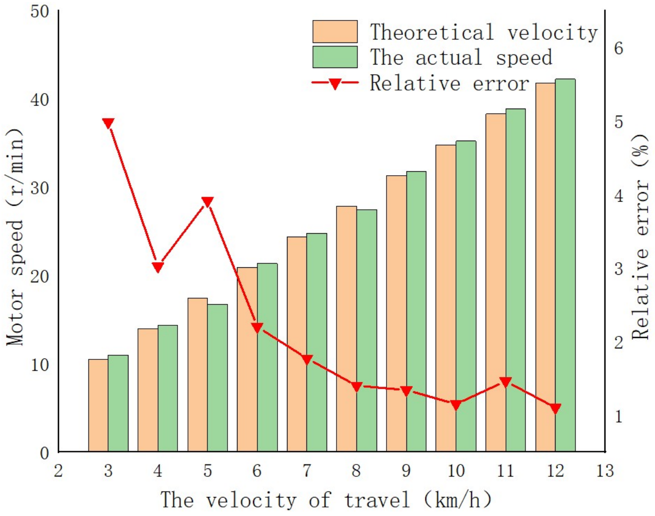

FIGURE 11. Traditional PID speed accuracy detection.

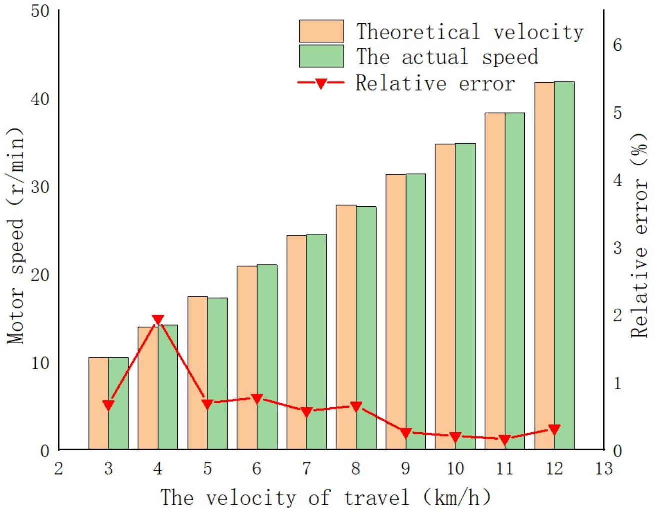

FIGURE 12. Detection of fuzzy PID speed accuracy.

Field trials and discussions

Field trials

The experiment was conducted at the experimental field of the Heilongjiang Modern Agriculture High-tech Demonstration Park. The experiment followed the procedure specified in the GB/T 6973-2005 Test Method for Single Grain (Precision) Seeder and the qualified index A, reseeding index D, missed seeding index M, and grain distance variation coefficient C were selected as the sowing performance indicators. To ensure the experimental accuracy, a total of 250 samples were collected. The theoretical plant spacing was set at 20 cm, and the sowing effect was tested at the machine travel speeds of 3–6 km/h, 6–9 km/h, and 9–12 km/h. Three sets of data were collected for each group of experiments, and the average qualified index, reseeding index, missed seeding index, and coefficient of variation were calculated. The experimental results are illustrated in Tables 2 and 3.

TABLE 2. Traditional PID test results.

Running Speed km/h	Leakage Index M/%	Replay Index D/%	The coefficient of variation C/%
Low-speed operation（3-6）	3.59	3.18	4.32
Medium-speed operation（6-9）	4.78	3.98	5.67
High-speed operation（9-12）	5.65	6.05	7.65

TABLE 3. Fuzzy PID test results.

Running Speed km/h	Leakage Index M/%	Replay Index D/%	The coefficient of variation C/%
Low-speed operation（3-6）	2.81	2.54	3.49
Medium-speed operation（6-9）	2.68	2.82	3.68
High-speed operation（9-12）	3.11	3.25	4.93

For the field experiments using traditional PID, the seed sowing qualification rates under different driving speeds were 92.82%, 91.24%, and 88.31%, respectively. By contrast, the seed sowing qualification rates under different driving speeds obtained using fuzzy PID were 94.78%, 94.5%, and 92.69%, respectively. Under different operating conditions, the maximum resowing index was 3.24%, 3.64%, and 4.47%, respectively, while the maximum missed sowing index was 2.83%, 3.19%, and 3.25%, respectively. The maximum coefficient of variation values were 3.57%, 3.84%, and 5.02%, respectively. The experimental results indicate that the seed sowing qualification rate decreases significantly with increasing speed, and the use of fuzzy PID yields improved seed sowing results compared to traditional PID.

The combination of the PSO algorithm and fuzzy algorithm in this study effectively improves the overall accuracy and response speed of the system, thereby enhancing the sowing qualification rate. However, there is still room for improvement in the accuracy and response speed of the system, which can be achieved through the use of various algorithms or through the optimization of existing algorithms. Radar speed measurement can effectively avoid the impact caused by wheel/chain slippage, greatly improving the sowing efficiency. However, the harsh field environment, noise, and uneven ground can affect the precision of the system, leading to errors and phenomena such as missed sowing and resowing, resulting in a decrease in sowing quality. The speed measurement accuracy errors can be reduced or avoided by improving radar speed measurements, combining them with measurements performed by other devices, and developing improved speed measurement methods. The harsh field environment will lead to a decrease in the lifespan of electronic devices. There is still great room for improvement in this field, and further research is needed.

CONCLUSIONS

(1) In response to the requirements of precision agriculture and the current issues of low seeding quality and inadequate system accuracy, a comprehensive electronic control seeding system has been developed. Adopting a dual closed-loop control system, this system utilizes a radar speedometer to monitor the travel speed in real time, effectively addressing the inaccuracies caused by wheel/chain slippage. The control of the sowing machine is achieved by utilizing a brushless DC motor. A motor transfer function is established, and a Simulink control model is developed using MATLAB software. The PID parameters are optimized and tuned through a combination of the PSO algorithm and fuzzy algorithm, resulting in a significant improvement in the system accuracy.

(2) The experimental evaluation of motor precision indicates that the average error is 2.223% when employing conventional PID control; however, it decreases to 0.622% when using fuzzy PID control. Therefore, the fuzzy PID control method exhibits higher precision.

(3) Field experiments have demonstrated that the utilization of fuzzy PID control results in an average increase of 3.2% in the qualification index compared to the traditional PID control. Additionally, the reseeding index, miss seeding index, and coefficient of variation showed average decreases of 1.21%, 1.8%, and 1.85%, respectively. Excellent sowing effectiveness is achieved.

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