Design and experiment of fuzzy-PID based tillage depth control system for a self-propelled electric tiller

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Abstract: The research on the self-propelled electric tiller is vital for further improving the quality and efficiency of greenhouse rotary tillage operation, reducing the work intensity and operation risk of operators, and achieving environmentally friendly characteristics. Most of the existing self-propelled tillers rely on manual adjustment of the tillage depth. Moreover, the consistency and stability of the tillage depth are difficult to guarantee. In this study, the automatic control method of tillage depth of a self-propelled electric tiller is investigated. A method of applying the fuzzy PID (Proportional Integral Derivative) control method to the tillage depth adjustment system of a tiller is also proposed to realize automatic control. The system uses the real-time detection of the resistance sensor and angle sensor. The controller runs the electronically controlled hydraulic system to adjust the force and position comprehensively. The fuzzy control algorithm is used in the operation error control to realize the double-parameter control of the tillage depth. The simulation and experimental verification of the system are conducted. Results show that the control system applying fuzzy PID can improve the soil breaking rate by 3% in the operation process based on reducing the stability variation of tillage depth by 24%. The control strategy can reach the set value of tillage depth quickly and accurately. It can also meet the requirement of tillage depth consistency during the operation.
Keywords: fuzzy PID, self-propelled electric tiller, tillage depth, electro-controlled hydraulic system, comprehensive adjustment of force and position
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1 Introduction

Facility agriculture is the inevitable trend and development direction of modern agricultural development. Compared with the rapid development of international facility agriculture, the mechanization degree of facility agriculture in China only accounts for approximately 33%. The low level of mechanization and intelligent operation remains one of the current difficulties[1]. Ploughing is an important and basic link in agricultural production, and the quality of the operation determines crop growth[2]. Micro rotary tillers (MRTs), which can perform rotary tillage operations in small and scattered fields and greenhouses, not only improve the mechanization level of facility agriculture but also greatly reduce the labor intensity of farmers[3]. In recent years, the demand for intelligent agricultural vehicles in greenhouses has grown rapidly with the annual increase in greenhouses. The remote unmanned rotary tillage operation in the greenhouse has become a breakthrough for solving the safety problems of traditional tillers[4,5]. The emergence of self-propelled electric MRTs has accelerated the process of remote unmanned rotary cultivation in greenhouses. However, it has also led to the key issue of whether the quality of deep cultivation can be guaranteed. On the one hand, it is the influence of battery capacity and power, and more importantly, whether the consistency and stability of the rotary tillage depth can be maintained during the rotary tillage operation[6].

For a long time, domestic tillage machinery adjustment mostly adopts the methods of force adjustment and displacement adjustment to realize tillage depth control. Xia et al. used the inclination sensor to realize the position adjustment during the tractor operation[7]. Zhou et al. obtained the kinematic model of the depth control system by analyzing the Angle of the tractor four-bar mechanism[8]. Liu et al. proposed a dynamic pressure feedback correction method during tractor operation[9]. The use of these two adjustment methods combines mechanical and hydraulic systems. The resistance and position of the farming machinery are impossible to detect during the actual operation. The tillage depth is controlled by manual judgment. The precision of the tillage depth control is low, whereas the operation stability is poor. Control methods that combine force and displacement are widely used in mechanical control. Zhang et al.[10] used the hybrid force/position control technology in studying the automatic blade grinding robot to ensure the stability of the contact force and improve the quality of the aviation blade. Wang et al.[11] proposed a hybrid force/position controller for robotic manipulator workspace based on adaptive fuzzy control, which improves the control performance of contact force and position in uncertain environments. Hence, a tillage depth control method that can comprehensively adjust the force and position was proposed. Ma et al.[12] applied the weighting coefficient to the analysis of the comprehensive control of the force and

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position of the tractor. The research on the comprehensive adjustment of force and position is mainly aimed at large tillage equipment, such as tractors. However, the studies on the tillage depth control of small self-propelled electric tillers are few. Li et al.[13] designed an electrohydraulic tillage depth adjustment system based on the integral separation PID control method. The simulation results showed that a considerable tillage depth overshoot exists and the oscillation time is long. Unlike the linear system, the electro-controlled hydraulic system for the self-propelled electric microtiller cannot establish an accurate mathematical model; therefore, the traditional control method based on the mathematical model is difficult to realize in this system[14]. Mohammadikia et al.[15] applied fuzzy control theory to design an interval-2-type fractional-order fuzzy PID (FPID) strategy, which effectively reduces uneven surface fluctuations during tractor driving. Shafaei et al.[16] developed fuzzy depth and draft control system to decrease variations in plowing depth as well as increase tractive efficiency of a moderate power tractor in primary tillage operations with mounted implements. The fuzzy control strategy has a good effect on the intelligent control of nonlinear systems.

In summary, this paper innovatively applies the double parameter control method of tillage depth to the self-propelled electric micro tiller and puts forward the automatic measurement method of rotary tillage depth through the control coefficient. The FPID strategy is applied to convert the comprehensive adjustment of force and position into the control of electric hydraulic expansion through the control coefficient. The simulation and field experiments were carried out to verify the reliability of the control method. The innovative application of this control method can effectively improve the operation accuracy of the self-propelled electric micro tiller, make it meet the requirements of agricultural modernization, reduce the labor force and improve the safety of operation. It provides technical support for energy saving, cost saving, and efficiency increase in facility agriculture, and plays a certain role in promoting the development of agricultural unmanned operation machinery.

2 System structure and working principle

2.1 Gross structure of self-propelled electric tiller

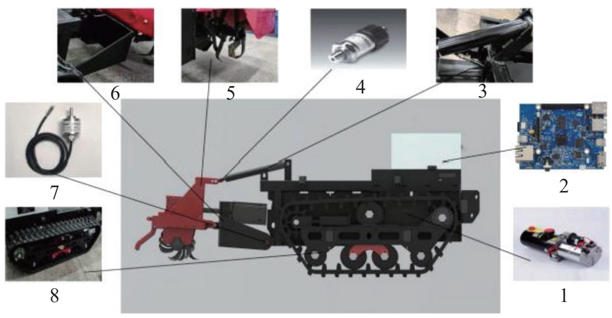
The gross structure of the self-propelled electric tiller is shown in Figure 1. This electric tiller consists of three parts: electric control part, mechanical part, and hydraulic part. The electronic control part includes an angle sensor, a resistance sensor, and a controller. The mechanical part includes a hydraulic lifting rod, triangular support, and rotary tiller. The structure of the hydraulic part, including the hydraulic gear pump, hydraulic cylinder, hydraulic control valve, and pipeline, is illustrated in Figure 2. The working principle of the electro-controlled hydraulic system is as follows:

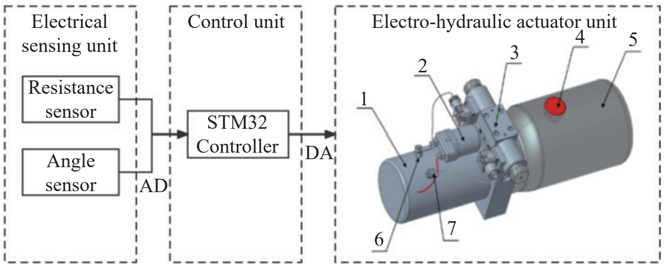
1) The angular displacement sensor and the resistance sensor detect data. They convert these data into an electrical signal, which is transmitted to the controller. After the controller calculates, it obtains the actual rotary tillage depth signal.

2) The controller simultaneously collects the set signal as the target signal of the tillage depth, compares the actual signal with the target signal, and obtains the adjustment amount according to the corresponding algorithm.

3) Then, the controller converts the adjustment amount into an electrical signal and transmits this signal to the hydraulic system control valve, which controls the lifting and lowering of the rotary tiller. The angle sensor and the resistance sensor collect data after completing the lifting and lowering of the rotary tiller.

4) The data are detected by the sensor and fed back to the controller to realize the closed-loop control of the whole process.





1.Gear pump motor 2.Motor relay 3.Oil pressure lift solenoid valve 4.Hydraulic oil injection port 5.Tank 6.Gear pump motor positive terminal 7.Gear pump motor negative terminal

Figure 2 Schematic diagram of hydraulic unit structure

2.2 Structure of tillage depth control system

As shown in Figure 2, the structure of the tillage depth control system consists of three main units, including electrical sensing, control, and electro-hydraulic actuator units. The electrical sensor unit uses the angular displacement sensor to obtain the lifting Angle of the support end of the rotary tillage tool in real time and uses the resistance sensor to obtain the resistance information of the hydraulic lifting rod end in real time. The control unit adopts an STM32 microcontroller, and the microprocessor transmits the corresponding control signal to the electro-hydraulic execution unit by comparing and calculating the input data of the electrical sensing unit. The hydraulic control unit response can be divided into two categories: controlling the hydraulic cylinder to raise and controlling the hydraulic cylinder to descend. When the hydraulic system control valve receives the rising signal, it controls the 48 V battery to energize the motor relay. One wire connects the main power supply to the positive pole of the relay, whereas the other wire connects the negative pole of the relay to the negative pole of the main power supply of the hydraulic motor to allow the current to drive the hydraulic gear. The hydraulic gear pump delivers hydraulic oil to the bottom of the hydraulic cylinder through the pipeline. Thus, the piston rises to increase the rotary tiller height. The control relay stops the power supply when the hydraulic system control valve receives the descending signal. Moreover, the rotary tiller relies on its weight to pull back the cylinder slide valve and guide the hydraulic oil to return the hydraulic oil in the cylinder to the oil tank through the pipeline; hence, the depth of the rotary tillage operation is increased[17-19].

1.Hydraulic unit 2.Controller 3.Hydraulic lift rod 4.Resistance sensor 5.Rotary tiller 6.Triangular support 7.Angular displacement sensor 8.Microtillage locomotive body

Figure 1 Gross structure diagram of the self-propelled electric tiller

3 Automatic control method of tillage depth

3.1 Automatic detection model of tillage depth

The automatic detection of tillage depth during tractor farming can be divided into direct measurement methods and indirect measurement methods. In the direct measurement method, the tillage depth is converted by measuring the relative position change of the single-joint or parallel four-bar linkage profiling mechanism and the plow frame[20]. This method is also commonly used in the tillage depth detection of walk-behind tillers. In this method, auxiliary devices must be added to construct the geometric relationship and deduce the tillage depth. Moreover, automatic control is difficult. In comparison, the indirect method uses a position sensor to calculate the tillage depth value by measuring the distance of the suspension from the ground or the change of the rotation angle of the lifting arm of the suspension mechanism[7]. The wheelbase of large-scale agricultural machinery, such as tractors, is long. The posture of these vehicles is greatly affected by terrain fluctuations. Thus, a combination of dual sensors is often used to ensure the accuracy of tillage depth measurement. For this research, the self-propelled electric tiller has the characteristics of small size, flexibility, low vibration, and a relatively flat working environment. The detection method of a single-angle displacement sensor is adopted because of its economic benefits and other factors[6,21]. The angular displacement sensor is placed at the hinge between the triangular support and the microtiller body to detect the lifting angle of the rotary tiller tool, establish the geometric relationship between the tillage depth and the angle, and finally build the tillage depth detection model.

Figure 3 shows the schematic diagram of the rotary tiller support mechanism. The hydraulic lifting rod moves from the red line position to the blue line position during the process. The piston rod rises, thereby driving the cutter of the tiller to rise as a whole. The hydraulic rod rotates clockwise around point *A*. The triangular support rotates clockwise around point *F*, and the rotation angle is *a*. The height of the rotary tiller shaft from the surface layer is increased from h_2 to h_1. Thus, the rotary tillage depth is reduced from S_2 to S_1. The following equations can be obtained by using the geometric relationship to establish a mathematical model:

$$S1 = \frac{DE}{2} - h1 \tag{1}$$

$$S2 = \frac{DE}{2} - h2 \tag{2}$$

where, S_1 and S_2 are the depth of rotary tillage, mm; *DE* is known as the diameter of the rotary tiller, mm; h_1 and h_2 are the distance of the cutter shaft from the ground, mm.

The value of the rotary tillage depth can be obtained as long as the distance between the knife axis and the ground during the rotary tillage process of the tiller is known. The angular displacement sensor can indirectly measure the distance from the rotary tiller shaft to the ground. The rotation angle of the triangular support around point F is set as a percentage of travel: set as 0% when the rotary tiller is at the lower limit position and set as 100% when it is at the upper limit position. The vertical height H of the rotary cutter shaft relative to the ground is measured and recorded every 5% of the stroke when the cutter rises from the lower limit position[22,23]. The relationship between the percentage of corner travel and the height H of the cutter axis from the ground is obtained by fitting the curve in a linear relationship, as shown in Figure 4.

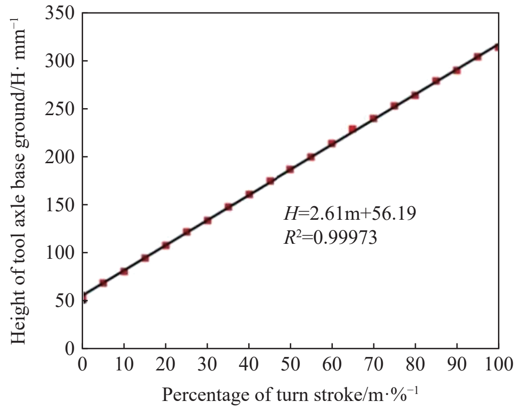


Figure 4 Linear fitting plot of angular travel percentage and ground clearance

As shown in Figure 4, the linear relationship between the height *H* of the rotary tiller shaft from the ground and the percentage *m* of the angled stroke of the triangular support *F* is

$$H = 2.61m + 56.19 \tag{3}$$

The maximum angular displacement of the tiller's triangular support from the upper limit position to the lower limit position is 40°, corresponding to 100% of its angular travel percentage. The percentage change of the corner stroke is 1%, and the corresponding triangular support rotates 0.4° around point *F*. The linear relationship between the height *H* of the rotary tiller shaft from the ground and the rotation angle *a* of the triangular support around point *F* is

$$H = 6.525a + 56.19 \tag{4}$$

Then, the linear relationship between the rotary tillage depth *S* and the angle *a* is obtained as

$$S = \frac{DE}{2} - H = 108.81 - 6.525a \tag{5}$$

Since the working environment of self-propelled electric micro-tillage is primarily flat land such as a greenhouse or orchard, and the working width of micro-tillage is small, the self-propelled track chassis on both sides has a certain flexibility. Therefore, the tilt angle error in the model of tillage depth detection is neglected without considering the left and right tilt of the body caused by the poor surface flatness of the land[24,25].

3.2 Comprehensive regulation system of force and position

The traditional methods of adjusting the tillage depth of the mechanical hydraulic system include force adjustment and position adjustment. The electro-controlled hydraulic system can realize various control methods, such as force adjustment, position adjustment, and comprehensive adjustment of force and position[9]. The force adjustment and position adjustment of the electronically controlled hydraulic lifting system have advantages and

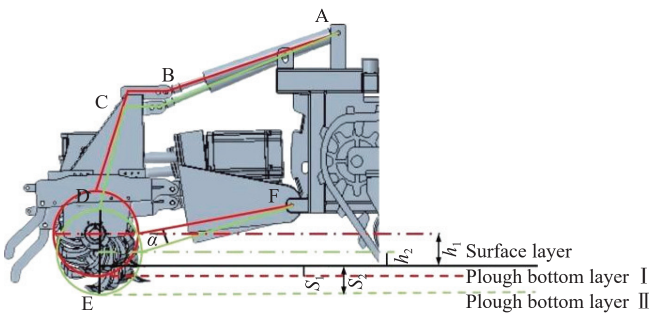


Figure 3 Geometric relationship diagram of the rotary tiller support mechanism

disadvantages. The position adjustment keeps the difference within a small range by comparing the feedback signal of the tillage depth sensor with the value of the input control signal. This method is not affected by soil-specific resistance but is prone to large errors when the terrain fluctuates greatly. The force adjustment obtains a control signal by comparing the converted tillage depth value fed back by the resistance sensor with the input tillage depth value to maintain the rotary tillage resistance within a certain range[26]. This method is prone to large errors in land with small soil-specific resistance. Nevertheless, it is not affected by terrain fluctuations. The comprehensive adjustment of force and position combines the force adjustment and position adjustment. The comprehensive adjustment method of force and position can be easily realized in the electro-controlled hydraulic system and has a good effect[27]. Tillage depth control generally has two methods: switch switching and control coefficient. The latter can obtain a good control effect by setting parameters with long-term research and utilization value[28]. In summary, the present research adopts the control coefficient method to realize the comprehensive adjustment of the force and position of the electric tiller.

The specific process is as follows: First, the data collected by the angular displacement sensor and the resistance sensor are converted into the actual rotary tillage depth by using the control coefficient. Then, the obtained actual tillage depth value is compared with the preset target tillage depth value. The difference between the two is converted into a control signal output after the fuzzy operation. The described principle of the comprehensive adjustment of force and position is displayed in Figure 5.

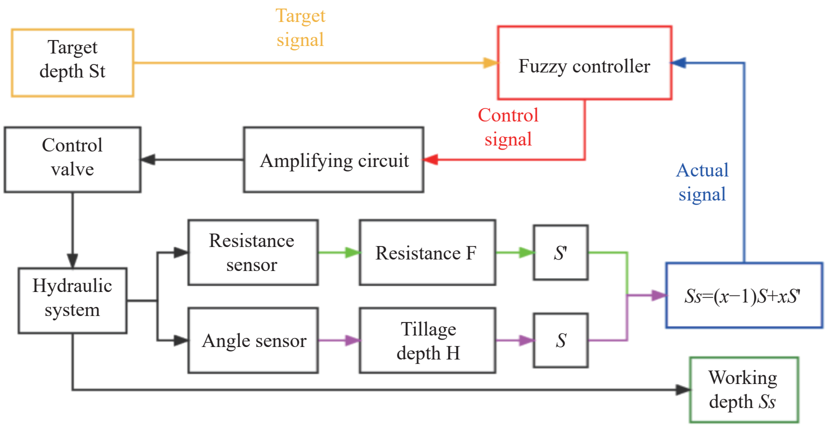


Figure 5 Principle diagram of comprehensive adjustment of force and position

The integrated control of force and position in the electro-controlled hydraulic system takes the tillage depth as the control signal[29,30]. Hence, the control coefficient x, defined as the proportion of force regulation in the comprehensive regulation of force position, is introduced. The proportion of force regulation in the comprehensive regulation of force position can be controlled by setting any value of x between 0 and 1.

As mentioned above, the actual tillage depth value S can be obtained by converting the measured value of the angular displacement sensor, and the soil resistance F can be obtained from the measurement of the resistance sensor. Moreover, the soil resistance can be converted into the tillage depth value S':

$$S' = \frac{F}{k \times b} \tag{6}$$

where, k is soil-specific resistance, N/mm^2; b is tillage width, mm.

Then the actual tillage depth value S_S can be expressed by controlling the proportion of S and S' according to the control coefficient x:

$$S_S = (x-1)S + xS' \tag{7}$$

The force-position comprehensive adjustment system can simultaneously perform force adjustment and position adjustment. The proportion of force adjustment to the whole adjustment is determined by the size of x. The closer the x is to 1, the larger the force adjustment is in the adjustment. The x value can be appropriately increased when the cultivator encounters land with large undulations, and the fuselage is not level during the rotary tillage operation. The hydraulic system is adjusted depending on the resistance change detected by the resistance sensor to adapt to the changing direction of the tillage depth. When the soil-specific resistance increases during the rotary tillage operation of the microtiller, the adjustment direction of the tillage depth can be corrected by appropriately reducing the x value and relying on the angular displacement sensor to detect the change in the tillage depth. This method of adjusting the tillage depth has a good effect on the land with large changes in soil-specific resistance and the ground with large variations in topography.

3.3 Control of tillage depth through the application of the PID method

Fuzzy control does not depend on the mathematical model of the control system; it is suitable for the electro-controlled hydraulic system and is an intelligent control method[31]. A comprehensive synchronous control strategy-FPID control system is formed by combining fuzzy control with traditional PID control. FPID control has a short response time, small overshoot, and good dynamic and steady-state performance[32].

The following is the basic principle of the FPID controller applied in the present study: the depth control of the rotary tillage is transformed into the displacement control of the oil cylinder according to the corresponding relationship between the hydraulic cylinder displacement of the microtiller and the depth of the rotary tillage. Then, the control rule is established according to the relationship between the correction parameter K of PID control and the displacement error E and the error rate of change ΔE of fuzzy control. The input quantities are set as E and ΔE, moreover, the output quantity is the control signal. The FPID control principle of tillage depth is shown in Figure 6.

As shown in the Figure 6, the comprehensive adjustment system of the force and position of the electric tiller comprises a fuzzy controller and a PID controller. The input of the fuzzy

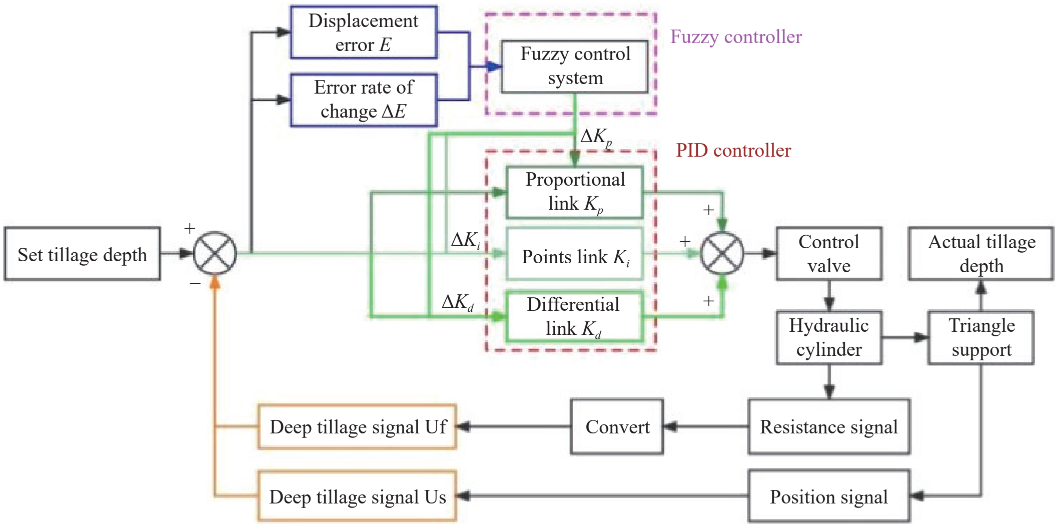


Figure 6 Schematic diagram of FPID tillage depth control system

controller is the displacement error E and the error rate of change $\varDelta E$. The output includes the three correction coefficients $\varDelta Kp$, $\varDelta Ki$, and $\varDelta Kd$ of the PID controller. Then, the three parameters of the PID controller can be taken as

$$\begin{cases} K_p = K_{p0} + \Delta K_p \\ K_i = K_{i0} + \Delta K_i \\ K_d = K_{d0} + \Delta K_d \end{cases} \tag{8}$$

where, K_{p0}, K_{i0}, and K_{d0} are the initial values of proportional, integral, and differential links, respectively, which are determined by experience.

In the electric microtiller's electro-controlled hydraulic system, the displacement of the oil cylinder during farming is 0-55 mm. Thus, the basic domain of the displacement deviation E of the oil cylinder is [−55, 55]. The basic domain of the error rate of change $\varDelta E$ is [−100, 100]. The basic domains of the three correction signals $\varDelta Kp$, $\varDelta Ki$, and $\varDelta Kd$ are [−6.5, 6.5], [−2, 2], [−0.8, 0.8]. Given that the fuzzy controller can only receive discrete data, the continuous variable input by the system must be discretized [33]. The discrete universe of each parameter takes {−6, −5, −4, −3, −2, −1, 0, 1, 2, 3, 4, 5, 6}, and the linguistic variables take seven fuzzy subsets {*NB, NM, NS, O, PS, PM, PB*}. According to the basic domain and quantization level of the input and output quantities, the quantization factor and scale factor can be calculated as follows: $k_E = 6/55 = 0.109$, $k_{\varDelta E} = 6/100 = 0.006$, $k_{\varDelta Kp} = 6.5/6 = 1.083$, $k_{\varDelta Ki} = 2/6 = 0.333$, $k_{\varDelta Kd} = 0.8/6 = 0.133$.

The fuzzy control rules of the electric tiller summarize the experience of human operation, which is expressed by fuzzy control rules; the control rules should ensure the optimal dynamic and static performance of the controlled system[34]. The common membership functions of each fuzzy state are triangular, Gaussian, S, and Z[33]. The triangular membership function has a simple operation and small memory occupation. Thus, the membership functions of each variable in this study are selected as triangles, as demonstrated in Figure 7.

The fuzzy control rules used in this research are established based on the summary of the operating experience according to the magnitude of the input value at different times during the operation of the self-propelled electric tiller and the relationship between the three correction coefficients. According to the working characteristics of the electronic control system and the relationship between the FPID control parameters, the fuzzy control rules are listed in Tables 1-3.

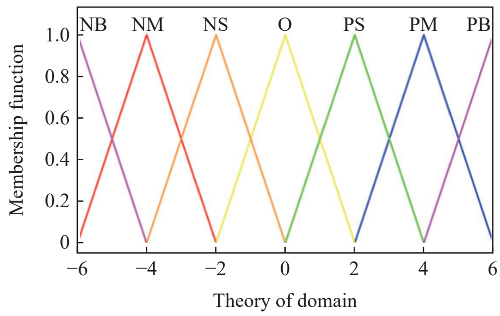


Figure 7 Membership function diagram of each parameter

Table 1 Fuzzy control rule table of $\varDelta K_p$

E	ΔE						
	NB	NM	NS	O	PS	PM	PB
NB	PB	PB	PM	PM	PS	O	O
NM	PB	PB	PM	PS	PS	O	NS
NS	PM	PM	PM	PS	O	NS	NS
O	PM	PM	PS	O	NS	NM	NM
PS	PS	PS	O	NS	NS	NM	NM
PM	PS	O	NS	NM	NM	NM	NB
PB	O	O	NM	NM	NM	NB	NB

Table 2 Fuzzy control rule table of $\varDelta K_i$

E	ΔE						
	NB	NM	NS	O	PS	PM	PB
NB	NB	NB	NM	NM	NS	O	O
NM	NB	NB	NM	NS	NS	O	NS
NS	NB	NM	NS	NS	O	PS	PS
O	NM	NM	NS	O	PS	PM	PM
PS	NM	NS	O	PS	PS	PM	PB
PM	O	O	PS	PS	PM	PB	PB
PB	O	O	PS	PM	PM	PB	PB

The Table 1-3 above shows that the fuzzy rule bases are constructed in this research to adjust the PID correction coefficients Kp, Ki, and Kd, which are all two-dimensional. The K value is determined on the basis that the displacement error E and the error change rate $\varDelta E$ jointly determine $\varDelta K$. The surface graph of the K value based on the fuzzy rule base is shown in Figure 8.

The output of the fuzzy controller must be de-fuzzified because the output of the PID controller used in this study should be

Table 3 Fuzzy control rule table of ΔK_d

E	ΔE						
	NB	NM	NS	O	PS	PM	PB
NB	NB	NB	NM	NM	NS	O	O
NM	NB	NB	NM	NS	NS	O	NS
NS	NB	NM	NS	NS	O	PS	PS
O	NM	NM	NS	O	PS	PM	PM
PS	NM	NS	O	PS	PS	PM	PB
PM	O	O	PS	PS	PM	PB	PB
PB	O	O	PS	PM	PM	PB	PB

accurate data[35,36]. Fuzzy judgment should be used in converting output into a precise quantity to achieve a good operation result of the membership function and obtain a precise control effect. In this study, the center of gravity method is used to make fuzzy judgments[11]. It can be expressed as

$$u = \frac{\sum \mu N(xi)\cdot xi}{\sum \mu N(xi)} \tag{9}$$

3.4 Simulation analysis of deep tillage FPID control system

According to the above method, the FPID control model (Figure 9) are designed and established in Simulink of the Matlab software. The control effects under different control coefficients are compared. The simulation model of the self-propelled electric tiller's hydraulic system is finally established (Figure 10).

The simulation model established in Figure 11 is used to simulate and analyze the comprehensive control of force and

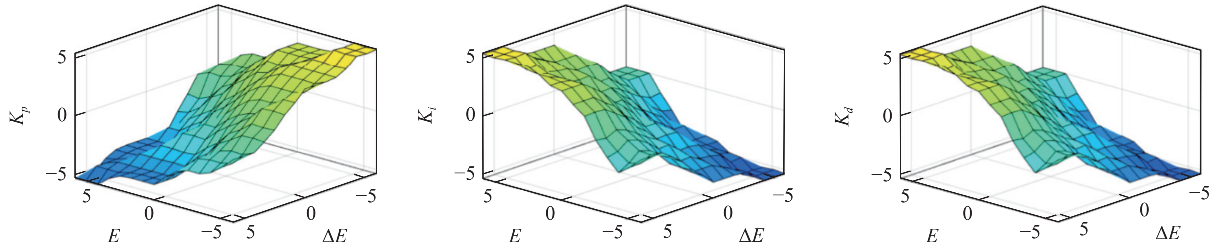


Figure 8 Visualized surface map of gain coefficient K

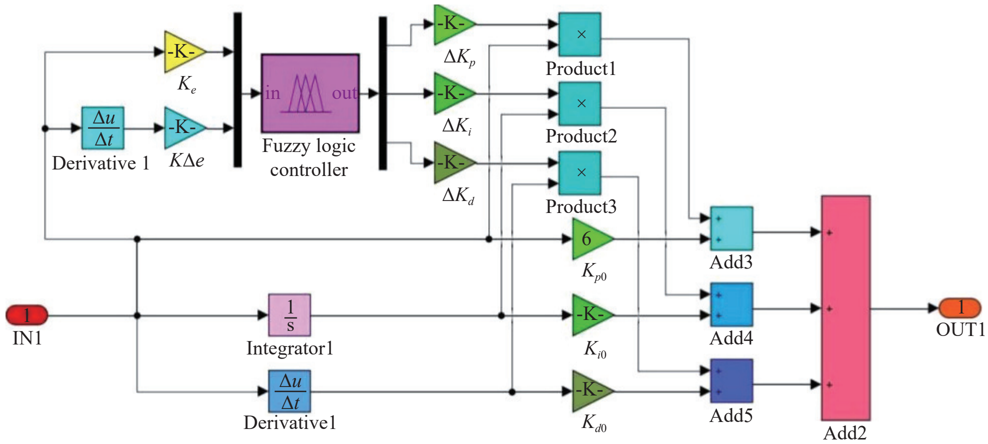


Figure 9 FPID controller model diagram

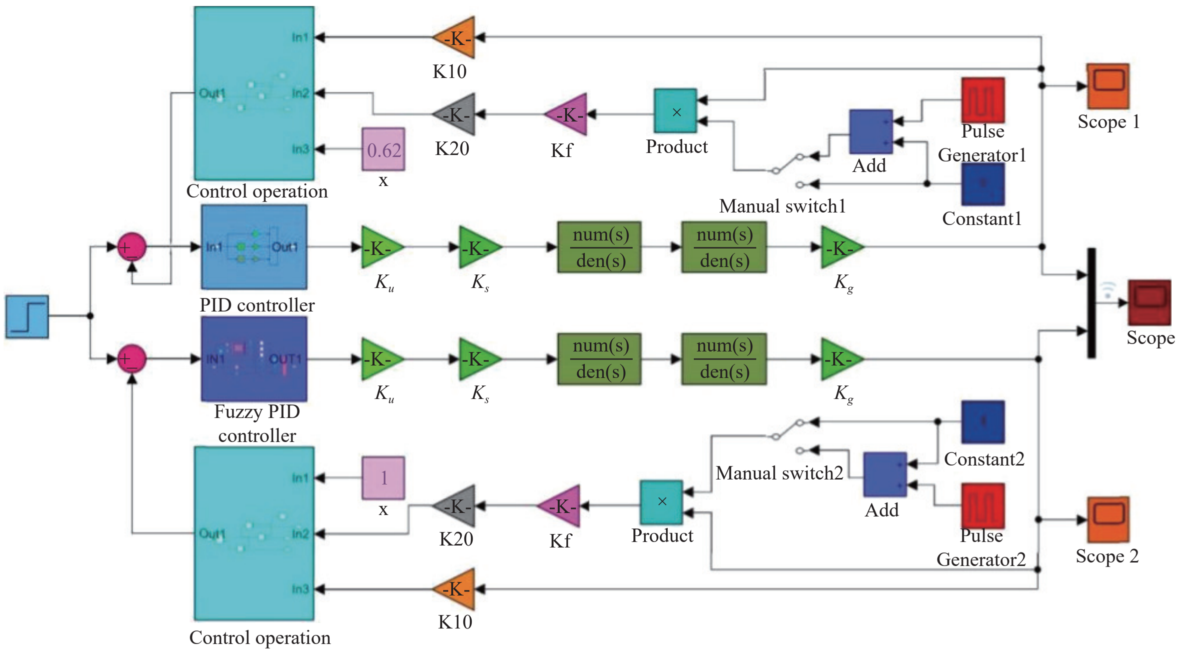


Figure 10 Simulation model of the self-propelled electric microtiller's electro-hydraulic system

position of the self-propelled electric microtiller's electro-controlled hydraulic system. In the simulation, the response effect of the FPID controller and the PID controller and the change of the tillage depth under different control coefficients are detected by adjusting the value of x to compare the response speed and maximum overshoot of the two controllers. During the simulation, the control coefficients are taken as 0.2, 0.5, and 0.8, and the corresponding tillage depth target values are 13, 14, and 15 cm, respectively, to reduce the influence of the tillage depth on the response time and overshoot.

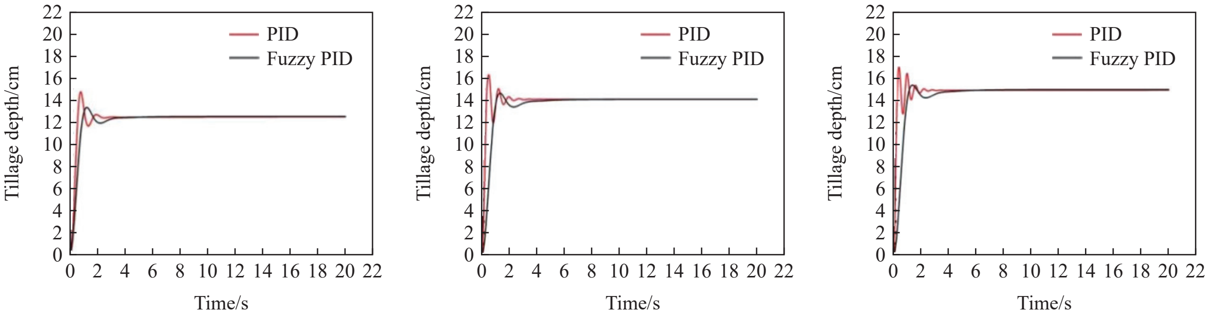


Figure 11 Simulation results of the self-propelled electric microtiller's electro-hydraulic system

The simulation results in Figure 11 show that the response speed of the two controllers used in the self-propelled electric tiller is fast. The difference is that when PID control is used, tillage depth takes a 2.3 s transition time to reach the target tillage depth value, and the maximum overshoot is more than 15%. The transition time of FPID control is 2 s, and the overshoot is only within 5%. The FPID control strategy can shorten the time required for the tillage depth to reach the set value to a certain extent on the premise of reducing the fluctuation amount. On the contrary, for FPID control, when the control coefficients are 0.2, 0.5, and 0.8, the fastest response time is 1.8, 2, and 2.3 s, and the maximum overshoot is 5%, 4%, and 3%. When the control coefficient is close to 0 and the in situ adjustment plays the main control role, the response time is relatively short, but the overshoot is large. The response time is relatively long, but the overshoot is small when the control coefficient is close to 1, that is, the force regulation plays the main control role. The self-propelled electric microtiller with comprehensive adjustment of force and position can adjust correspondingly to different expected requirements. It can also meet the active adjustment under different operating conditions and the automatic adjustment of the entire operation process.

In summary, the control strategy of applying FPID to the force-position integrated electro-hydraulic control system has high control precision, fast response speed, and small fluctuation range. It meets the requirements for the uniformity and stability of tillage depth control.

4 Fieldwork quality experiment of tillage depth automatic control system

4.1 Experimental principle

The PID control system and the FPID control system are used in adjusting the height and low position of the rotary tiller of the self-propelled electric tiller, respectively, under different working conditions to control the tiller depth and verify the field operation performance of the tillage depth automatic control system using the FPID control strategy. The quality of the rotary tillage operation of the microtiller under different control modes is also tested to verify whether it can meet the requirements for the uniformity and stability of the tillage depth control[37,38]. According to the specified agricultural machinery operation standards, the important indicators for judging the quality of rotary tillage are the coefficient of variation V of the stability of the tillage depth and the rate of broken soil E:

$$V = \frac{S}{a} \times 100\% \tag{10}$$

where, V is the coefficient of variation for stability; S is the standard deviation of tillage depth, mm; a is the average tillage depth, mm.

$$E = \frac{Ma}{M} \times 100\% \tag{11}$$

where, E is the broken soil rate, M_a is the mass of the soil block with the longest side not greater than 5 cm, and M is the mass of the soil block in the whole tillage layer within the area of 0.3 m×0.3 m.

4.2 Fieldwork quality experiment method

As displayed in Figure 12, the length of the experimental field is 30 m. The soil moisture content of the experimental field is 20%, obtained by the drying weighing method. The average rotational speed of the rotary tiller during the experiment is selected as 300 r/min[39]. Given the factors such as low weight and low power of the self-propelled electric tiller, the tiller slips when the speed of the rotary tiller is too fast and the tiller depth is deep; moreover, the tillage operation is incomplete and other abnormal working considerations occur[40]. Therefore, the two average operating speeds are set to be 0.8 and 1.6 km/h. The target tillage depth values under each operating speed are set as 100 and 150 mm, respectively. The average operating speed and tillage depth values are combined into four groups, as listed in Table 4.

The tillage depth adjustment system test is conducted under the

Figure 12 Experiment diagram of the working quality of the self-propelled electric tiller

Table 4 Combination of test conditions of the tiller

Working condition number	Target tillage depth/mm	Working speed/km·h^{-1}
1	100	0.8
2	150	0.8
3	100	1.6
4	150	1.6

above four working conditions. Moreover, 20 m is taken as the stable working area of the tiller, and 5 m at the front and back is taken as the distance required for the tillage depth to reach the set depth. The experiment is repeated three times under each working condition, and the average value is taken as the test result. The above experiments of micro-tiller under PID control and fuzzy PID control are carried out respectively, and the specific experimental process is as follows:

(1) Check the status of the machine to ensure the normal operation of the electronic control system and the hydraulic system;

(2) Set up PID control algorithm or fuzzy PID control algorithm;

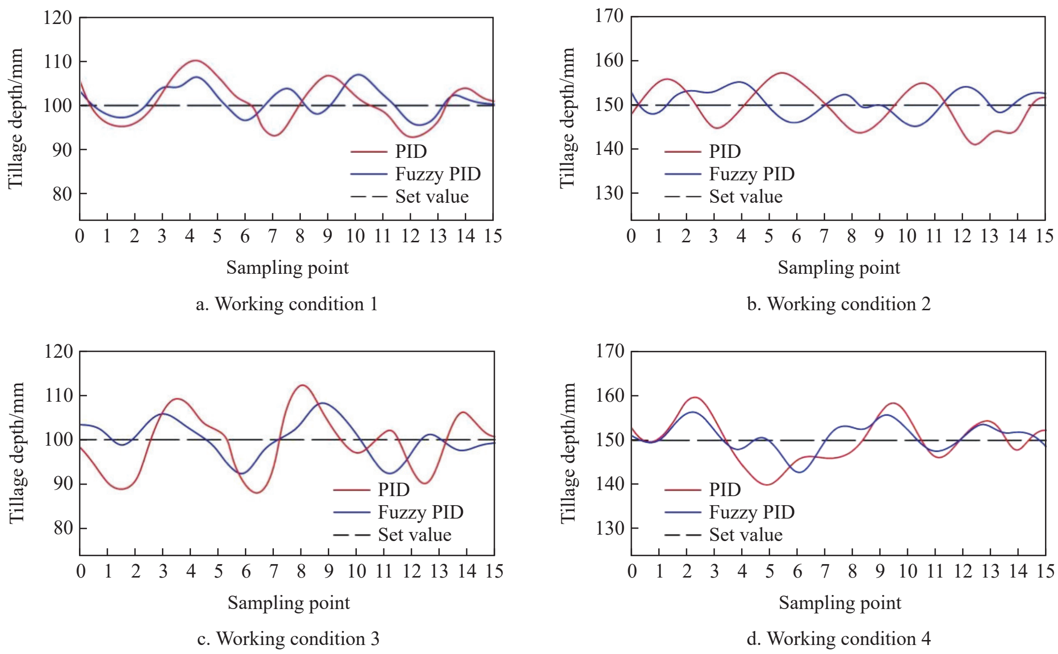
(3) After the timing starts, make the micro-tiller start operation and control the rotary tillage unit to reach the set height;

(4) Mark every 5 s the points that the micro-tiller passes through as sampling points, and select 15 sampling points in total;

(5) When the micro-tiller has finished its operation, the actual rotary tillage depth and soil breakage at the marked points are measured manually.

4.3 Experimental results and analysis

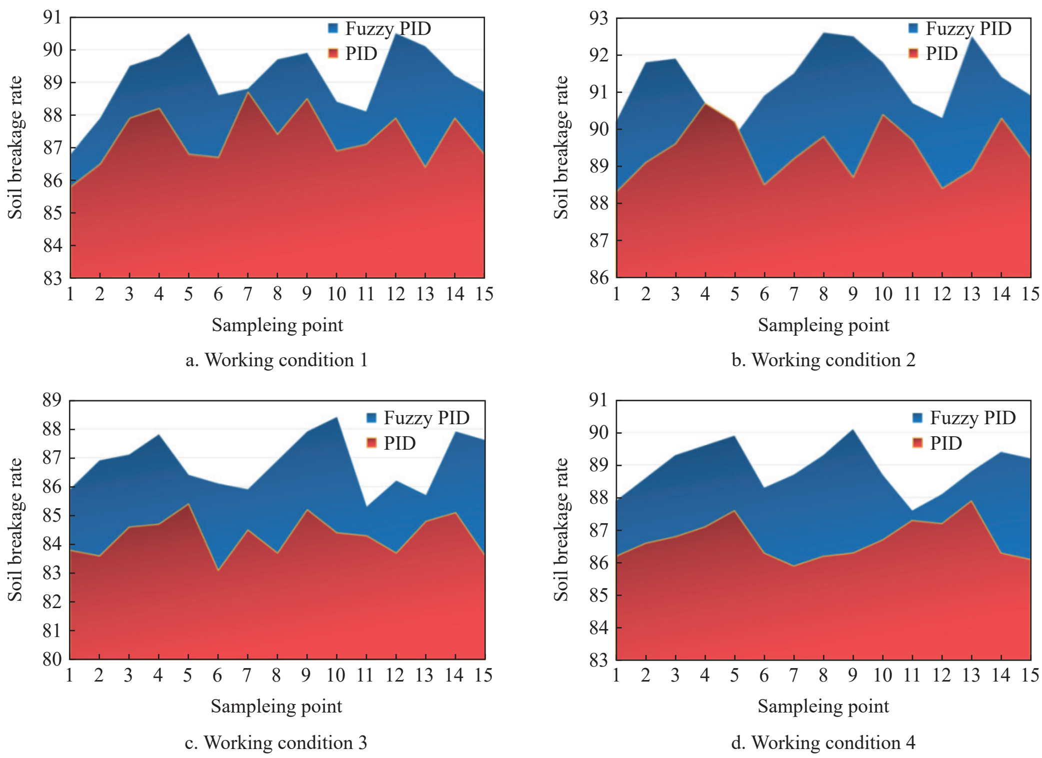
The experiments are performed according to the above experimental method, and the tillage depth value and soil breakage rate of each marked point under different working conditions are recorded. After data sorting, the fitting curve of the rotary tillage depth under different working conditions is shown in Figure 13. The broken soil rate of the rotary tillage operation is shown in Figure 14.



a. Working condition 1 b. Working condition 2

c. Working condition 3 d. Working condition 4

Figure 13 Rotary tillage depth fitting curve under different control methods



a. Working condition 1 b. Working condition 2

c. Working condition 3 d. Working condition 4

Figure 14 Area chart of the broken soil rate under different control methods

The calculated standard deviation of tillage depth and the coefficient of variation of tillage depth stability are listed in Table 5.

Table 5 FPID control of deep tillage performance parameters

No.	Control method	Working speed/ $km \cdot h^{-1}$	Target tillage depth/mm	Average tillage depth/mm	Standard deviation of tillage depth/mm	Tillage depth stability coefficient of variation/%	Broken soil rate/%
1	PID	0.8	100	98.6	6.35	6.44	87.3
2	FPID	0.8	100	101.2	5.68	5.62	89.1
3	PID	0.8	150	147.8	7.64	5.17	89.4
4	FPID	0.8	150	149.0	5.25	3.52	91.3
5	PID	1.6	100	100.9	9.97	9.88	84.3
6	FPID	1.6	100	100.4	6.62	6.60	86.8
7	PID	1.6	150	150.6	11.26	7.48	86.7
8	FPID	1.6	150	151.1	9.43	6.24	88.9

As shown in Figure 13 and Table 4, the self-propelled electric tiller using PID control and FPID control in the actual operation process can reach the set tillage depth value in a short time, according to the simulation results of Simulink. The fluctuation is kept stable within a certain range during the whole process of rotary tillage. During the experiment, the obtained working results under different working conditions vary because of the different set tillage depth values and working speeds. As illustrated in Figure 13, the maximum deviation between the actual tillage depth value and the set value under different working conditions is 12 mm, and the minimum deviation is 3 mm using the PID control method. The average value of the standard deviation of the tillage depth is 8.8 mm, and the coefficient of variation of the average tillage depth stability is 7.25%. The maximum deviation between the actual tillage depth value and the set value under different working conditions obtained using the FPID control method is 8 mm, and the minimum deviation is 0 mm. The average value of the standard deviation of the tillage depth is 6.7 mm, and the coefficient of variation of the average tillage depth stability is 5.50%. Compared with simple PID control, the PID control strategy using a fuzzy algorithm reduces the variation of tillage depth stability by 24%. In particular, the rotary tillage device using FPID control can decrease the fluctuation range of tillage depth and keep the tillage depth stable. The broken soil rate refers to the change rate of the soil block volume before and after the rotary tillage operation of the microtiller. The main factors affecting the broken soil rate include the operating speed of the tiller, the rotational speed of the rotary tiller, the depth of the rotary tillage, the soil moisture content, and the rate of change of the tillage depth. In the present experiment, the operating speed of the tiller, the rotational speed of the cutter, and the soil moisture content are controlled to a certain value. Moreover, the change in the broken soil rate under different working conditions with different control methods is obtained, as shown in Figure 14. The average broken soil rate under PID control is 86.93%, and the average broken soil rate under FPID control under the same conditions is 89.03% which increased the soil crushing rate by 3%. Table 4 indicates that the microtiller using FPID control can reduce the variation rate of tillage depth while maintaining the fluctuation range of tillage depth. Thus, a high soil breakage rate can be obtained, and the quality of rotary tillage operations can be improved.

5 Conclusions

According to the farming characteristics and requirements of the self-propelled electric tiller, the method of introducing the control coefficient is used in the present study to investigate the comprehensive control of the force and position of the tiller's electro-controlled hydraulic system. A dual-parameter control model of tillage depth is established. In the process of variable analysis, the control strategy of FPID is applied to control tillage depth uniformity. The main conclusions from the simulation analysis and field experiments are as follows:

(1) The tillage depth control system designed in this study can reach the set operating depth within 2.4 s after issuing the instruction. Moreover, the maximum overshoot is less than 5%. The tiller obtains high control accuracy, fast response speed, and small fluctuation range by applying the comprehensive control strategy of force and position. It also reaches the preset tillage depth quickly and accurately.

(2) Compared with PID control alone, the PID control strategy using fuzzy algorithm reduced the variation of tillage depth stability by 24%, and the soil breakage rate is increased by 3%. The microtiller applying the FPID control strategy can maintain tillage depth stability at all times during the operation process and meet the requirement of tillage depth consistency.

(3) The application of the FPID control strategy and the comprehensive adjustment of force and position realized the electro-hydraulic control of the electric tiller's tillage depth. The control precision and work efficiency of the self-propelled electric tiller's rotary tillage operation is improved. Moreover, the utility model has strong practicability. Furthermore, the research on the depth control of self-propelled electric tillers is elevated to a certain extent.

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