INVESTIGATION OF THE CONTROL SYSTEM FOR MAIZE SEEDER SOWING DEPTH BASED ON SOIL MOISTURE CONTENT

基于土壤含水率的玉米播种机播深控制系统的研究

Xianliang LIU[1)], Rui ZHANG[*1)], Yubin ZHAI[1)] , Wenjie LI[1)], Haozhe WEI[1)]
[1)]College of Mechanical and Electrical Engineering, Qingdao Agricultural University, Qingdao 266109, China;
Tel: +86-19905421696; E-mail: 19905421696@163.com
Corresponding author: Rui Zhang
DOI: https://doi.org/10.35633/inmateh-75-25

***Keywords:** Sowing depth; Downforce; Moisture content; PLC controller; Proportional directional valve; Mamdani fuzzy control*

ABSTRACT
To ensure the stability of seeding depth for a corn planter unit under different soil moisture conditions, a control system was designed to adjust the seeding depth of the unit based on soil moisture content. Using a PLC controller as the control foundation, the system employs a hydraulic system as its actuator. Soil moisture content is detected by moisture sensors, and the PLC controller processes the analog signals from the sensors. The controller then adjusts the forward and reverse rotation and speed of one motor via a variable frequency drive, thereby controlling the vertical displacement of the depth-limiting wheel to regulate the seeding depth. At the same time, a pressure sensor provides feedback to the PLC controller to control the switching time of the solenoid directional valve, driving the hydraulic cylinder stroke. The profiling mechanism connected to the hydraulic system moves the depth-limiting wheel accordingly, achieving stability in the planter's seeding depth. The control system is further optimized using the Mamdani fuzzy PID algorithm. Experimental results demonstrate that the designed seeding depth control system is stable and reliable, accurately adjusting the seeding depth according to different soil moisture levels. When the unit operates at speeds of 8 ~10 km/h, the stability of the seeding depth reaches 90%, significantly improving the stability of the unit's seeding depth.

摘 要
为了使玉米播种机单体在不同含水率土壤播种工作时保持播种深度的稳定性，设计了一种根据土壤含水率控制播种单体播种深度的的控制系统。以 PLC 控制器为控制基础，系统采用液压系统作为其执行机构，通过水分传感器检测土壤含水率，PLC 控制器分析处理传感器检测所获得的模拟信号后，控制器通过控制变频器调节电机正反转和转速，实现对限深轮的上下位移，完成对播种深度的控制。同时压力传感器将信号反馈给 PLC 控制器控制电磁换向阀的开断时间来驱动液压缸行程，与之相连接的仿形机构带动限深轮一同运动，实现对播种机播深的稳定性调节。利用 Mamdani 模糊 PID 算法对控制系统进行优化。实验结果表明，所设计的播种深度控制系统稳定可靠，能根据不同土壤含水率精确控制播种深度，单体作业速度在 8～10 km/h 时，播深稳定性达到 90%，系统提高了单体的播种深度稳定性。

INTRODUCTION
At present, precision seeding technology is one of the important measures to save and increase efficiency of dry farming, reduce production cost and increase economic income for modern agriculture *(Xu et al., 2023)*. There are many factors affecting the sowing quality of precision sowing, among which soil moisture content, pressure and sowing depth are one of the many factors, among which suitable and consistent sowing depth can effectively improve the yield of corn crops *(Zhu et al., 2019; Fu, 2022)*.

Since the middle of the last century, countries began to study the control of sowing depth. Through a series of basic theoretical and experimental studies, a variety of excellent performance of sowing machines and tools have been developed *(Li et al., 2018)*. *Jia et al., (2018),* designed an adaptive tillage depth monitoring system, which used the surface adaptive swing arm and optical encoder to measure the rotation of the swing arm, and then converted the measured angle into the tillage depth through a formula.

Xianliang LIU, M.S. Stud. Eng.; Rui ZHANG, Prof. Ph.D. Eng.; Yubin ZHAI, M.S. Stud. Eng.; Wenjie LI, M.S. Stud. Eng.; Haozhe WEI, M.S. Stud. Eng.;*

Nielsen et al., (2018), designed two kinds of depth measurement systems based on angle sensor, linear displacement sensor and ultrasonic sensor and a set of electro-hydraulic control system. Ultrasonic detection technology was adopted and ultrasonic detector was installed on the trencher to complete real-time detection of the trench depth *(Du et al., 2021; Fu et al., 2019)*. A CAN bus monitoring and evaluation system for down pressure and sowing depth of multi-row seeder were designed *(Gao et al., 2019; Romaneckas, 2022)*. A measuring device for sowing depth and sowing pressure with angle and shaft pin sensors was adopted, the design of hydraulic drive and zonal controlled pneumatic drive device was optimized, and real-time monitoring and quality evaluation of sowing pressure and sowing depth in precision sowing operations were achieved *(Rao A.S., 2023; Suomi, 2024)*.

At present, new progress has been made in the development of precision sowing devices in China. However, the comprehensive effects of soil moisture content, sowing depth and soil compaction on seed emergence were less studied *(Xu Bing et al., 2023; Hao et al., 2023; Wang et al., 2023)*. Therefore, this paper proposes an automatic control system for sowing depth of corn seeder based on soil moisture content. PLC is used as the main controller of the control system, and water content sensor and pressure sensor are used as signal input, the three-phase motor and hydraulic cylinder as the actuator realize the real-time control of the sowing depth and the downforce, so as to realize the precise control of the sowing depth of the single seeder.

MATERIALS AND METHODS

System structure and working principle

The system is composed of PLC controller, moisture content sensor, pressure sensor, seeding monomer, proportional reversing valve, hydraulic cylinder, frequency converter and AC motor, as shown in Figure 1.

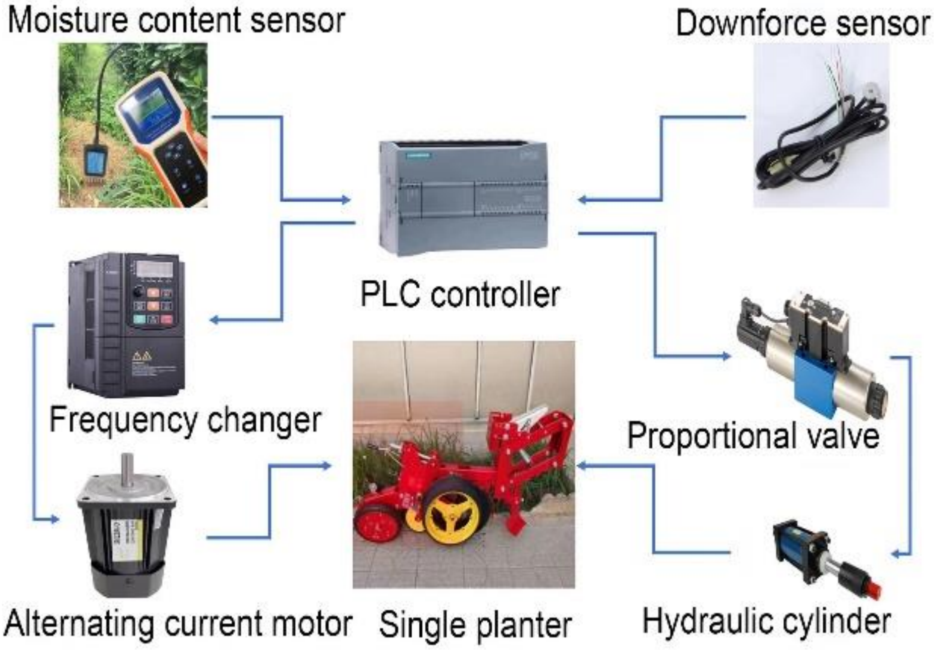

Fig. 1 - Composition of control system

The working process is as follows: PLC as the core processor of the system, equipped with analog input/output module, can collect the value of the moisture content sensor and pressure sensor, analyze and process the output control signal to the actuator, namely the frequency converter and solenoid valve. The adjustment mechanism of the system is divided into sowing depth adjustment and hydraulic feedback adjustment. The former collects soil moisture content through static moisture content sensor before the test starts, and the signal is output to the inverter after PLC processing, and the inverter controls the motor action, thus controlling the sowing depth of the seeder. The latter is to collect the signal of the lower pressure sensor, after the PLC controller analysis and processing, the result is output to the proportional valve, the proportional valve according to the signal range to control the hydraulic oil flow rate and flow, so as to control the expansion and stroke of the hydraulic cylinder, to achieve the real-time feedback action of the lower pressure, so as to achieve the stability control of the sowing depth.

PLC Controller

Siemens S7-1200PLC controller, model 6ES7214-1AG40-0XB0 is used. The controller comes with 24 digital I/O points, including 14 input points and 10 output points. In addition to the switching signal, it is necessary to use the input and output of the analog signal to control the acquisition of the sensor signal and the adjustment of the proportional valve. The control cabinet is shown in Figure 2. At the same time, TIA Portal V18 software was used for PLC configuration and programming. The Ethernet protocol was used to communicate with third-party devices, and I/O assignments are shown in Table 1.

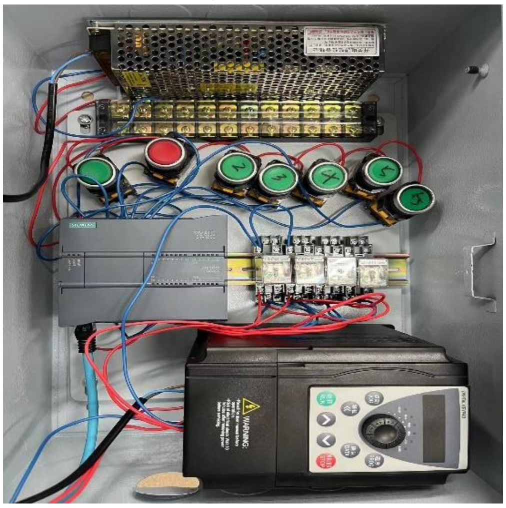

Fig. 2 - Electrical control cabinet

Table 1

PLC I /O distribution table

Input	Feature	Output	Feature
I0.0	activate	Q1.0	Solenoid valve 1 action
I0.1	stop	Q1.1	Solenoid valve 2 action
I0.2	Solenoid valve 1 opens	Q1.2	Forward motor rotation
I0.3	Solenoid valve 2 opens	Q1.3	Motor reversal
I0.4	Measuring pressure	Q0.5	Flicker time
I0.5	Forward motor rotation	QW96	Pressure output value
I0.6	Motor reversal		
I0.7	Starting PID		
IW96	Water content input		
IW98	Pressure input		

Design of depth control system

First of all, the depth limiting wheel is used as a farming reference component, and the relative height difference between it and the trenching plate directly corresponds to the sowing depth. RS485 soil moisture content sensor is used as the detection mechanism, the measurement range is 0-100%, the accuracy is ±3%, the sampling frequency is 1Hz, and the PLC analog input module is connected. The actuator is a combination of frequency converter and three-phase motor, while the three-phase motor and the monomer are connected through a coupling, and their rotation can drive the movement of the monomer. The frequency converter is selected from Instar AE200 model (input 220VAC/50Hz, output 0-400Hz), and the motor is selected from Matsuoka three-phase 220V asynchronous motor (rated torque 5.2Nm).

Fig. 3 - Installation of frequency converter and motor

By observing the pressure sensor signal installed in the groove of the depth limiting wheel arm to reflect the change of pressure on the depth limiting wheel, the pressure sensor is directly connected to the PLC analog input module, and the pressure signal is fed back to the PLC controller. The output end of the PLC controller is connected to the proportional reversing valve. By receiving the voltage signal transmitted by the PLC controller to control the flow rate and direction of the oil in the solenoid valve, the hydraulic cylinder connected with it moves with the change of the position of the valve core, driving the parallel four-link copying mechanism to complete the upward and downward movement, controlling it to reach the predetermined pressure, and realizing the stable control of the depth. The stress analysis diagram of the pressure sensor is shown in Figure 4. The force analysis formula is shown in equation (1).

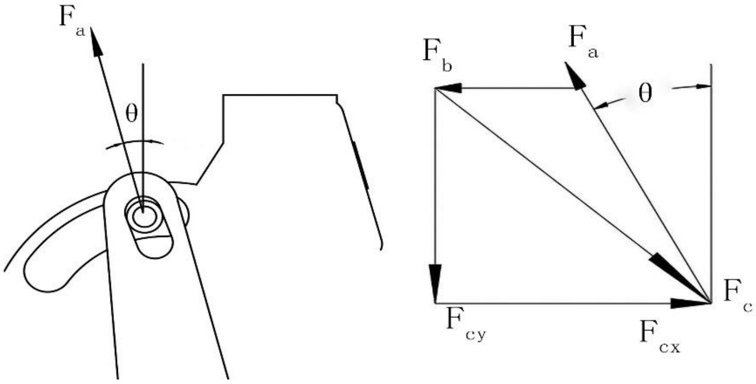

Fig. 4 - Force analysis diagram of pressure sensor

$$\begin{aligned} F_{cx} &= F_a \sin\theta + F_b \\ F_{cy} &= F_a \cos\theta \end{aligned} \tag{1}$$

where:

F_a - Reaction force of the depth limiting arm on the depth limiting block, N; F_b - Force of single frame on depth limiting block, N; F_c - Sensor force on depth limiting block, N; θ-- the Angle between the depth limiting arm and the sowing unit frame, (°); F_{cx}-F_c component in the horizontal direction, N; F_{cy}-F_c in the vertical direction, N.

The installation position of the force sensor is the limit pin of the depth limiting wheel, which does not rotate itself, and the force stability is limited only by the reaction force in the vertical direction of the deep wheel arm. Therefore, the sensor uses a high-precision micro-pressure sensor, the selected model is DYHW-108, the force range is 0 ~ 2000 N, the output voltage range is 0 ~ 10 V, and the working voltage is 15 ~ 30 V.

According to the weight of the single unit of the corn planter, the hydraulic cylinder of model MOB40X100 was selected. The inner diameter of the hydraulic cylinder D is 40 mm, the diameter of the piston rod is 20 mm, the maximum pulling force is 6.59 KN and the maximum thrust is 8.80 KN. The hydraulic cylinder can satisfy the motion control of the monomer. The installation position of hydraulic cylinder is shown in Figure 5. The oil source of the system adopts the hydraulic output after the tractor, and its output rated flow rate is generally 36 L/min, the rated working pressure is 12 MPa, and the safe working pressure is 15 MPa. Therefore, the pilot relief valve integrated block is used to stabilize the oil pressure in the cylinder, the rated flow rate is 36 L/min, the maximum pilot flow rate is 60 L/min, and the pressure range is 0 ~ 50 bar.

Fig. 5 - Installation position of hydraulic cylinder

Fuzzy PID control

In order to obtain more rapid and stable control effect, based on the traditional PID control theory, fuzzy control theory is introduced into the traditional PID control with the help of MATLAB. Fuzzy PID control has the characteristics of short response time, small overkill and good dynamic performance. According to the corresponding relationship between the pressure of the monomer and the displacement of the hydraulic cylinder, the pressure control of the monomer of the planter is transformed into the displacement of the hydraulic cylinder. After the fuzzy control algorithm processes the deviation between the given value and the output value of the system and the deviation change rate of the two through the proportion, integral and differential coefficients, the control system can get more accurate control effect.

A fuzzy PID controller suitable for the system was optimized and designed. A Mamdani dual-input-three-output fuzzy controller was constructed with the deviation e and the deviation change rate ec as inputs and the three PID control parameters kp, ki and kd as outputs. e, ec, kp, ki and kd are replaced by 5 fuzzy subsets respectively, namely, large positive deviation (NB), small positive deviation (NS), zero deviation (Z), small negative deviation (PS) and large negative deviation (PN). According to the actual situation, the argument domain of parameter change was set as {-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6}. The input of the fuzzy controller is Gaussian membership function and the output is trigonometric membership function.

According to the parameter function of PID controller and expert experience, the fuzzy rules suitable for control system are optimized. The fuzzy rules of kp, ki and kd are designed, as shown in Table 2~4.

Table 2

Kp fuzzy rules

e/ec	NB	NS	Z	PS	PB
NB	PB	PS	PS	PS	Z
NS	PS	PS	PS	Z	NS
Z	PS	PS	Z	NS	NS
PS	PS	Z	NS	NS	NS
PB	Z	NS	NS	NS	NB

Table 3

Ki fuzzy rules

e/ec	NB	NS	Z	PS	PB
NB	NB	NS	NS	NS	Z
NS	NB	NS	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PS	PB
PB	Z	PS	PS	PS	PB

Table 4

Kd fuzzy rules

e/ec	NB	NS	Z	PS	PB
NB	PS	NB	NB	NB	PS
NS	Z	NS	NS	NS	Z
Z	Z	NS	NS	NS	Z
PS	Z	Z	Z	Z	Z
PB	PB	PS	PS	PS	PB

Through the fuzzy rule table formulated by MATLAB software analysis and reasoning, the relationship diagram of input parameters e and ec and output parameters kp, ki and kd is obtained, as shown in Figure 6.

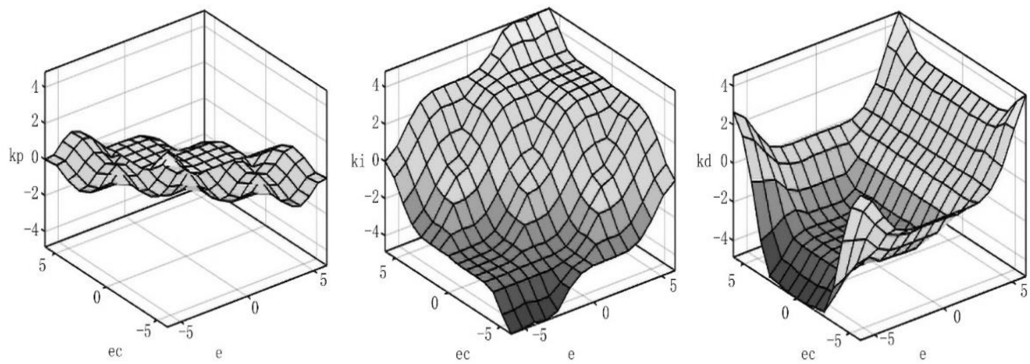

Fig. 6 - Fuzzy control relation surface

In order to verify the optimization effect of fuzzy PID control, a fuzzy controller model was built on Simulink simulation software, as shown in Figure 7. The simulation model of the pressure control system was established, as shown in Figure 8.

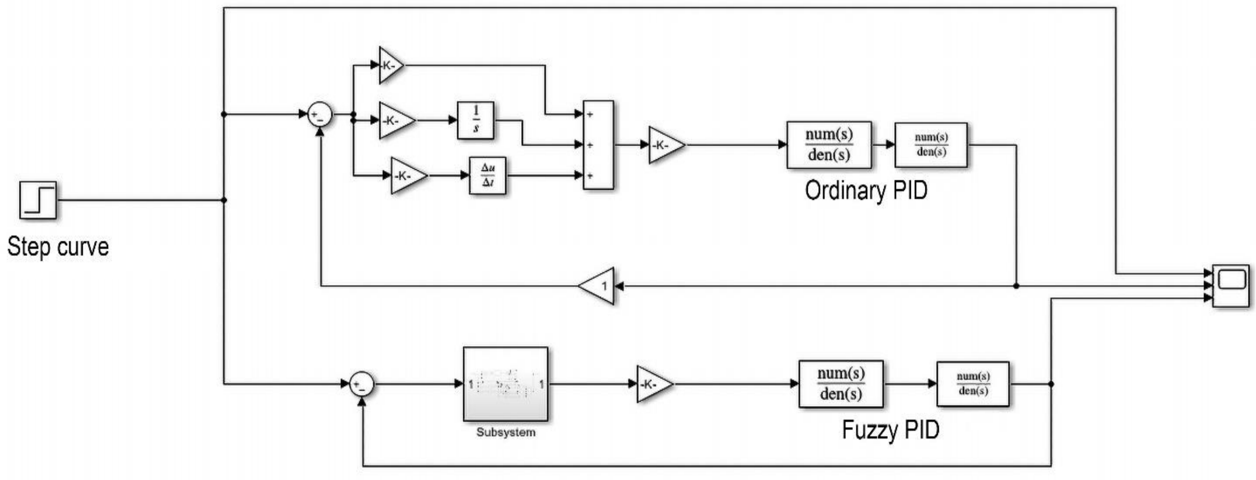

Fig. 7 - Fuzzy controller model

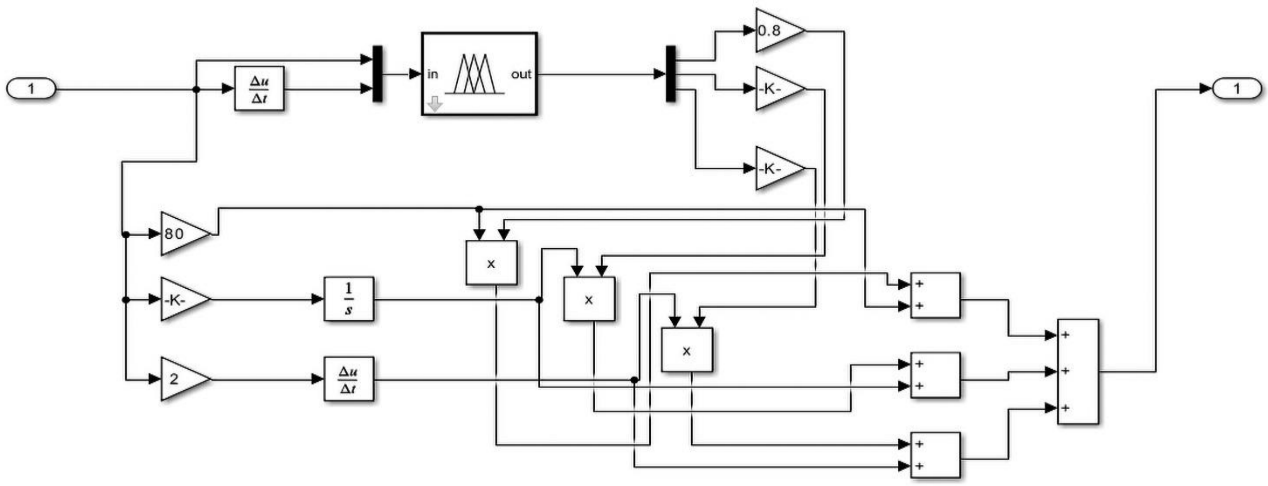

Fig. 8 - Simulation model of downforce control system

The above model is simulated by MATLAB software and the simulation results are observed through the scope window, as shown in Figure 9. As can be seen, compared to the traditional PID controller, the adjustment time of the system increases by 2.572s and the overshoot is reduced from 27% to 14% when using fuzzy PID control instead of the ordinary PID control. Fuzzy PID control can shorten the system response time to a certain extent on the premise of reducing system fluctuations, and the system control effect is significantly improved. This approach meets the stability requirements for sowing depth control.

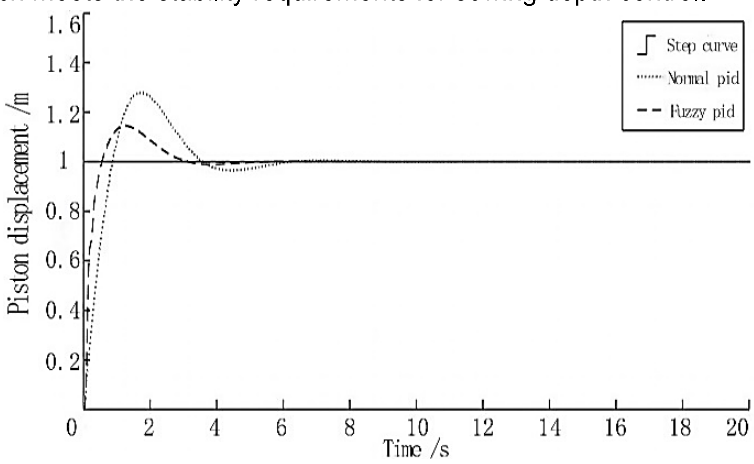

Fig. 9 - Step response curve of the system

RESULTS

A pre-experiment of soil moisture content was carried out before the field experiment. Three groups of variables (moisture content, pressure and sowing depth) were designed, and three levels were set for each group of variables. Without considering the interaction between the variables, the optimal values corresponding to the sowing depth and downforce under each group of moisture content interval were solved to achieve the highest corn emergence rate (The emergence rate is calculated by multiplying the ratio of the actual number of seedlings to the sowing amount by 100%). Multiple sets of data were measured through experiments and the emergence rate was obtained, as shown in Table 5. These results will be used as reference for subsequent tests of the control system.

Table 5

Soil moisture pretest

number	Moisture content(%)	Downforce(N)	Sowing depth(cm)	Emergence rate(%)
1	16 ~ 18	250	5	61
2	16 ~ 18	500	6	79
3	16 ~ 18	750	7	86
4	18 ~ 20	250	5	82
5	18 ~ 20	500	6	92
6	18 ~ 20	750	7	74
7	20 ~ 22	250	5	88
8	20 ~ 22	500	6	65
9	20 ~ 22	750	7	77

The results showed that the optimal value of the lower pressure and the sowing depth were 750 N and 7 cm respectively in the range of 16% ~ 18% moisture content. The optimal value of the water content was in the range of 18% ~ 20% corresponding to the lower pressure of 500 N, the optimal value of the sowing depth was 6 cm. In the range of 20% ~ 22%, the optimal value of the lower pressure was 250 N, and the optimal value of the sowing depth was 5 cm.

In order to test the sowing depth control performance of the control system under different moisture content, the performance test was conducted in the test soil tank of Qingdao Agricultural University in the summer of 2024, as shown in Figure 10. The field environment of the soil tank was measured before the test. The measured soil volume density of 3 ~ 7 cm depth was 1.2 g/cm^3, the average seed bed firmness was 2.5 kg/cm^2. The control system was installed in Weifang Letian Company's Grand stamping no-tillage seeder. The mechanical parallel four-link copying system was used in the control test, and the depth of the trencher was adjusted to the corresponding sowing depth according to the soil moisture content.

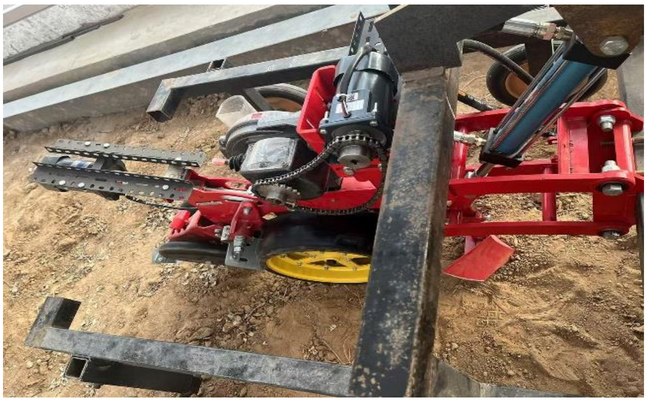

Fig. 10 - Soil tank test diagram

The standard operation speed of tractors in the field was 8 ~ 10 km/h. Two groups of controlled experiments were conducted. The first group adopted the sowing depth control system and added fuzzy control method, while the control group adopted ordinary mechanical copying. The corresponding relationship of different sowing depth was set according to the different moisture content of the earlier sowing data and each group of experiments was repeated six times to reduce errors. According to the agricultural industry standard NY/T 1768-2009 "Technical Specification for Quality Evaluation of no-till seeder", the average sowing depth, the qualified rate of sowing depth and the coefficient of variation of sowing depth were calculated. The test results are shown in Table 6 ~ 8.

Table 6

Consistency test results of sowing depth at different speeds (16% ~ 18% moisture content)

Argument	Regulation mode	Tractor operating speed/(km/h)		
		8	9	10
Average sowing depth /mm	Control system	71	69	72
	Mechanical copying	65	62	63
Pass rate of sowing depth /%	Control system	96	95	93
	Mechanical copying	72	66	62
Coefficient of variation of sowing depth /%	Control system	10.4	12.3	13.4
	Mechanical copying	14.8	15.6	17.6

Table 7

Consistency test results of sowing depth at different speeds (18% ~ 20% moisture content)

Argument	Regulation mode	Tractor operating speed/(km/h)		
		8	9	10
Average sowing depth /mm	Control system	62	58	63
	Mechanical copying	56	54	52
Pass rate of sowing depth /%	Control system	97	96	92
	Mechanical copying	75	68	65
Coefficient of variation of sowing depth /%	Control system	9.8	11.8	12.2
	Mechanical copying	14.1	15.4	16.9

Table 8

Consistency test results of sowing depth at different speeds (20% ~ 22% moisture content)

Argument	Regulation mode	Tractor operating speed/(km/h)		
		8	9	10
Average sowing depth /mm	Control system	49	52	53
	Mechanical copying	53	57	62
Pass rate of sowing depth /%	Control system	95	94	93
	Mechanical copying	71	64	62
Coefficient of variation of sowing depth /%	Control system	10.5	12.5	13.6
	Mechanical copying	14.6	16.1	18.6

From Table 6 ~ 8, it can be seen that the qualified rate of sowing depth control system is higher than 90% at different speeds, and the qualified rate of sowing depth control system is obviously better than that of mechanical copying device. In summary, compared with ordinary mechanical copying device, the automatic sowing depth control system can maintain the stability of sowing depth at different operating speeds and with different compatibility. According to different moisture content, the monomer can be accurately controlled to reach the predetermined sowing depth, and the sowing depth control system has reliable performance.

CONCLUSIONS

Field tests on sowing depth control were conducted for three soil moisture content ranges of 16% ~ 18%, 18% ~ 20% and 20% ~ 22%. When the moisture content was within the range of 18% ~ 20% and the sowing depth was set at 60 mm, the qualification rate of sowing depth was the highest when the vehicle speed of the control system was 6 km/h. The qualified rates of the corresponding control system and mechanical profiling were 97% and 75%, respectively. Compared with the mechanical profiling mechanism, the sowing depth control system increased by 22 percentage points. Thus, the sowing depth control system is obviously superior to the traditional mechanical profiling device.

ACKNOWLEDGEMENT

This research received financial support from the National Key Research and Development Program of China (No. 2023YFD2000402-2) and Open Project of Collaborative Innovation Center for Mechanized Production Equipment of Major Crops in Shandong Province, China. Thanks to the International Field Test Mechanization Association for providing us with the research foundation and platform.

REFERENCES

[1] Du M., (2022). Design and test analysis of corn planter based on PLC (基于 PLC 的玉米播种机设计与试验分析). *Modern Agricultural Machinery*, Vol.2, pp. 62-73, China.

[2] Fu W., (2019). Research on Key technologies of quality control for precision seeding of maize without tillage (玉米免耕精准播种质量控制关键技术研究). *China Agricultural University*, China.

[3] Fu Y., (2022). Design and experimental study of real-time monitoring system for sowing depth of maize no-till seeder (玉米免耕播种机播种深度实时监测系统的设计与试验研究). *Heilongjiang Bayi Agricultural University*, China.

[4] Gao, Y., Z, Chan., Y, S., (2019). Research on CAN Bus Monitoring and Evaluation System for Down Pressure and sowing Depth of Precision planter (精密播种机下压及播种深度 CAN 总线监测评估系统研究). *Transactions of the Chinese Society for Agricultural Machinery*, Vol.51, pp. 15-28, China.

[5] Guo, Y., Liu, P., (2019). Design and application of a small planter controlled by PLC (PLC 控制的小型播种机的设计与应用). *Agricultural Mechanization Research*, Vol.43, pp. 107-138, China.

[6] Hao N., (2023). Research on depth detection and control system based on multi-sensor data fusion (基于多传感器数据融合的深度检测与控制系统研究). *Heilongjiang Bayi Agricultural University*, China.

[7] Li, M., Xu, X., Zheng, L., (2018). Intelligent sowing depth adjustment system for no-till seeder based on Flex sensor and Mamdani fuzzy model (基于柔性传感器和 Mamdani 模糊模型的免耕播种机播种深度智能调节系统). *Journal of Agricultural Engineering and Technology*, Vol.42, pp.18-24, China.

[8] Jia, H., Guo, M., Yu, H., (2016). An adaptable tillage depth monitoring system for tillage machine (一种自适应播种深度监测系统). *Biosystems Engineering*, Vol.151, pp. 187-199, China.

[9] Nielsen, S., Munkholm, L., La, E., (2018). Seed drill depth control system for precision seeding (用于精密播种的播种机深度控制系统). *Computers and Electronics in Agriculture*, Vol.144, pp.174-180, China.

[10] Romaneckas, K., Steponavicius, D., (2022). How to Analyze, Detect and Adjust Variable Seedbed Depth in Site-Specific Sowing Systems: A Case Study. *Agronomy-Basel*, Vol.12, pp. 5-8, Lithuania.

[11] Rao, AS., Mounika, S., (2023). Development of Low-cost Automatic Sowing Depth Measurement Unit for Groundnut Planter. *Agricultural mechanization in Asia, Africa and Latin America*, Vol.54, pp. 4-9, India.

[12] Suomi, Pasi., Oksanen, Timo., (2024). Automatic working depth control for seed drill using ISO 11783 remote control messages. *Computers and Electronics in Agriculture*, Vol.116, pp. 30-35, Germany.

[13] Wang C H., (2023). Research on Electrical Control System of planter based on PLC technology (基于 PLC 技术的播种机电气控制系统研究). *Agricultural Mechanization Research*, Vol.45, pp. 140-143, China.

[14] Xue, B., Zhou L., Niu, K., (2023). Research on fuzzy adaptive PID Control System for sowing depth of Wheat seed (小麦播种深度模糊自适应 PID 控制系统的研究). *Transactions of the Chinese Society for Agricultural Machinery*, Vol.12, pp. 42-49, China.

[15] Xu H W., (2023). Design of sowing depth control system for no-tillage seeder (免耕播种机播种深度控制系统设计). *Agricultural Machinery Use and Maintenance*, Vol.07, pp. 26-28, China.

[16] Zhang W., (2021). Application of PLC Technology in Electrical Control of Agricultural Machinery (PLC 技术在农机电气控制中的应用). *Modern Agricultural Machinery*, Vol.05, pp. 120-121, China.