DEVELOPMENT AND VALIDATION OF A SOWING QUALITY MONITORING SYSTEM FOR A PRECISION CORN PLANTER
/
玉米精量播种机播种作业质量监测系统开发与验证

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ABSTRACT

To address the problems of unstable sowing depth and poor system coordination in corn precision sowing operations, an integrated monitoring and control system was developed. The system achieves closed-loop control of sowing depth by applying controllable downward pressure via a hydraulic circuit, combined with feedback from pin-type pressure and angle sensors. A coupled cooperative controller (SPC-SFMC-X2214A) was implemented to connect the tractor and planter CAN networks, enabling navigation data parsing and fault linkage. A CODESYS-based interface was developed for real-time data visualization and parameter configuration. Field tests showed that at operating speeds of 6–10 km/h, the sowing control error remained ≤2.00%. The response time of the seeding rate was 0.85 s (for 90–225 kg/hm²), exceeding the design requirement of less than 1 s. The developed system provides an intelligent and adaptive solution for improving the quality of corn precision planting.

摘要

针对玉米精准播种中播种深度不稳定及系统协同性差的问题，研发了一套集成监测与控制系统。该系统通过液压回路施加可控下行压力，结合针式压力与角度传感器的反馈实现播种深度闭环控制。采用基于 SPC-SFMC-X2214A 的耦合协同控制器，实现拖拉机与播种机 CAN 网络的桥接，完成导航解析与故障联动。开发了基于 CODESYS 的界面用于实时数据可视化与参数设置。田间测试表明，在 6～10 km/h 行驶速度下，播种控制误差保持在≤2.00%。播种量响应时间达 0.85 s（90～225 kg/hm²范围），小于 1 秒的设计指标。该系统为提升玉米精准播种质量提供了智能自适应解决方案。

INTRODUCTION

As one of the world’s most important food crops, the planting efficiency and sowing quality of corn directly impact grain yield and agricultural production efficiency (*Liu et al., 2023; Sahu et al., 2021; Shi et al., 2023*). Traditional corn sowing operations largely rely on manual experience, leading to issues such as inconsistent sowing depth, uneven plant spacing, and missed or repeated sowing, which fail to meet the demands of modern agriculture for precision, intelligence, and efficiency (*Zhao et al., 2021; Chen et al., 2020; Kumar et al., 2021*). In China, corn is the most widely cultivated and highest-yielding grain crop, playing a crucial role in the agricultural production system. However, traditional corn sowing operations have long depended on manual labor and empirical judgment, resulting in uneven sowing depth, significant variations in plant spacing, frequent occurrences of missed or repeated sowing, and low operational efficiency (*Zhang et al., 2021; Xia et al., 2022; Karimi et al., 2022*). These issues not only result in the waste of seeds and fertilizers, thereby increasing production costs, but also significantly affect seedling uniformity, plant population structure, and ultimately the yield per unit area, becoming a major bottleneck that limits the full production potential of corn. Corn is sensitive to insufficient seeding depths, and the recommended seeding depth typically ranges from 4.4 to 6.3 cm (*Monsanto, 2009; Thomison et al., 2012*). Corn should not be planted at depths lower than 1.9 cm to ensure the development of a strong nodal root system, which provides structural support to the plant and increases resistance to drought stress (*Thomison et al., 2012*). Therefore, developing modern sowing technologies and equipment characterized by precision, efficiency, and intelligence, and achieving precise control and real-time quality monitoring of the sowing process, have become urgent needs and inevitable trends in promoting the modernization and intelligent transformation of corn production (*Yatskul et al., 2019; Zheng et al., 2021; Kocher et al., 2020; Zhai et al., 2022*).

The core of precision sowing lies in the precise control and real-time monitoring of key parameters such as sowing depth, plant spacing, and downward pressure. Currently, researchers worldwide have conducted a series of studies on the intelligentization of seeders (*Li et al., 2019; Maleki et al., 2020; Parihar et al., 2020*), focusing primarily on the following areas: optimization of the mechanical structure and drive control of seed metering devices, such as studying the working mechanisms of different types of seed metering devices to improve single-seed rates and sowing frequency stability through improved orifice design, optimized airflow fields, or the use of electric direct drives; navigation and autonomous driving technologies for seeders, which integrate Global Navigation Satellite Systems (GNSS) and Inertial Measurement Units (IMU) to achieve precise planning and tracking of sowing paths, reducing missed or overlapping sowing areas; variable-rate sowing control technology based on prescription maps, which adjusts seeding and fertilization rates in real time according to spatial variability in soil fertility and moisture; and monitoring of sowing depth and compaction pressure, typically using angle sensors, displacement sensors (*Li et al., 2022; Perez-Ruiz et al., 2012;Zhao et al., 2019*), or pressure sensors to indirectly or directly measure relevant parameters. While these studies have significantly improved the mechanization and automation of sowing operations, research on adaptive adjustment of sowing depth, multi-system cooperative control, and integrated monitoring of sowing quality remains relatively limited. Particularly under no-till sowing conditions, factors such as uneven soil texture and complex surface residues further increase the difficulty of sowing depth control, necessitating the development of intelligent monitoring systems integrating sensing, control, and decision-making *(Bochtis et al., 2014; Wang et al., 2023; Shi et al., 2019*).

To address these challenges, this study developed a sowing quality monitoring system based on the Zhongnongji 2BJ-470B corn no-till precision planter. The system integrates a sowing depth measurement and control system, a coupled cooperative controller, and a display terminal. It achieves adaptive adjustment of sowing depth through hydraulic servo control, uses multi-sensor fusion technology to collect key parameters such as downward pressure, compaction pressure, and sowing depth in real time, and enables information exchange and cooperative control with navigation and seed metering systems via CAN bus. Finally, the display terminal enables real-time monitoring, storage, and dynamic display of operational parameters. This study focuses on the structural design, control logic, software implementation, and experimental validation of the system, aiming to provide a feasible technical solution for the intelligent upgrading of precision corn planters and to offer theoretical and technical support for the promotion and application of precision agriculture and intelligent agricultural equipment.

MATERIALS AND METHODS

Design of the sowing depth measurement and control system

Components of the sowing depth measurement and control system

The hydraulic circuit of the sowing depth measurement and control system primarily consists of electromagnetic directional valves, proportional pressure-reducing valves, and hydraulic cylinders. The selection of hydraulic components is related to the required working pressure. Since the target downward pressure depends on various factors such as soil texture, moisture conditions, surface residue, terrain, and planter speed, and considering no-till sowing conditions, the target force range applied to the four-link profiling device in this study is set at 600–2000 N. A direct-acting proportional pressure-reducing valve from SUN Hydraulics was selected, with a pressure adjustment range of 0.7–7.75 MPa corresponding to a current control signal of 0–1150 mA. Considering the working pressure and stroke of the hydraulic cylinder, the cylinder's inner diameter was determined as 32 mm, piston rod diameter as 22 mm, cylinder length as 250 mm, and stroke as 150 mm, providing a downward force range of 562–6230 N, which meets the design requirements.

To achieve electro-hydraulic adaptive adjustment of sowing depth, pressure sensors and hydraulic cylinders were installed, and partial modifications were made to the sowing unit structure of the CAAMS 2BJ-470B corn no-till precision planter. The sowing unit structure is shown in Figure 1, consisting mainly of a downward pressure sensor, depth-limiting wheel, depth-limiting block, disc opener, downward pressure hydraulic cylinder, compaction wheel, compaction pressure sensor, spring, spring rod, and compaction hydraulic cylinder. As pin-type sensors have been widely used for detecting downward pressure in sowing units due to their reliability and adaptability, they were selected as the downward pressure and compaction pressure sensors. The LZ-HZ11-25 pin-type sensor from Hefei Lizhi Sensor System Co., Ltd. was used, with a range of 1000 kg and a comprehensive accuracy of 0.5%.

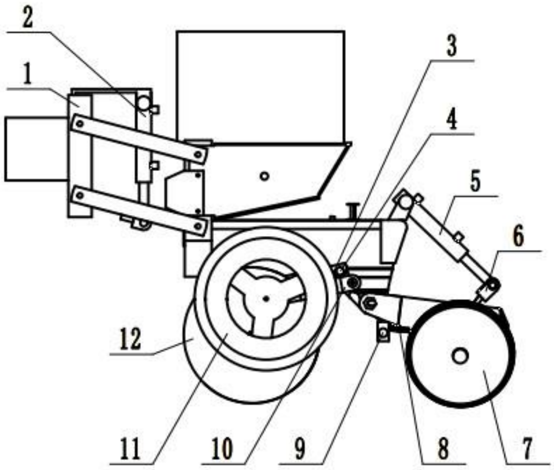

Fig. 1 - Structure diagram of the sowing unit

1.Frame; 2.Downward pressure hydraulic cylinder; 3.Depth-limiting block; 4.Downward pressure sensor; 5.Compaction hydraulic cylinder; 6.Spring rod; 7.Compaction wheel; 8.Spring; 9.Compaction pressure sensor; 10.Depth-limiting wheel arm; 11.Depth-limiting wheel; 12.Disc opener;

The installation method of the downward pressure sensor is shown in Figure 2. The sensor is mounted on the depth-limiting block mount. The depth-limiting block is provided with a mounting hole and is hinged to the downward pressure sensor, with a small clearance between the outer wall of the depth-limiting block and the inner wall of the mounting hole to allow relative movement. The depth-limiting wheel arm rotates around rotating shaft I and transmits force to the depth-limiting block. The downward pressure sensor measures the force acting between the wheel arm and the depth-limiting block, which represents the downward pressure applied to the depth-limiting wheel.

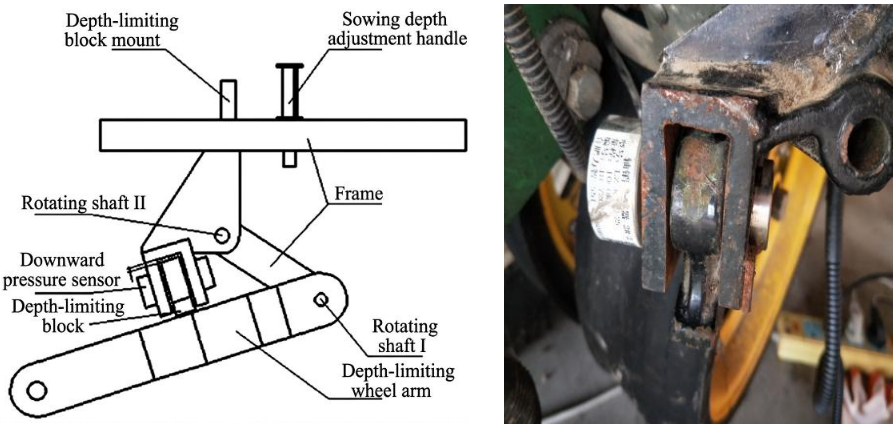

Fig. 2 - Schematic and physical diagram of downward pressure sensor installation

The installation method of the compaction hydraulic cylinder and compaction pressure sensor is shown in Figure 3.

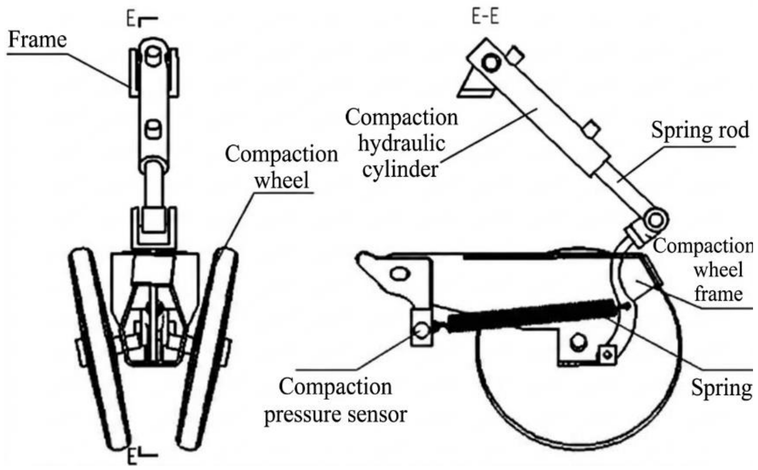

Fig. 3 - Schematic diagram of compaction pressure sensor installation

The compaction hydraulic cylinder is installed between the frame and the spring rod. The compaction pressure sensor is mounted on the frame, with one end of the spring connected to the compaction pressure sensor and the other end to the spring rod. Under the action of the compaction hydraulic cylinder, the spring rod can rotate around its hinge point with the compaction wheel frame, causing the spring to extend or retract. Thus, the compaction pressure sensor can measure the spring force, and based on the relationship between spring force and compaction pressure, it indirectly measures the compaction pressure.

The furrow depth is obtained by measuring the angle between the depth-limiting wheel arm and the horizontal plane. An angle sensor widely used in deep loosening operations by the Chinese Academy of Agricultural Machinery was installed on the depth-limiting wheel arm to measure the angle θ(rad) between the depth-limiting wheel arm and the horizontal plane in real time, as shown in Figure 4.

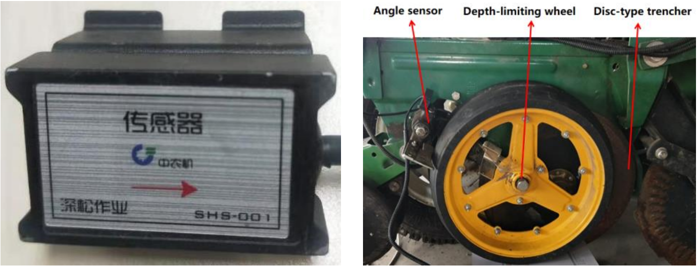

Fig. 4 - Physical diagram of angle sensor and installation

Program design of the sowing depth measurement and control system

The program of the sowing depth measurement and control system consists of a main program and subprograms for main circuit working state control, downward pressure control, and compaction pressure control. The main program calls the subprograms, and its flowchart is shown in Figure 5.

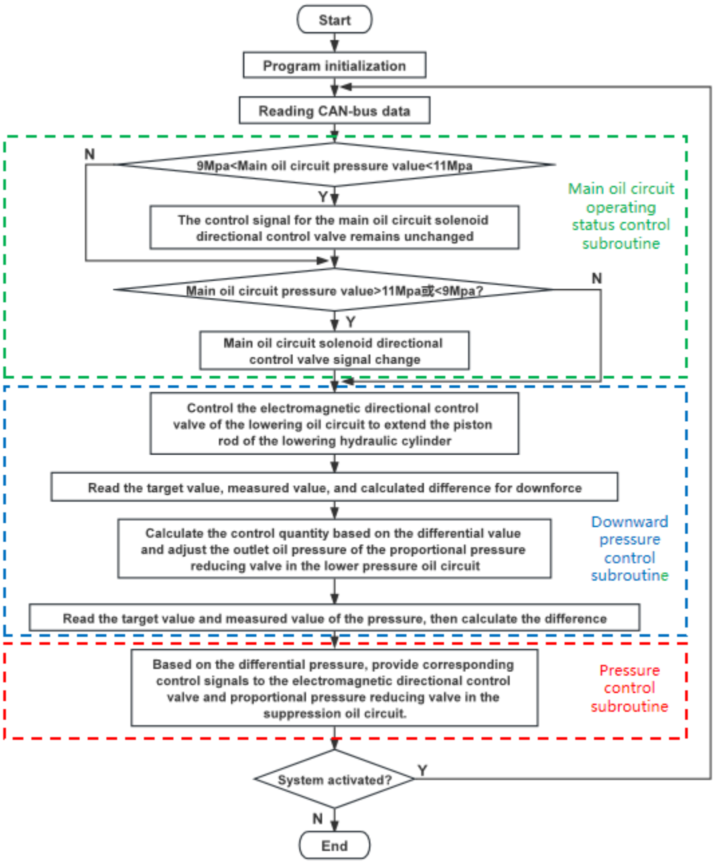

Fig. 5 - Flowchart of the sowing depth measurement and control system program

The main circuit working state control subprogram switches the main circuit between two working states by controlling the main circuit electromagnetic directional valve: State Ⅰ, where the hydraulic pump supplies oil to the main circuit and accumulator; and State Ⅱ, where the accumulator supplies oil to the main circuit, and the pressure oil returns directly to the tank via the main circuit electromagnetic directional valve. Switching between these two states allows the hydraulic pump to supply oil intermittently, reducing oil heating and ensuring the oil pressure remains within the 9–11 MPa range. The main circuit oil pressure is detected by an oil pressure sensor. When the oil pressure is within 9–11 MPa, the control signal of the main circuit electromagnetic directional valve remains unchanged. When the oil pressure is below 9 MPa, the main circuit is in State Ⅱ, and the signal is changed to switch the main circuit to State Ⅰ. When the oil pressure exceeds 11 MPa, the main circuit is in State Ⅰ, and the signal is changed to switch the main circuit to State Ⅱ.

The downward pressure control subprogram indirectly controls downward pressure by directly controlling the force applied by the downward pressure hydraulic cylinder to the four-link profiling device. During program execution, the downward pressure hydraulic cylinder piston rod is kept in the extended state by controlling the downward pressure circuit electromagnetic directional valve. The outlet oil pressure of the downward pressure circuit proportional pressure-reducing valve is controlled to adjust the force applied by the hydraulic cylinder to the four-link profiling device. Specifically, the target and measured downward pressure values are read, and their difference is calculated. Based on the control algorithm, the change in control corresponding to the difference is calculated, added to the current control value, and assigned to the proportional pressure-reducing valve to adjust its outlet oil pressure. This process is repeated to achieve downward pressure control.

The compaction pressure control subprogram indirectly controls compaction pressure by directly controlling the spring force via the compaction hydraulic cylinder. During program execution, the compaction hydraulic cylinder piston rod is controlled to extend, retract, or remain stationary by controlling the compaction circuit electromagnetic directional valve, while the pulling force of the hydraulic cylinder on the spring is controlled by adjusting the compaction circuit proportional pressure-reducing valve. Specifically, the target and measured compaction pressure values are read, and their difference is calculated. When the difference exceeds a set threshold and the measured value is greater than the target, the compaction circuit electromagnetic directional valve is controlled to retract the hydraulic cylinder piston rod, with zero current supplied to the proportional pressure-reducing valve, causing the spring to retract. When the difference is within the threshold range, the hydraulic cylinder piston rod is kept stationary, with zero current supplied to the proportional pressure-reducing valve to maintain spring length. When the difference exceeds the threshold and the measured value is less than the target, the hydraulic cylinder piston rod is extended, and a calibrated current of 500 mA is supplied to the proportional pressure-reducing valve to pull the spring at an appropriate speed. This process is repeated to achieve compaction pressure control.

Design of the coupled cooperative controller

Working principle of the coupled cooperative controller

The working principle of the coupled cooperative controller is shown in Figure 6. The controller serves as a protocol conversion and cooperative interaction hub between the CAN communication network of the unmanned tractor and the CAN network of the sowing robot, enabling integrated decision-making and cooperative control between the robot's execution device and the power unit. The controller first communicates with the unmanned navigation control ECU to collect tractor navigation messages for determining the current position and working status of the sowing robot. It then outputs hydraulic valve control signals and tractor start/stop/brake signals to the tractor ECU to control the lifting/lowering hydraulic circuit of the ground wheel and the sowing depth control hydraulic circuit, as well as the forward movement and braking of the tractor. An inclination sensor collects the tilt angle of the ground wheel hydraulic cylinder to determine its lifting/lowering state and converts the angle signal into a 4–20 mA current signal for transmission to the coupled cooperative controller. The controller also communicates with the seed metering control ECU. When a seed metering fault occurs, the seed metering control ECU sends an alarm signal to the coupled cooperative controller to interrupt the current sowing task and initiate rapid braking.

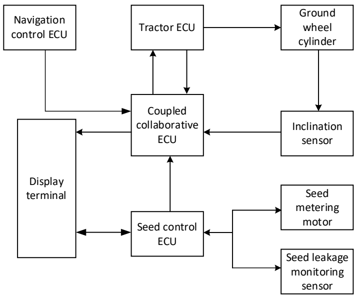

Fig. 6 - Working principle diagram of the coupled cooperative controller

Design of the display terminal system

The display terminal of the sowing robot variable measurement and control system was developed based on the CODESYS platform and installed on the upper computer of the sowing robot. The software program follows modular and structured design principles. The system software is primarily responsible for collecting and displaying the operational status information of the planter, real-time acquisition of GPS positioning information, variable control of sowing and fertilization, and real-time storage and processing of system data. The software functions mainly include a data acquisition module, a data storage and display module, and a parameter configuration module. Data acquisition and control are key components of the corn planter variable measurement and control system software, primarily responsible for collecting various data such as sowing quality, seed/fertilizer box levels, and GPS information. The communication methods between the system's external devices and the interactive terminal mainly include RS232 serial communication and CAN bus communication. The main control interface of the sowing robot variable measurement and control system is shown in Figure 7. The displayed values on the main control interface include Beidou navigation position information, sowing depth, downward pressure, and planter operational parameters (travel speed, seed/fertilizer box level status, etc.). The system software also saves all information for subsequent analysis and processing.

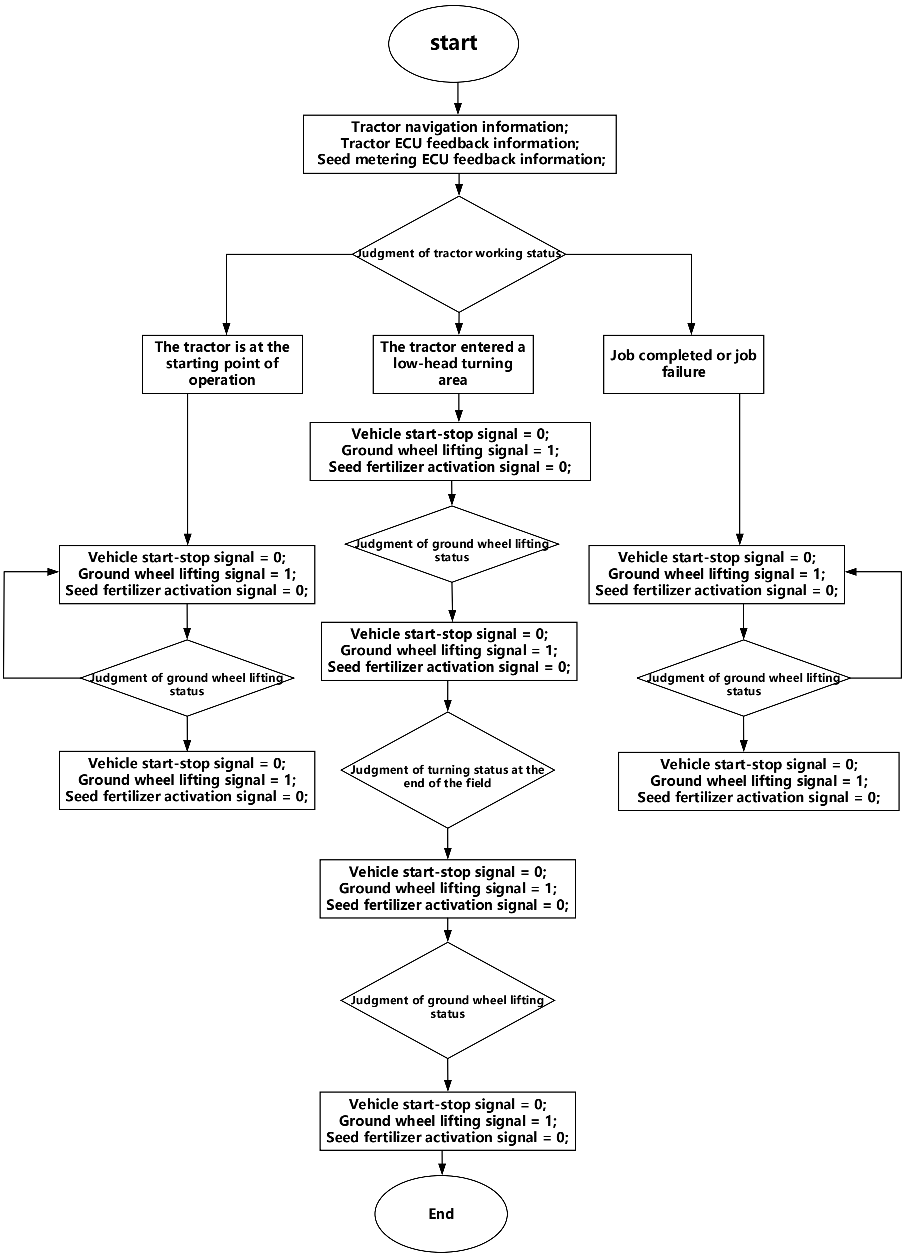

Fig. 7 - Flowchart of the coupled cooperative controller program

Design of the display terminal system

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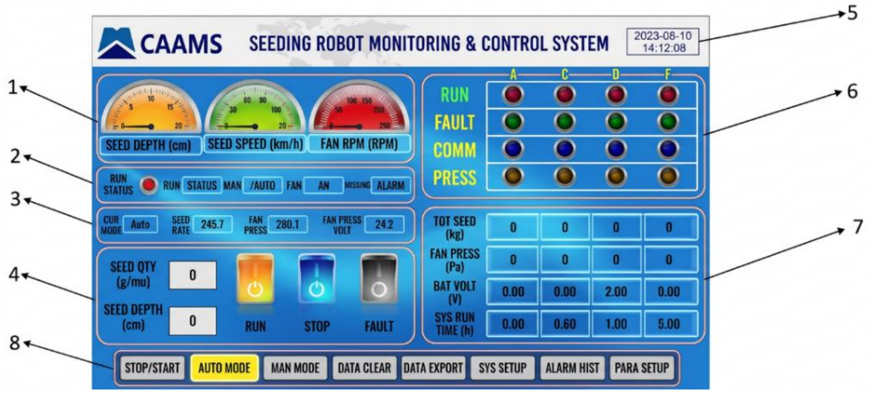

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CUR MODE Auto SEED RATE 245.7 FAN PRESS 280.1 FAN PRESS VOLT 24.2

SEED QTY (g/mu) 0

SEED DEPTH (cm) 0

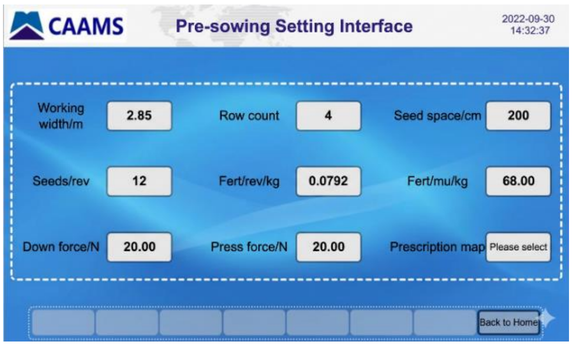
	A	C	D	F
TOT SEED (kg)	0	0	0	0
FAN PRESS (Pa)	0	0	0	0
BAT VOLT (V)	0.00	0.00	2.00	0.00
SYS RUN TIME (h)	0.00	0.60	1.00	5.00

Fig. 8 - Main control interface of the sowing robot variable measurement and control system

1.Speed/rotation speed feedback display area; 2.Beidou navigation information display area; 3.Pre-sowing parameter display area; 4.Manual setting area for operational parameters; 5.Time information display area; 6.Alarm information display area; 7.Sowing depth/downward pressure information display area; 8.System parameter setting area;

Pre-sowing parameter setting interface

As shown in Figure 9, the pre-sowing parameter setting interface primarily allows pre-setting of important parameters before sowing operations, including working width, number of rows, seed spacing, number of seeds per revolution, fertilizer amount per revolution, fertilizer application rate per mu, preset downward pressure, preset compaction pressure, and selection of operational prescription maps. After setting the pre-sowing parameters, clicking the "Return to Main Interface" button switches back to the main control interface.



2022-09-30 14:32:37

Working width/m 2.85 Row count 4 Seed space/cm 200

Seeds/rev 12 Fert/rev/kg 0.0792 Fert/mu/kg 68.00

Down force/N 20.00 Press force/N 20.00 Prescription map Please select

Fig. 9 - Parameter setting interface

Seed/fertilizer dynamic display interface

As shown in Figure 10, the seed/fertilizer dynamic display interface primarily displays real-time trends in seed metering and fertilizer application rotation speeds via line charts during sowing operations. Clicking the "Return to Main Interface" button switches back to the main control interface. Clicking button 6 in the system parameter setting area of the main interface opens the sowing depth dynamic display interface, which displays real-time trends in sowing depth and downward pressure via line charts during sowing operations. Clicking the "Return to Main Interface" button switches back to the main control interface.

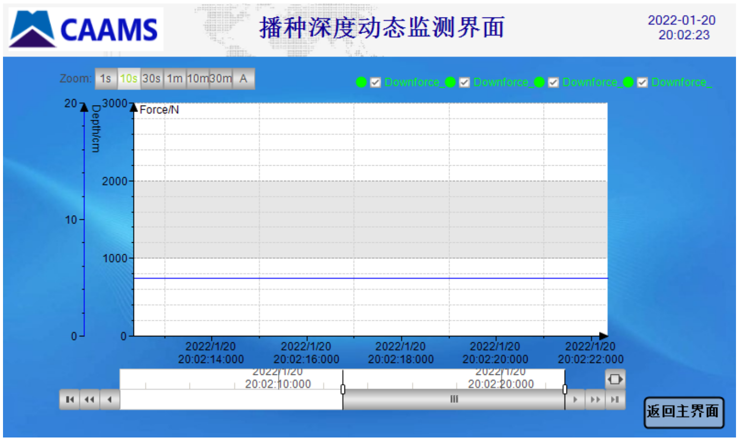


Fig. 10 - Seed/fertilizer dynamic display interface

Sowing operation control accuracy test

Test purpose

The field experiment is shown in Figure 11. To verify whether the sowing operation control error of the sowing robot variable measurement and control system meets the design requirements, the test aimed to statistically analyze the difference between the number of seeds dropped after rotating the same number of revolutions under different set plant spacings and the target value.

Fig. 11 - Field experiment of sowing operation control accuracy

Test method

The seed metering device drive motor was set to position control mode. The electric seed metering device was controlled to rotate 50 revolutions under low-speed (6 km/h), medium-speed (8 km/h), and high-speed (10 km/h) conditions. The number of seeds dropped was manually counted, and the test was repeated five times.

Test results

The results of the sowing operation control accuracy test are shown in Table 1.

Table 1

Sowing operation control accuracy test data

Test No.	Forward speed (km/h)	Target seed count	Actual seed count	Difference	Sowing control error
1	6	600	591	9	1.33%
2	6	600	609	9	
3	6	600	608	8	
4	6	600	593	7	
5	6	600	607	7	
6	8	600	610	10	1.23%
7	8	600	605	5	
8	8	600	591	9	

Test No.	Forward speed (km/h)	Target seed count	Actual seed count	Difference	Sowing control error
9	8	600	605	5	
10	8	600	608	8	
11	10	600	608	8	2.00%
12	10	600	588	12	
13	10	600	604	11	
14	10	600	594	9	
15	10	600	590	14	

The test results show that the sowing control error was smallest at 8 km/h (1.23%) and largest at 10 km/h (2.00%). Thus, the optimal operating speed for the sowing robot is 8 km/h. The sowing control errors at 6 km/h, 8 km/h, and 10 km/h were all below 3%, with the maximum error not exceeding 2.00%, meeting the design requirements.

Seeding rate response time test

Test purpose

Electric seed metering devices have a certain response time, referring to the delay between the actuator receiving a signal and the change in drive motor speed. The response time of the actuator has a minor impact when the planter operates at a constant speed, but it reduces sowing accuracy during acceleration and deceleration. During acceleration, the axial motion of the motor lags behind the machine’s movement, increasing missed sowing rates. During deceleration, the motor’s response time leads to repeated sowing, reducing sowing accuracy [46]. Therefore, analyzing and validating the response time is important for optimizing control algorithms and improving sowing accuracy. For this purpose, a seeding rate response time test was conducted on the sowing robot variable measurement and control system.

Test method

(1) Set the preset seeding rate to the minimum value of 90 kg/hm², start the control system, gradually adjust the seeding rate to the maximum value of 225 kg/hm², time the adjustment process with a stopwatch, and repeat the test three times.

(2) Set the preset seeding rate to the maximum value of 225 kg/hm², start the control system, gradually adjust the seeding rate to the minimum value of 90 kg/hm², time the adjustment process with a stopwatch, and repeat the test three times.

(3) Take the longest adjustment time among the six trials as the seeding rate adjustment response time.

(4) Calculate the seeding rate adjustment response time using Equation (1):

$$t_{\text{response}} = t_{\text{measured}} \tag{1}$$

where:

t_{response} = seeding rate adjustment response time (seconds, s);

t_{measured} = measured seeding rate adjustment time (seconds, s).

Test Results

The seeding rate response time test results are shown in Table 2.

Table 2

Seeding rate response time test data

Test No.	Seeding rate adjustment range (kg/hm²)	Adjustment time (s)	System response time (s)
1	90~225	0.78	0.85
2	90~225	0.82	
3	90~225	0.79	
4	90~225	0.83	
5	90~225	0.86	
6	90~225	0.81	
7	90~225	0.92	
8	225~90	0.85	
9	225~90	0.84	
10	225~90	0.91	

Test No.	Seeding rate adjustment range (kg/hm²)	Adjustment time (s)	System response time (s)
11	225~90	0.82	
12	225~90	0.93	
13	225~90	0.81	
14	225~90	0.83	

The test results show that the seeding rate response time after adopting electric seed metering control was 0.85 seconds, meeting the design requirement (<1 second).

CONCLUSIONS

(1) Closed-loop adaptive adjustment of sowing depth was achieved. Based on an electro-hydraulic servo system composed of a hydraulic proportional pressure-reducing valve and hydraulic cylinder, combined with real-time feedback from pin-type pressure sensors and angle sensors, the system dynamically adjusts the downward pressure applied to the four-link profiling device of the sowing unit according to soil conditions. This effectively overcomes fluctuations in sowing depth caused by uneven surfaces under no-till conditions, significantly improving the consistency and stability of sowing depth.

(2) The developed coupled cooperative controller effectively achieved cross-platform intelligent coordination. The cooperative control hub, based on the SPC-SFMC-X2214A controller, successfully bridged the CAN network of the unmanned tractor and the planter's CAN network. It enabled efficient information exchange and coordinated decision-making among multiple systems, including navigation command parsing, precise control of hydraulic valve groups, and fault alarm linkage, enhancing the intelligence and automation of the entire sowing operation system.

(3) Field experiments validated the system's high control accuracy and rapid response capability. Sowing operation control accuracy tests showed that at forward speeds of 6 km/h, 8 km/h, and 10 km/h, the maximum sowing control error was only 2.00%, meeting the design requirement (<3%), with the best performance at medium speed (8 km/h, error 1.23%). Seeding rate response time tests indicated that the system's adjustment response time within the range of 90–225 kg/hm² was only 0.85 seconds, surpassing the design target of 1 second. This demonstrates the system's rapid execution of commands, which helps reduce missed and repeated sowing during start-stop processes. The validation was performed under the tested field conditions and speeds up to 10 km/h. Further tests are required for other soil types and higher speeds.

ACKNOWLEDGEMENT

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