DEVELOPMENT AND TESTING OF A VARIABLE-RATE SEEDING MONITORING AND CONTROL SYSTEM FOR UNMANNED TRACTOR-TOWED SEEDING MACHINES / 无人牵引式播种机变量播种测控系统开发与试验

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ABSTRACT

Aiming at the problems of poor seed distribution uniformity and low sowing accuracy in traditional sowing operations, this paper studies and develops a variable-rate monitoring and control technology system based on an unmanned tractor-towed seeding machine. The system adopts a distributed controller architecture, including a cooperative control ECU, a seed-metering monitoring and control ECU, and a sowing depth monitoring and control ECU, achieving multi-source information interaction and cooperative decision-making through a CAN bus. In terms of hardware, the seed-metering device's electric drive scheme has been improved by replacing the original split-type chain transmission scheme with an integrated torque servo motor, enhancing the system integration and transmission efficiency. Field test results show that the optimized electric drive seed-metering device, at forward speeds of 4 km/h, 8 km/h, and 12 km/h, outperforms the traditional ground wheel-driven method in terms of seed spacing qualification index, standard deviation, and coefficient of variation. Especially under the medium-speed condition of 8 km/h, the performance is optimal, with the coefficient of variation as low as 6.45%. The system demonstrates good robustness and adaptability in complex field environments, providing reliable technical support for achieving precise, efficient, and intelligent sowing operations.

摘要

本文针对传统播种作业方式存在的种子分布均匀性差、播种精度低等问题，研究开发了一种基于播种机器人的变量测控技术系统。系统采用分布式控制器架构，包括协同控制ECU、排种测控ECU和播深测控ECU，通过CAN 总线实现多源信息交互与协同决策。硬件方面，改进了排种器电驱方案，采用一体式力矩伺服电机替代原分体式链传动方案，提升了系统集成度与传动效率。田间试验结果表明，优化后的电驱排种器在 4 km/h、8 km/h 和12 km/h 前进速度下，播种粒距合格指数、标准差和变异系数均优于传统地轮驱动方式，尤其在8 km/h 中速条件下性能最优，变异系数低至 6.45%。系统在复杂田间环境下表现出良好的鲁棒性与适应性，为实现精准、高效、智能化的播种作业提供了可靠的技术支撑。

INTRODUCTION

In the critical transition period of modern agriculture towards precision and intelligence, traditional sowing methods are facing severe challenges. Relying on manual experience or equipment with a low degree of mechanization for sowing commonly leads to issues such as poor seed distribution uniformity, inconsistent sowing depth, and inadequate control over row and plant spacing accuracy (*Wang et al., 2024, Qian et al., 2025*). This not only results in low utilization rates of agricultural resources like seeds and fertilizers but also directly affects seedling emergence, crop uniformity, and final yield. With the continuous growth of the global population and the increasing scarcity of arable land, developing intelligent agricultural machinery that can significantly enhance production efficiency and resource utilization has become an urgent need to ensure food security and sustainable agricultural development (*Xu et al., 2023, Zhang et al., 2024*).

As a cutting-edge representative of intelligent agricultural equipment, the core function of the unmanned tractor-towed seeding machine lies in replacing or assisting human labour to autonomously, precisely, and efficiently complete sowing operations (*Jia et al., 2024, Ding et al., 2024, Chang et al., 2025*). The key to achieving this advanced capability is its variable rate monitoring and control system. This system is a closed-loop control system integrating perception, decision-making, and execution, with technical connotations that far surpass the mechanical furrowing and seed metering of traditional seeders (*Rong et al., 2020, Qiu et al., 2018*). By integrating various advanced sensors, it acquires variable information of the operating environment in real-time and dynamically, such as soil moisture, compaction, spatial variability in fertility, as well as the machine's own posture, speed, and seed metering status. Subsequently, based on built-in agricultural models and decision algorithms, it processes and intelligently analyses these multi-source heterogeneous data to generate variable operation instructions tailored to the local environment (*Albasheer et al., 2025, Tang et al., 2024*). Finally, through highly responsive electro-hydraulic or motor-driven mechanisms, it achieves measurement and control—precise measurement and closed-loop control—of end actuators such as the seed meter, furrow opener, and soil covering and pressing devices, thereby accomplishing complex tasks such as on-demand seeding, variable depth sowing, and obstacle avoidance. Therefore, the performance of the unmanned tractor-towed seeding machine's variable rate monitoring and control system directly determines the precision, adaptability, and reliability of the sowing operation and represents a concentrated manifestation of the robot's level of intelligence (*Li et al., 2024, Tang et al., 2023*).

At present, although significant progress has been made domestically and internationally in agricultural robotics and precision seeding technology, the variable rate monitoring and control system for unmanned tractor-towed seeding machines operating in complex, unstructured field environments still faces a series of core technical challenges. At the perception level, achieving reliable fusion of multiple sensors and high-precision information acquisition under harsh working conditions is a major difficulty (*Deng et al., 2024, Wang et al., 2024, Zhang et al., 2021, Zhang et al., 2024*). At the decision-making level, constructing general or self-learning intelligent decision models that adapt to different crops and field conditions requires further breakthroughs. At the execution level, achieving high-precision control and rapid response for small seed metering quantities under high-speed and vibratory conditions remains an urgent issue to be solved. These challenges constrain the transition of unmanned tractor-towed seeding machines from laboratory prototypes to large-scale industrial application (*Qian et al., 2025, Jing et al., 2016*).

This research aims to systematically conduct design and optimization studies on the variable rate monitoring and control system for unmanned tractor-towed seeding machines in response to the aforementioned challenges. By innovating sensor configurations and data fusion methods to enhance the robustness and accuracy of environmental perception, constructing intelligent decision models based on multi-source information and agronomic knowledge to achieve dynamic optimization of sowing parameters, and designing high-precision, fast-responding electric drive seed metering and depth adjustment actuators, the expected outcomes of this research will provide core technical support for the independent research and development of high-performance unmanned tractor-towed seeding machines. This holds significant theoretical value and practical importance for promoting the intelligent upgrading of China's agricultural equipment.

MATERIALS AND METHODS

Control requirement analysis for unmanned tractor-towed seeding machines

The variable control system of an unmanned tractor-towed seeding machine is primarily used for the acquisition of various operational parameters of the sowing execution body, precise control of seed spacing and sowing depth, and interactive decision-making based on the synergy between operational parameters and tractor information. The entire system should include a data acquisition unit, an electric drive control unit, a collaborative decision-making unit, and an information display unit. The data acquisition unit is responsible for collecting various information, such as seeding volume, forward speed, position, seed box material level, body downforce, and cylinder status, and transmitting this data via the CAN bus. The electric drive control unit must be capable of implementing electric drive control for multiple seed meters, including DC motors and drive control, and this unit should also support CAN bus communication. The collaborative decision-making unit must enable information exchange with the power body based on standard bus protocols, while also undertaking collaborative operation decisions based on data information and sharing decision commands with the power unit and the execution body.

The information display unit is used for the visual presentation of various information and human-machine interactive parameter settings, and it should also support bus communication.

To meet the collaborative control requirements between the sowing execution body and the power body, operational parameter information such as sowing volume, seed box material level, and seed shaft speed, as well as position and posture information, are first acquired. Based on this information, the operational status of the seeder is identified for decision-making, with the coordinated lifting and lowering of the trailed sowing body set as the control objective. Based on multi-source decisions regarding the operational status, the desired action for body lifting and lowering is accurately predicted, and commands are sent to the power body. The power body then drives the lifting and lowering of the sowing body via electro-hydraulic control to achieve the goal of coordinated movement.

Overall design of the variable monitoring and control system for unmanned tractor-towed seeding machines

The variable monitoring and control system for unmanned tractor-towed seeding machines is primarily used for acquiring various operational parameters of the unmanned tractor-towed seeding machine's execution body, precise control of seed spacing and sowing depth, and interactive decision-making based on the synergy between operational parameters and tractor information. The entire system should include three distributed controllers—a coupled cooperative control ECU, a seeding monitoring and control ECU, and a sowing depth monitoring and control ECU—along with an upper computer. Among them, the coupled cooperative control ECU is mainly used for cooperative interaction and decision analysis between the tractor and the seeding machine's control units. The seeding monitoring and control ECU is mainly responsible for collecting information such as the speed of the seeding machine, the material level in the seed box, and the status of missed sowing, as well as the electric drive control of the seed metering device. The sowing depth monitoring and control ECU is primarily used for measuring parameters such as sowing depth and hydraulic circuit pressure, and for controlling the downforce cylinder and the compacting force cylinder. The upper computer is used for the visual display of various types of information and human-machine interactive parameter settings, and it should also support bus communication. The structure of the variable monitoring and control system for the unmanned tractor-towed seeding machine is shown in Fig. 1.

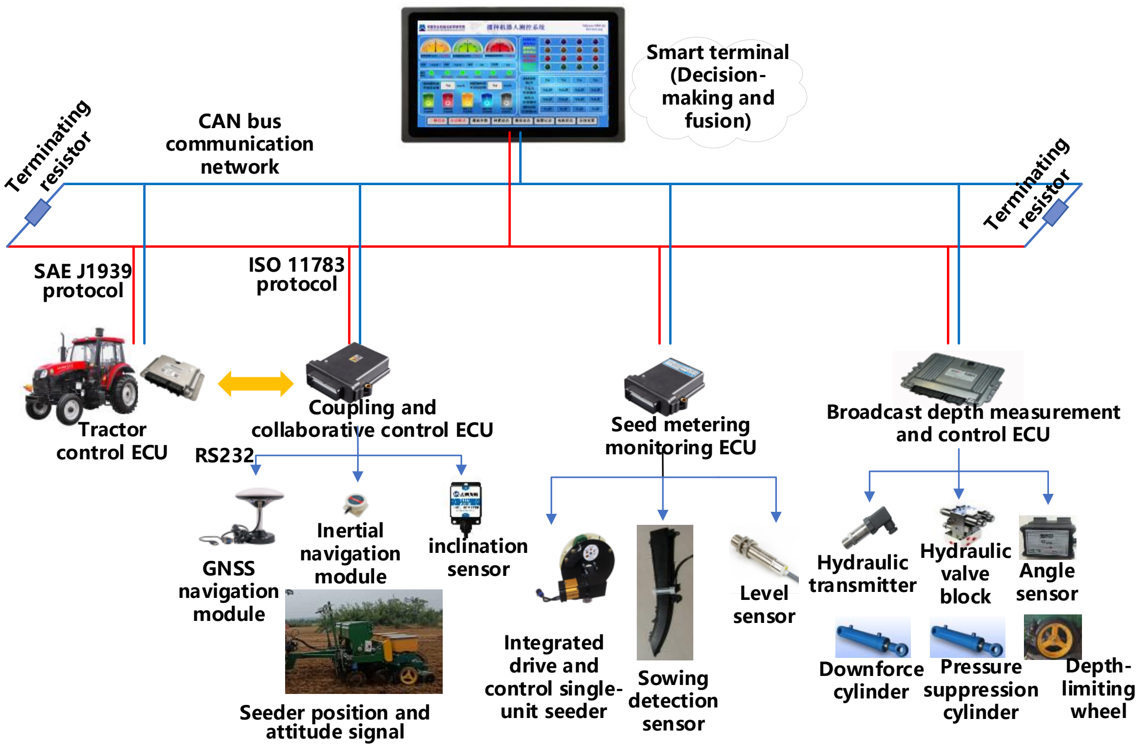

Fig. 1 - Variable monitoring and control system of the unmanned tractor-towed seeding machine

Hardware of variable measurement and control system for unmanned tractor-towed seeding machines

The host computer of the variable measurement and control system for the unmanned tractor-towed seeding machine adopts the 7-inch capacitive touch display SPD-070-AVTG-K from Sonnepower Electronics, as shown in Fig. 2. This display is based on a CortexA7 high-performance MCU as its core, integrating storage, communication, display, and input/output modules. It offers good compatibility and scalability, facilitating operation and maintenance. At the same time, it can effectively meet the needs of multi-source data acquisition and storage, operation process monitoring, and information analysis and decision-making during precision agricultural field operations. The terminal integrates a GPS positioning module, CAN bus module, and DTU unit. This display supports Codesys 3.5 programming; it supports wide voltage input, with an input range of 8~32 V; all ports support misconnected power and ground, and the output ports have short circuit and overheat protection; it features 2 CAN buses, 1 RS232 (or RS485 (hardware optional)) serial communication, 1 USB2.0 OTG, 1 Ethernet (dedicated for program debugging and downloading), 2 CVBS videos, and 6 IO resources; all output ports have open circuit detection function, facilitating fault diagnosis, and it possesses advantages such as high protection level and compact and flexible port resources.

Fig. 2 - SPD－070－AVTG-K display screen

Table 1

SPD-070-AVTG-K Hardware Parameters

Item	Description
Operating voltage	DC 8–32V wide voltage input
Processor	Cortex-A7 high-performance MCU
Display type & size	7-inch 24-bit colour screen
Positioning function	Supports GPS/GLONASS/BeiDou/Galileo/QZSS
Connector	26-Pin AMP
Input/Output channels / Total IO	6 / 2 / 6
Number of programmable Keys	8
CAN communication Port 1/2	CAN 2.0A/B
Baud rate	20 kbits/s ... 1 Mbits/s (default setting: 125 kbits/s)
4G communication	Supported Bands: • LTE FDD: B1/B3/B8 • LTE TDD: B38/B39/B40/B41 • TD-SCDMA: B34/B39 • WCDMA: B1/B8 • GSM: 900/1800

Speed measurement module design

The speed measurement module mainly consists of a speed signal acquisition board, a Hall speed sensor, and a sensor bracket, as shown in Fig. 3 (a). A Hall speed sensor is installed on the sensor bracket, with the sensor aligned to the gear teeth.

When the ground wheel rotates, the sensor captures the pulse signals generated as the gear teeth pass by. The pulse output terminal of the sensor is connected to the speed signal acquisition board, which calculates the ground wheel rotation speed based on the frequency of the pulse signals from the sensor and transmits this ground wheel speed information to the vehicle-mounted terminal. The sensor used is the NJK-5002C from Zhejiang Odilon Electronics Technology Co., Ltd., and its installation position is shown in Fig. 3(b).

Fig. 3 - Vehicle speed detection module based on hall sensor
a) Sensor installation diagram b) Sensor installation method c) Hall sensor

The Hall speed measurement module is primarily used to detect the forward speed of the unmanned tractor-towed seeding machine. The module's speed signal acquisition board counts and calculates pulses to determine the traveling speed of the unmanned tractor-towed seeding machine. The speed of the unmanned tractor-towed seeding machine is then transmitted via the CAN bus to the upper computer.

Improvement of the electric drive solution for the seed-metering device

This study employs a split-type electric drive solution consisting of "motor + reducer + chain transmission + seed-metering device," which presents issues such as poor integration and low transmission efficiency. The motor used is the BG45×15SI integrated drive-control DC brushless motor from the German company Dunkermotoren, serving as the drive motor for the seed-metering device, as shown in Fig. 4. This motor features an integrated drive circuit and uses a DC analogue voltage signal to dynamically adjust the motor speed, with a signal range of 0–10 V. The motor has an output power of 52.5 W, operates at DC 12 V, achieves a maximum speed of 3080 rpm, and is equipped with a PLG52 planetary reducer with a reduction ratio of 50. However, this solution can only control the motor speed via 0–10 V analogue signals, necessitating the additional configuration of an analogue output module, C-3402, as shown in Fig. 4. Furthermore, this motor does not support CAN bus communication, preventing real-time feedback of motor speed.

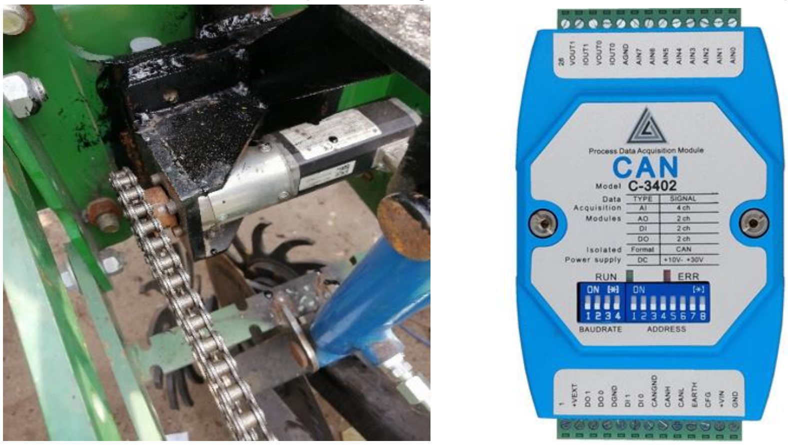

Fig. 4 - Split-type electric drive solution
a) Brushless DC motor type BG45×15SI; b) CAN analogue output module

In order to enhance the integration of the seed-metering device's electric drive system and simplify its transmission scheme, an integrated electric drive solution of "motor + right-angle reducer + seed-metering device" has been proposed. The motor and the right-angle reducer are directly assembled on one end face of the output shaft of the seed-metering device. The motor drives the seed-metering device directly after passing through the reducer, eliminating the chain transmission structure and significantly improving transmission efficiency. For this solution, the drive motor selected is the integrated torque servo motor 57AIM30L, which features an internally integrated driver and supports CAN bus communication. The motor parameters are shown in Table 2.

Table 2

57AIM30L motor parameters

Item	Description
Operating voltage	24–36 VDC
Rated current	4.4 A
Rated speed	1000 RPM
Maximum speed	1500 RPM
Rated power	100 W
Rated torque	0.96 N·m
Feedback signal	Multi-turn absolute encoder (32,768 pulses per revolution, 15-bit per revolution)
Communication interface	EasyCAN (CAN communication, 1 Mbps)

Considering the lateral installation space issue of the seed metering device, a 57 right-angle gear reducer with a speed ratio of 10 was selected. The maximum speed of the motor after being decelerated by the gear reducer is 100 RPM, and the rated torque is 9.8 Nm, which meets the operational requirements of the finger-clamping seed metering device. The assembled integrated electric-driven seed metering device is shown in Fig. 5.

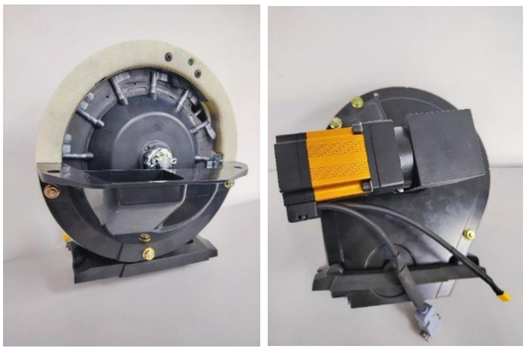

Fig. 5 - Integrated electric drive seed metering device

Precision control test of seed spacing

Test objective

To verify the effectiveness of the control scheme for the electrically driven seed metering device of the unmanned tractor-towed seeding machine, and to confirm through field trials that the electrically driven seed metering device can reliably perform the seeding function. The qualified index of seed spacing, standard deviation, and coefficient of variation were selected as test indicators. With seeding qualification rate as the target, the test aimed to evaluate the seeding qualification index, response time, and reliability of the variable-rate measurement and control system of the unmanned tractor-towed seeding machine at different forward speeds. Under identical conditions, a comparison was made between the seeding qualification rates of the integrated electrically driven seed metering device and the mechanically driven seed metering device. As shown in Fig. 6, at the field test site.

Fig. 6 - Experimental prototype of unmanned tractor-towed seeding machine

Test materials and equipment

Test Material: Zhengdan 958 maize seeds. Specifications: 6000 seeds per bag, moisture content 12.8%. Seed size range: long axis 11.00-12.50 mm, short axis 6.00-7.50 mm. Angle of repose: 23.2°. Sowing can be conducted under atmospheric temperature of 19-23°C and soil temperature of 17-22°C. The agricultural machinery operation parameters are shown in Table 3.

Test Time: April 28 to May 4, 2025.

Test Site: Mengjin Test Field of Yituo Group, Luoyang City, Henan Province.

Table 3

Technical parameters of the unmanned tractor-towed seeding machine

Item	Unit	Parameter
Matched power	kW	66.15
Structural mass	kg	1700
Dimensions (L×W×H)	mm	3920×4450×2125 (Transport mode)
Row spacing	mm	700
Number of working rows	rows	4
Working width	cm	280
Seed metering device type	/	Finger-pickup type
Number of seed meters	unit	4
Number of fertilizer applicators	unit	4
Transmission mechanism type	/	Chain drive
Furrow opener type		Double disc (seeding), Single disc (fertilization)
Anti-clogging component type	/	Corrugated disc

Test method

Relatively flat and loose plots were selected as the test fields. The total length of each test area was approximately 120 m, with a 20 m buffer zone arranged at both the start and end for tractor acceleration and deceleration. During the test, after the tractor speed reached and stabilized at the preset value, the start button on the human-computer interaction interface was pressed. The seed metering device then started to work, and the seed feeding device supplied seeds simultaneously. After sowing, the sown seeds were manually excavated. The plant spacing was measured by a tape measure, and no fewer than 30 seeds were recorded. Each speed level test was repeated three times to reduce random errors. The qualified seeding rate, missing seeding rate and multiple seeding rate were calculated accordingly.

According to the "Test Method for Single-seed (Precision) Seeders" (GB/T 6973-2005), the qualified index of seed spacing, standard deviation, and coefficient of variation were selected as test indicators for the field trial of the electrically driven seed metering device. During statistics, a seed spacing greater than 1.5 times the theoretical spacing is recorded as a miss. If the distance between two seeds is less than 0.5 times the theoretical spacing, it is termed a double drop. For this test, the target plant spacing was set at 25 cm. During counting, a seeding spacing (L) between 12.5 cm and 37.5 cm is considered qualified.

The test primarily aimed to examine the seeding qualification rate of the electrically driven seed metering device at different operating speeds. The average plant spacing $\bar{L}$, standard deviation S, and coefficient of variation V were selected as three parameters to evaluate seeder performance. The formulas used to calculate these indicators are as follows:

(1) Average Seeding Spacing $\bar{L}$: The average distance between seeds.

$$\bar{L} = \frac{1}{n}\sum_{i=1}^{n} L_i \tag{1}$$

(2) Standard Deviation S: The square root of the average of the squared differences between individual seeding spacings and the average seeding spacing during seeder operation. This parameter reflects the dispersion of seeding quality.

$$S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(L_i - \bar{L})^2} \tag{2}$$

(3) Coefficient of Variation $\boldsymbol{V}$: The ratio of the standard deviation of seeding spacing to the average seeding spacing.

$$V = \frac{S}{\bar{L}} \times 100\% \tag{3}$$

Test results

(1) When the forward speed was 4 km/h and the target plant spacing was 25 cm, the distribution of seeding spacings is shown in Fig. 7, and the test results are presented in Table 4.

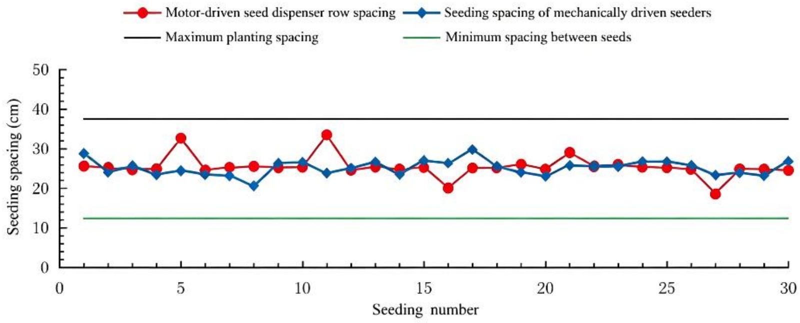

Fig. 7- Seeding spacing distribution at 4 km/h forward speed

Table 4

Test data at 4 km/h forward speed

Statistical parameter	Ground wheel driven meter	Electrically driven meter
Maximum plant spacing (cm)	31.2	29.5
Minimum plant spacing (cm)	18.9	19.2
Average plant spacing $\bar{L}$ (cm)	25.4	25.2
Standard deviation S (cm)	2.105	1.782
Coefficient of variation V	8.23%	6.46%

(2) When the forward speed was 8 km/h and the target plant spacing was 25 cm, the distribution of seeding spacings is shown in Fig. 8, and the test results are presented in Table 5.

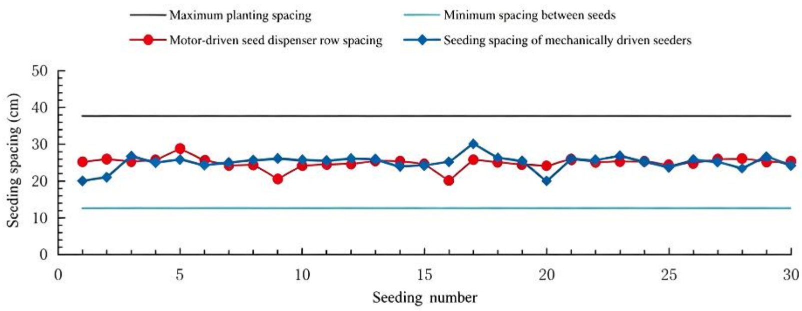

Fig. 8- Seeding spacing distribution at 8 km/h forward speed

Table 5

Test data at 8 km/h forward speed

Statistical parameter	Ground wheel driven meter	Electrically driven meter
Maximum plant spacing (cm)	31.8	29.8
Minimum plant spacing (cm)	18.7	19.6
Average plant spacing $\bar{L}$ (cm)	25.5	25.3
Standard deviation S (cm)	2.203	1.864
Coefficient of variation V	8.75%	6.45%

(3) When the forward speed was 12 km/h and the target plant spacing was 25 cm, the distribution of seeding spacings is shown in Fig. 9, and the test results are presented in Table 6.

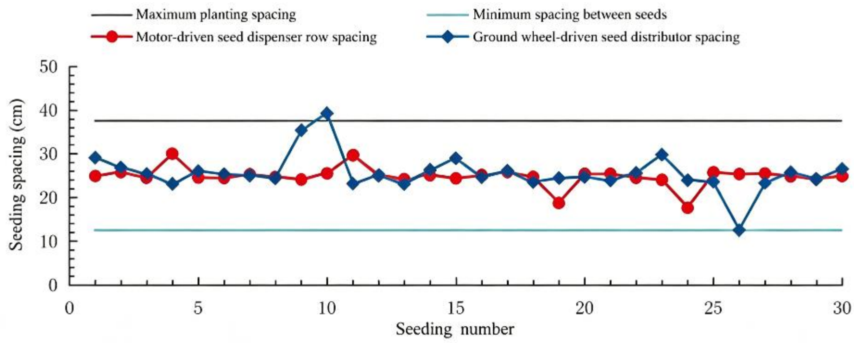

Fig. 9- Seeding spacing distribution at 12 km/h forward speed

Table 6

Test data at 12 km/h forward speed

Statistical parameter	Ground wheel driven meter	Electrically driven meter
Maximum plant spacing (cm)	32.8	29.2
Minimum plant spacing (cm)	17.3	19.1
Average plant spacing $\bar{L}$ (cm)	25.8	25.4
Standard deviation S (cm)	2.405	1.932
Coefficient of variation V	9.23%	7.21%

From the measured plant spacing data of the unmanned tractor-towed seeding machine's electrically driven seed metering device under different operating speed conditions recorded in Figs. 7 to 9, it can be observed that:

The average plant spacing $\bar{L}$, standard deviation S, and coefficient of variation V of the electrically driven seed metering device under low speed (4 km/h), medium speed (8 km/h), and high speed (12 km/h) conditions are all superior to those of the ground wheel driven seed metering device. Due to ground wheel slip, the seeding performance of the ground-wheel-driven system decreases as the tractor forward speed increases.

Limited by the structural factors of the finger-pickup type seed metering device itself, the electrically driven seed metering device achieves the highest seeding accuracy at a forward speed of 8 km/h. Beyond 8 km/h, the seeding performance gradually declines.

CONCLUSIONS

(1) The integrated electrically driven seed metering device significantly improves seeding accuracy and stability. By upgrading the original split scheme of "motor + reducer + chain drive" to an integrated electrically driven seed metering device using a "motor + right-angle reducer," the system integration level and transmission efficiency are enhanced. Field tests demonstrate that the electrically driven seed metering device outperforms the traditional ground wheel driven seed metering device in terms of the qualified index, standard deviation, and coefficient of variation of seed spacing at speeds of 4 km/h, 8 km/h, and 12 km/h. The seeding performance is optimal particularly at the medium speed of 8 km/h.

(2) The variable-rate measurement and control system achieves closed-loop control based on multi-source perception and coordinated decision-making. The system adopts a distributed controller architecture (including a Coordinated Control ECU, a Seeding Measurement and Control ECU, and a Seeding Depth Measurement and Control ECU), facilitating real-time data exchange and coordinated control between the seeder and the tractor via the CAN bus. By integrating high-precision sensors and intelligent decision-making algorithms, the system can dynamically adjust seeding parameters based on multi-source information such as soil conditions and machine posture, achieving precision seeding and depth control.

(3) The system maintains high reliability and adaptability even in high-speed operational environments. Test results show that even under the high-speed condition of 12 km/h, the seeding performance of the electrically driven seed metering device remains significantly superior to that of the mechanical transmission method, with the coefficient of variation controlled within 7.21%. The system exhibits good environmental adaptability and anti-interference capability, supporting stable operation under complex field conditions. This provides technical support for the transition of the unmanned tractor-towed seeding machine from a test prototype to large-scale field application.

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