DESIGN AND TESTING OF AN AUTOMATIC SEEDLING-LOADING SYSTEM FOR A HIGH-SPEED RIDE-ON RICE TRANSPLANTER

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高速乘坐式插秧机自动装秧系统设计与试验

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ABSTRACT

Seedling replenishment during the operation of high-speed ride-on rice transplanters still relies heavily on manual labor, thereby limiting the level of operational automation. To address this limitation, an automatic seedling-loading system comprising a longitudinal conveying mechanism, a lateral drive mechanism, and a tracking compensation mechanism was developed. Based on an STM32 embedded platform, a control strategy for detecting seedling shortages and performing precise seedling-loading operations was developed, enabling automatic shortage detection, lateral positioning, and targeted seedling replenishment. The main operating parameters—conveyor belt speed, lateral offset distance, and fore-aft tilt angle—were first investigated individually to determine their appropriate ranges. Subsequently, a second-order, three-factor, five-level rotatable orthogonal experiment was conducted. Seedling-loading success rate was used as the evaluation index, and a multifactor regression model was established to analyze the interactions among the factors. Bench tests were conducted to optimize the system parameters and determine the optimal parameter combination. Subsequent field trials confirmed the operational reliability of the system, with an average seedling-loading success rate of 90.67% over five batches of tests. The proposed system shows considerable potential for replacing manual loading of mat-type rice seedlings and provides a practical solution for advancing the full-process automation of rice transplanting operations.

摘要

在高速乘坐式插秧机作业过程中，补秧环节依赖人工、自动化程度不足。本文构建了由纵向输送装置、横向移动装置与随动装置组成的自动装秧系统，基于 STM32 嵌入式平台设计缺秧检测与执行机构控制逻辑，实现缺秧检测、横向定位与定点补秧。以输送带速度、横向偏移距离与前后倾斜角度为试验因素，开展单因素试验确定因素取值范围；采用三因素五水平二次旋转正交组合试验，以装秧成功率为评价指标建立多因素回归模型并分析各因素及其交互作用。通过台架试验优化关键参数。田间试验结果表明，系统完成 5 批次自动装秧任务，平均成功率为 90.67%。所研制的自动装秧系统能够实现毯状苗机插从缺秧识别到定点补秧的自动补秧作业，降低了补秧过程的人工依赖，可为水稻种植全程自动化提供技术支持。

INTRODUCTION

The development of agricultural machinery is steadily advancing toward full automation and intelligent operation (*Liu C.L. et al., 2020; Zhao C.J. et al., 2021*). Among various mechanized systems, rice transplanters have become a central component due to their widespread use and their role as key carriers of smart agricultural technologies *(Wang X., 2022)*. In recent years, the deployment of unmanned driving systems in rice transplanters has become increasingly common in China (*Liu X.W. et al., 2021; Yin Y.X. et al., 2022*). However, research on automatic seedling-loading systems specifically designed for high-speed ride-on rice transplanters remains limited. Consequently, the seedling-loading process continues to rely heavily on manual labor, which limits the realization of fully autonomous transplanter operations. Enhancing automation at this stage is thus critical for the practical implementation of unmanned rice farming systems. Studies on automatic seedling delivery have primarily focused on the mechanical design and technical development of systems that ensure the accurate transfer of mat-type or pot seedlings (*Liu M.H. et al., 2021; Deng G. et al., 2022; Liu M.H. et al., 2024; Xiao L.P. et al., 2018*). *Yu G.H. et al., (2024),* proposed a dual-belt longitudinal conveyor system integrated with lateral translation to realize automatic tray replenishment.

Wang X.F. et al., (2021), developed a push-type seedling delivery box that generates a dispensing opening through the relative motion of the box and its base, thereby improving replenishment reliability. *Fan Y.J. et al., (2016),* and *Yin C.et al., (2025),* introduced automated systems based on sliding-rail pushing and multi-layer tray delivery structures, aiming to reduce manual involvement through modular designs. These studies improved the efficiency and reliability of seedling replenishment through synchronized tray repositioning, push-type seedling delivery, and multi-layer tray conveying, respectively. However, relatively limited attention has been paid to seedling shortage detection, target positioning, and coordinated control of the seedling carrying platform. Despite these efforts, many of the existing devices remain at the conceptual or prototyping stage. In particular, performance issues such as poor vibration resistance under complex paddy field conditions and the lack of high-precision one-to-many seedling alignment persist. Robotic manipulation technologies may offer solutions in this regard (*Shen J.J. et al., 2023; Fountas S. et al., 2020; Bechar A. et al., 2017*).

Currently, multi-degree-of-freedom robotic systems have been widely applied in transplanting operations for crops like vegetables, corn, and tobacco. *Wang Z.Z. et al., (2017)*, employed a servo-driven module under PLC control to achieve accurate grasping and delivery of vegetable seedlings; *Shi T., (2015),* developed a fully automated corn transplanter with integrated seedling-picking and vertical delivery mechanisms; and *Chen B et al., (2024)*, used a staggered dual-disc configuration to improve the efficiency of a tobacco seedling feeding system. These studies demonstrate that Cartesian robotic systems, when combined with high-precision sensing technologies, can effectively address the challenges of automatic material handling in unstructured environments. Such insights provide valuable reference points for the design and control strategies of automatic seedling-loading systems tailored for paddy field operations (*Wu W.J. et al., 2016; Wang Z.Z. et al., 2019; Zhao C.L. et al., 2027*). However, existing systems still fall short in terms of operational stability, delivery precision, and system integration when exposed to real-world field disturbances. Developing a robust and adaptive automatic seedling-loading system remains a key technical challenge in advancing rice transplanter intelligence.

This study addresses the challenges posed by the distributed arrangement of multiple seedling-holding columns on high-speed ride-on rice transplanters, the difficulty in accurately aligning the conveying mechanism with the column requiring replenishment, and changes in their relative positions caused by the reciprocating lateral and vertical movements of the seedling-carrying platform. Based on a one-to-many seedling-replenishment concept, an automatic seedling-loading system comprising a longitudinal conveying mechanism, a lateral drive mechanism, and a tracking mechanism was developed. The lateral drive mechanism allows a single longitudinal conveying mechanism to move among multiple seedling-holding columns and align with the target column. The tracking mechanism accommodates the reciprocating lateral and vertical movements of the seedling-carrying platform, thereby reducing the relative positional deviation between the conveyor outlet and the target seedling-holding column. An STM32-based control system integrates seedling-shortage detection, lateral position feedback, and coordinated control of the lateral drive and conveyor motors, thus enabling the complete operational sequence of seedling-shortage detection, lateral positioning, and targeted seedling replenishment. The study focuses on developing and evaluating an automatic loading system for mat-type rice seedlings. To evaluate and optimize system performance, bench tests were conducted using three key operating factors: conveyor belt speed, lateral offset distance, and fore-aft tilt angle. The effects of these factors on the seedling-loading success rate were investigated, and their optimal combination was determined. The study ultimately aimed to establish a complete technical process—from seedling shortage detection to precise automatic replenishment—and provide a technical basis for structural optimization and overall performance improvement of automatic seedling-loading systems.

MATERIALS AND METHODS

Structure composition and working principle

In Fig. 1, the automatic seedling-loading system of the high-speed ride-on rice transplanter comprises four main components: ① a tracking mechanism, ② a lateral drive mechanism, ③ a longitudinal conveying mechanism, and ④ a lateral oscillation mechanism.

The front end of the mechanism is attached to the transplanter main body via the swing mechanism, which compensates for variations in machine posture and provides a stable front fulcrum for the loading structure. The rear end is connected to the seedling-carrying platform through a joint within the tracking mechanism, enabling synchronized moving with the carrier platform. The lateral drive mechanism, comprising a slide rail and rack-and-pinion assembly, is mounted at the rear of the rice transplanter body and drives the longitudinal conveying mechanism laterally.

The longitudinal conveying mechanism is mounted on the upper crossbeam of the sliding platform and conveys the seedlings longitudinally after alignment with the target seedling-holding column.

During automatic seedling loading, the operator manually places the seedling mats onto the belt of the longitudinal conveying mechanism. To initiate detection, the seedling mats must remain in firm contact with the detection switches mounted on the side baffles. Each seedling-holding column of the seedling platform is equipped with a seedling-shortage sensor. When a shortage is detected in any column, the control system activates the lateral drive mechanism, which moves the longitudinal conveying mechanism laterally toward the corresponding target position. Once the pull-wire displacement sensor confirms that the target position has been reached, the control system activates the conveyor drive motor to deliver the seedling mat to the column requiring replenishment. After leaving the conveyor belt, the seedling mat slides under gravity along the chute and into the target column, thereby eliminating the shortage and clearing the corresponding alarm signal. Upon completion of the replenishment operation, the longitudinal conveying mechanism automatically returns to its initial loading position and waits for the next seedling-shortage signal.

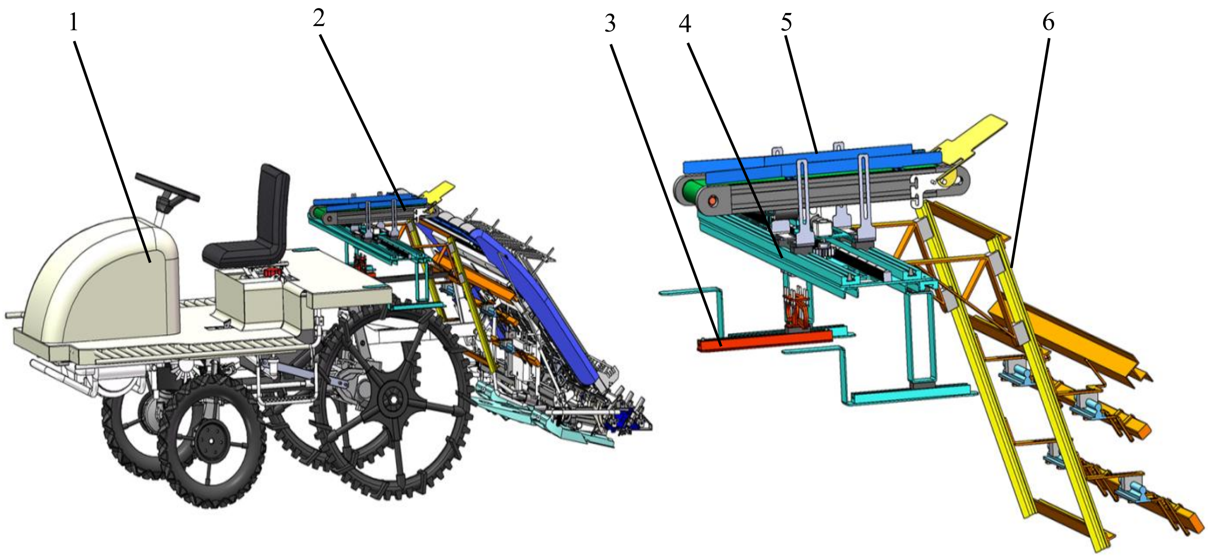


Fig. 1 - Schematic of the automatic seedling-loading system for a high-speed ride-on rice transplanter

1. Rice transplanter main body; 2. Automatic seedling-loading system (overall structure); 3. Tracking mechanism; 4. Lateral drive mechanism; 5. Longitudinal conveying mechanism; 6. Lateral oscillation mechanism

Key component design

(1) Longitudinal Conveying Mechanism

As shown in Fig. 2, the longitudinal conveying mechanism transports mat-type rice seedlings to replenish seedling shortages in the target columns of the seedling platform. It mainly comprises ① a connecting mechanism, ② a conveyor belt mechanism, ③ side baffles, ④ a support platform, ⑤ a drive unit, ⑥ a concave-convex roller assembly, and ⑦ a master-slave roller assembly. The conveyor belt mechanism is located at the top of the device and is supported by four structural members mounted on the support platform. The connecting mechanism is located at the rear of the conveyor belt mechanism, while the side baffles are installed on both sides of the conveyor belt to guide the seedling mats during loading and conveyance. The drive unit is located at the bottom of the device and transmits power to the conveyor system through a belt drive. The master-slave roller assembly consists of an intermediate drive shaft coupled to an external nylon roller. The assembly is mounted in bearing supports to prevent relative slippage between the nylon roller and the conveyor belt, thereby ensuring stable and reliable seedling conveyance. An MY5840-31ZY worm-geared DC motor is used to drive the longitudinal conveying mechanism. Under loaded conditions, the maximum torque required at the conveyor drive shaft was measured using a torque wrench and found to be 12.8 kgf·cm. The selected motor has a rated torque of 16 kgf·cm and a maximum load torque of 38 kgf·cm, thus satisfying the torque requirements of the longitudinal conveying mechanism. Based on the calculated transmission parameters, the conveyor belt can reach a maximum operating speed of 0.4 m/s, which meets the speed requirement for seedling replenishment.

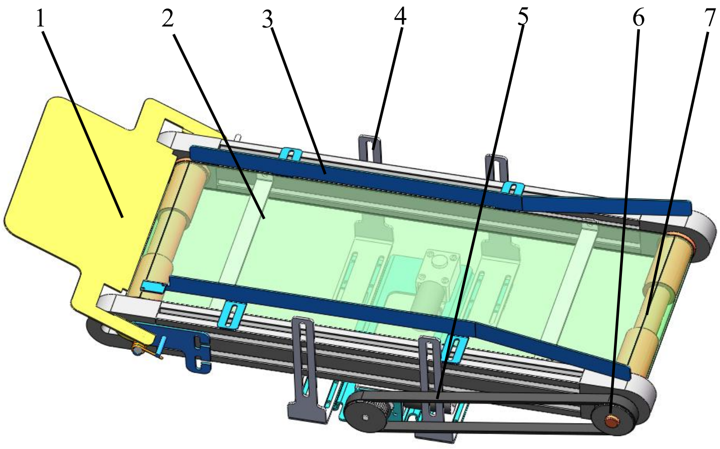


Fig. 2 - Schematic of the longitudinal conveying mechanism

1. Connecting mechanism; 2. Conveyor belt mechanism; 3. Side baffle; 4. Support platform; 5. Drive unit; 6. Concave-convex roller assembly; 7. Master-slave roller assembly

(2) Tracking mechanism

As shown in Fig. 3, the tracking mechanism is designed to accommodate the multidirectional motion of the seedling platform during operation. While awaiting a seedling-replenishment operation, the mechanism remains stationary relative to the seedling platform, thereby accommodating both lateral displacement and vertical offset. The mechanism mainly comprises ① a vertical slide rail, ② a horizontally movable beam, ③ an upper beam, ④ a horizontal slide rail, and ⑤ a lower beam. It is connected to the base plate through the lower beam and forms a sliding connection with the seedling platform. Its primary function is to enable the automatic seedling-loading system to move laterally in synchrony with the seedling platform while maintaining a stable relative height when the platform undergoes lifting, pitching, or swaying motions. To verify the structural feasibility of the conveying and positioning mechanisms, a SolidWorks interference check was performed for the longitudinal conveying mechanism throughout the full travel range of the lateral guide rail. The results showed no structural interference between the longitudinal conveying mechanism and the seedling platform. Furthermore, the position of the longitudinal conveying mechanism at the end of the lateral guide rail was selected as the worst-case operating condition, and a static deformation analysis was conducted on the 5-mm-thick aluminum-alloy base plate. The maximum displacement at the end of the base plate was less than 8 mm, indicating that the structure satisfied the basic positioning and conveying requirements of the automatic seedling-loading system.

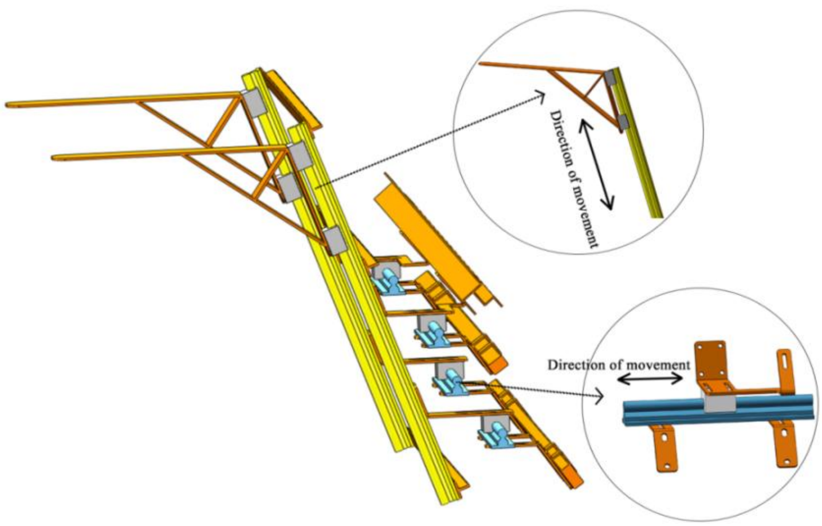


Fig. 3. Schematic of the vertical and horizontal slide-rail mechanisms

1. Vertical slide rail; 2. Horizontally movable beam; 3. Upper beam; 4. Horizontal slide rail; 5. Lower beam

Control system design

To achieve full automation of the rice seedling loading process, a dedicated control system was developed. In Fig. 4, the system uses the seedling shortage alarm signal from the high-speed ride-on rice transplanter as its input and employs an STM32-M3 microcontroller as the central processing unit.

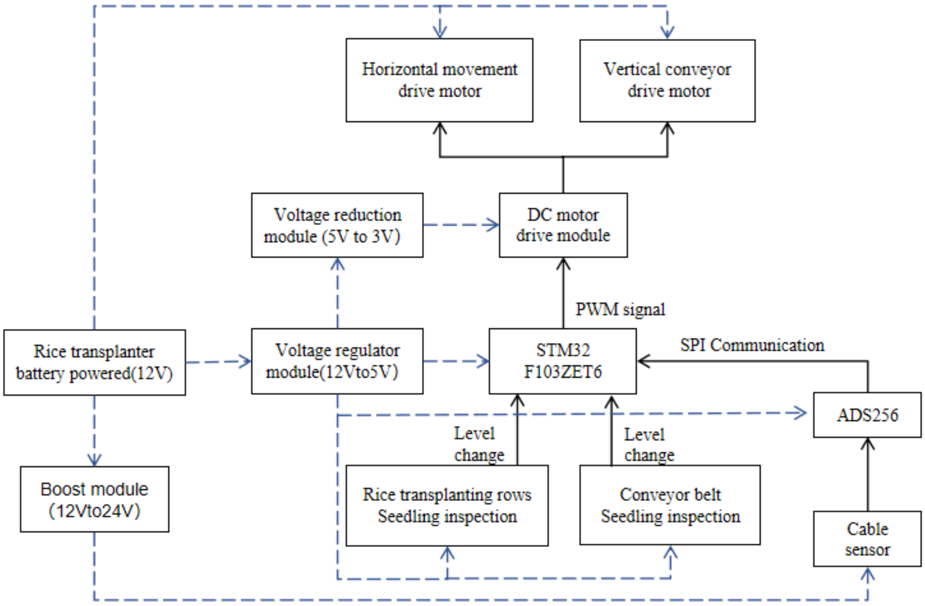


Fig. 4. System architecture of the automatic seedling-loading system

Note: The seedling-shortage switches detect the presence or absence of seedlings on the conveyor belt and in each seedling-holding column. The pull-wire displacement sensor measures the position of the laterally movable platform, and its signal is transmitted through the ADS1256 converter. Based on the detected seedling status and lateral-position feedback, the STM32 controller drives the lateral motor to align the longitudinal conveying mechanism with the target column and then activates the conveyor drive motor to complete the seedling-replenishment operation. Solid lines indicate control-signal or drive relationships, whereas dashed lines indicate power-supply connections.

The control architecture comprises four functional modules: ① seedling status detection, ② lateral position detection, ③ drive control, and ④ power management. A seedling-shortage switch installed on the rice transplanter detects the presence or absence of seedlings in each seedling-holding column of the seedling platform and determines whether the longitudinal conveying mechanism is ready to perform a replenishment operation.

An MPS-S-2500-V1-F pull-wire displacement sensor, used in conjunction with an ADS1256 analog-to-digital (A/D) converter, acquires real-time positional data from the laterally movable platform. The sensor has an output voltage range of 0–5 V, a linearity of ±0.15%, a repeatability of ±0.02%, a maximum operating speed of 1 m/s, and an IP65 ingress protection rating. The sensor output is acquired using the 24-bit ADS1256 A/D converter. Before the tests, the longitudinal conveying mechanism was sequentially aligned with the center of each seedling-holding column, and the corresponding digital output values were recorded as the calibrated target-position values for the respective columns.

Seedling shortage detection was performed using mechanically actuated switch sensors. When a seedling pressed the sensor lever, the corresponding controller input changed from a high level to a low level, and the system determined that seedlings were present at that position. When the lever was released, the system identified a seedling shortage. The shortage detection signal was assigned a relatively high interrupt priority to ensure timely recognition.

After identifying the seedling-holding column requiring replenishment and its corresponding lateral position, the STM32 controller employed a closed-loop control method based on position error and velocity feedback to regulate the PWM signal of the lateral drive motor, thereby moving the longitudinal conveying mechanism to the target shortage column. Once positioning was completed, the longitudinal conveyor motor was activated to perform point-specific seedling replenishment. The controller used a position-control cycle of 50 ms, during which the lateral positions measured by the pull-wire displacement sensor at the current and previous sampling instants were acquired.

The lateral velocity was then calculated from the difference between the two sampled positions:

$$V_k = \frac{x_k - x_{k-1}}{T_s} \tag{1}$$

where the two position variables denote the lateral positions at the current and previous sampling instants, respectively, and the sampling period is set to 50 ms. The controller considers both the distance between the target and current positions and the lateral velocity, and controls the lateral drive motor by adjusting the PWM duty cycle. As the mechanism approaches the target position, the PWM output is reduced to ensure that it stops smoothly at the seedling-holding column requiring replenishment. The conveyor belt of the longitudinal seedling conveying mechanism is then actuated to transport the seedlings and complete the replenishment operation, thereby enabling precise control of both the lateral moving mechanism and the conveyor belt mechanism.

The hardware configuration of the control system is shown in Fig. 5. It consists of the following components: ① a motor drive module, ② a main control unit, ③ an STM32F103ZET6 core board, ④ an A/D acquisition module, and ⑤ a boost module. The control system and the autonomous-driving controller are housed together in a sealed control box. To ensure reliable operation under field conditions, the control box is mounted within a protective frame that provides additional protection against water ingress, solar radiation, and mechanical vibration.

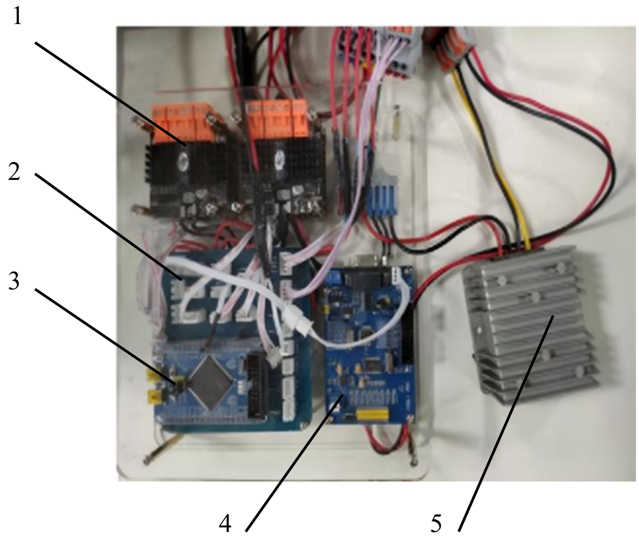


Fig. 5 - Component layout of controller unit

1. Motor driver module; 2. Main control unit; 3. STM32F103ZET6 core board; 4. AD acquisition module; 5. Boost module

In terms of software design, the system's logical workflow is illustrated in Fig. 6

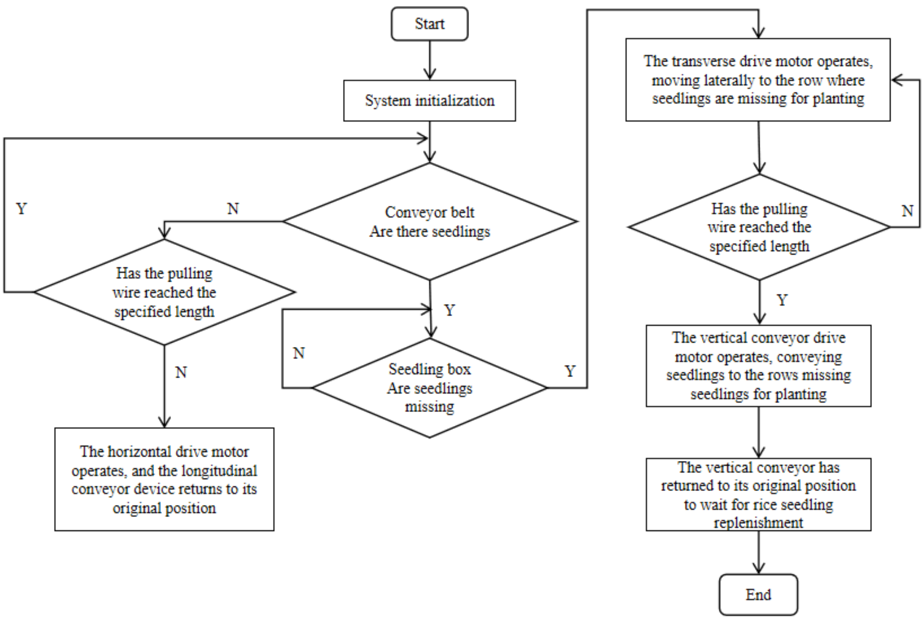


Fig. 6 - System flowchart of automatic seedling loading process

After the system is powered on, an initial self-check is performed, followed by the start of the replanting cycle. The control system continuously monitors the status of each seedling column in real time. When a missing seedling column is detected, the drive mechanism moves to the corresponding target position, and the conveying mechanism is activated to carry out the replanting operation. Upon completion of the replanting task, the system halts the conveyor motor and resets the mechanism to its initial position. It then proceeds to the next round of detection, thus enabling a closed-loop control process for fully automated seedling replenishment.

Bench test

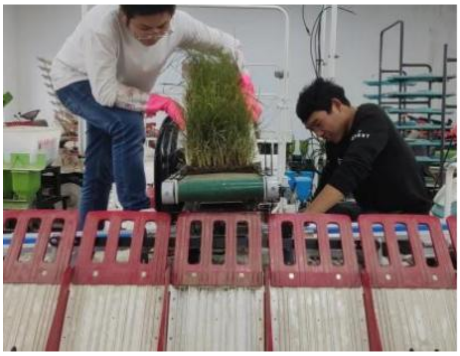
(1) Single-factor experiment

Preliminary experiments verified the reliability of the seedling delivery device, demonstrating its ability to move synchronously with the transplanting platform. However, several key parameters were found to significantly influence the seedling loading success rate, including the conveyor belt speed, the lateral offset distance between the conveyor belt and the seedling column, the left-right tilt angle deviation between the conveyor belt and the seedling platform, the fore-aft tilt angle of the conveyor mechanism, and the height difference between the conveyor belt and the seedling platform. To determine the optimal value range for each factor and improve seedling loading performance, single-factor bench tests were carried out. The seedling loading success rate (C) was used as the evaluation index. A loading operation was considered successful if the result was comparable to manual loading and did not interfere with the transplanter's normal seedling grasping process; otherwise, it was classified as failed loading.

$$C=\frac{R}{Z}\times100\% \tag{2}$$

where: R is the number of seedling trays successfully loaded (trays) and Z is the total number of seedling trays loaded (trays).

In Fig.7a, seedlings are manually placed onto the conveyor belt. The drive motor is then activated to initiate seedling transportation (Fig.7b). The motor speed is regulated via a speed controller, ensuring controlled moving of the seedlings. As the seedlings reach the end of the conveyor, they detach and drop into the seedling loading column, thereby completing the loading process (Fig. 7c and 7d).



(a) Manual placement of seedlings

(b) Seedling transport

(c) Seedlings falling into seedling platform

(d) Completion of seedling loading

Fig. 7 - Bench test process for seedling loading

(2) Multifactor experimental design

Based on the results of the single-factor experiments, the structure of the longitudinal conveying mechanism was optimized. Limit stops were installed to restrict the left-right tilt angle to within ±12°. By adjusting the longitudinal conveying mechanism along the vertical slide rail, the height difference between the conveyor belt and the seedling platform was maintained within 80 mm. Based on these modifications, the factor levels and coded values were determined from the ranges that yielded a seedling-loading success rate of 100% in the single-factor experiments. The selected factors were conveyor belt speed, lateral offset distance, and fore-aft tilt angle (Table 1).

Table 1

Factor level coding for experimental design

Encoded values	A: Conveyor belt speed (m/s)	B: Lateral offset distance (mm)	C: Fore-aft tilt angle (°)
−1.682	0.1	−17	−38
−1	0.2	−8.5	−24
0	0.3	0	−10
1	0.4	8.5	4
1.682	0.5	17	18
Horizontal interval value	0.1	8.5	14

Field verification experiment

To further evaluate the overall performance of the automatic rice seedling-loading system, field tests were conducted using the optimal combination of operating parameters obtained from the bench experiments. These tests aimed to verify the system's accuracy, stability, and reliability under actual field operating conditions.

On October 8, 2024, a field trial was conducted at the experimental field of Jiangxi Agricultural University. The experimental material consisted of 7-inch mat-type seedling trays, with seedlings aged 28 days, an average height of 15 cm, and a substrate moisture content of 28%. The seedlings were in healthy condition and met the agronomic requirements for mechanized rice transplanting. The automatic seedling loading process was divided into four stages (Fig. 9). Seedlings were firstly manually placed onto the longitudinal conveyor while the system awaited a seedling shortage signal. Once the seedling shortage detection system identified a column requiring replenishment, the longitudinal conveying mechanism was laterally positioned using the lateral moving device. The longitudinal conveyor belt was then activated to transport seedlings to the corresponding shortage column until the loading process was complete. A total of five batches of automatic seedling loading operations were performed, with 30 loading cycles per batch, successfully completing the loading of 150 seedling trays.

(a) Manual seedling planting *(b) Lateral moving*

(c) Conveying seedlings to transplanting row *(d) Completion of automatic seedling loading*

Fig. 9 - Field operation process of automatic rice seedling-loading system

RESULTS AND ANALYSIS

Bench test results

(1) Single-factor experiment results

During the experiment, the conveyor belt speed was varied across 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6 m/s; the lateral offset distance between the conveyor belt and the seedling carrier was set at 12, 13, 14, 15, 16, 17, and 18 mm; the left-right tilt angle deviation between the conveyor belt and the seedling carrier ranged from 0°, 2°, 4°, 6°, 8°, 10°, 12°, to 14°; the fore-aft tilt angle of the conveyor belt mechanism was tested at −35°, −30°, −25°, −20°, −15°, −10°, −5°, 0°, 5°, 10°, 15°, and 20°; and the height difference between the conveyor belt and the seedling carrier was set at 30, 40, 50, 60, 70, and 80 mm.

The statistical values corresponding to seedling loading success rates exceeding 60% were recorded, and their respective ranges are summarized in Table 2. Notably, a 100% success rate was achieved when the left-right tilt angle deviation reached ±12°, and the height difference ranged from 0 to 80 mm.

Table 2

Value ranges of key influencing factors for seedling loading performance

Category	Conveyor belt speed (m/s)	Lateral offset distance (mm)	Left/right tilt angle (°)	Fore-aft tilt angle (°)	Height difference (mm)
Upper limit	0.5	17	−12	18	80
Lower limit	0	−17	12	−38	0

(2) Results of the multifactor experiment

A three-factor, five-level quadratic rotatable orthogonal composite design was employed. The design comprised 20 experimental runs, including six replicates at the center point to evaluate experimental repeatability. Each run consisted of 10 seedling-loading trials, from which the seedling-loading success rate was calculated. The experimental results are presented in Table 3.

To evaluate the repeatability of the automatic seedling-loading system under identical parameter settings, the results of the six center-point runs were statistically analyzed. The center-point settings were a conveyor-belt speed of 0.3 m/s, a lateral offset distance of 0 mm, and a fore-aft tilt angle of −10°. The seedling-loading success rates obtained from the six center-point runs were 90%, 90%, 90%, 80%, 90%, and 90%, respectively. The mean success rate was 88.33%, with a standard deviation of 4.08 percentage points, a 95% confidence interval for the mean of 84.05%–92.62%, and a coefficient of variation of 4.62%. These results demonstrate that the automatic seedling-loading system exhibited good repeatability under identical bench-test conditions and operating parameters.

$$CV = \frac{S}{\bar{Y}} \times 100\% \tag{3}$$

where CV is the coefficient of variation, [%]; S is the standard deviation of the center-point results, [percentage points]; and $\bar{Y}$ is their mean value, [%].

Table 3

Test design and results for seedling loading success rate

Test No.	A: Conveyor belt speed (m/s)	B: Lateral offset distance (mm)	C: Fore-aft tilt angle (°)	Y: Seedling-loading success rate (%)
1	0	0	0	90
2	−1	−1	1	80
3	1.682	0	0	60
4	0	0	−1.682	70
5	0	0	0	90
6	1	1	−1	70
7	0	0	0	90
8	−1	1	1	70
9	0	−1.682	0	60
10	1	−1	1	60
11	−1	−1	−1	90
12	−1	1	−1	90
13	0	0	0	80
14	0	0	0	90

Test No.	A: Conveyor belt speed (m/s)	B: Lateral offset distance (mm)	C: Fore-aft tilt angle (°)	Y: Seedling-loading success rate (%)
15	0	1.682	0	80
16	0	0	1.682	50
17	1	1	1	60
18	0	0	0	90
19	1	−1	−1	70
20	−1.682	0	0	90

The experimental data were analyzed using Design-Expert software, and the corresponding results are outlined in Table 4.

Table 4

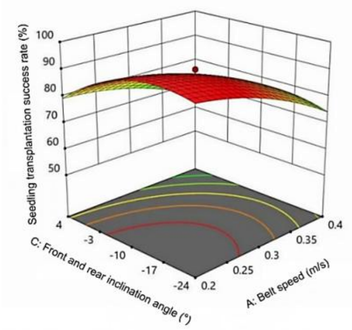
ANOVA for factors influencing seedling loading success rate

Sources of variance	Sum of squares	Degrees of freedom	Mean square	F-value	P-value
Model	3189.66	9	354.41	13.36	0.0002
A	1056.25	1	1056.25	39.81	< 0.0001
B	56.25	1	56.25	2.12	0.1761
C	506.25	1	506.25	19.08	0.0014
AB	12.5	1	12.5	0.4711	0.5081
AC	12.5	1	12.5	0.4711	0.5081
BC	12.5	1	12.5	0.4711	0.5081
A^2	273.05	1	273.05	10.29	0.0094
B^2	519.48	1	519.48	19.58	0.0013
C^2	1248.05	1	1248.05	47.04	< 0.0001
Residual	265.34	10	26.53		
Misfit	182.01	5	36.4	2.18	0.2057
Error	83.33	5	16.67		
Total	3455	19			
R^2	0.9232				
Adjusted R^2	0.8541				
Signal-to-noise ratio	5.15				
Coefficient of variation	6.73%				

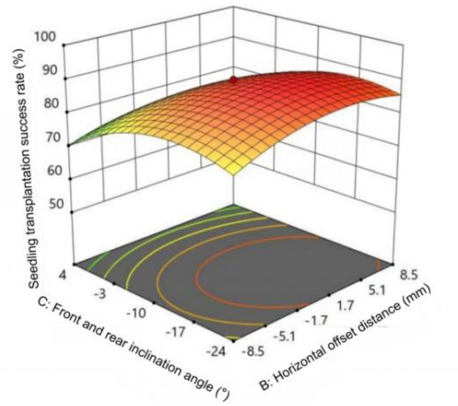
Note: P < 0.01 indicates highly significant and P < 0.05 indicates significant.

Analysis of variance indicated that the model's lack of fit was not significant (P > 0.05), suggesting that no unaccounted factors had a substantial influence on the rice seedling loading success rate. The coefficient of determination (R^2 = 0.9232) demonstrated an excellent model fit, reflecting high reliability and strong predictive capability. The overall model was statistically significant, and A, C, A^2, B^2, and C^2 had highly significant effects on the seedling loading success rate. Using Design-Expert software, the relationship between the multifactor response values and coded variables was analyzed, and a fitted regression equation was derived accordingly.

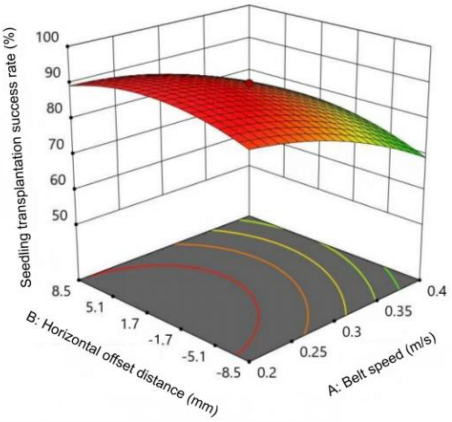
$$Y=88.41-8.13A+1.88B-5.63C+1.25AB+1.15AC-1.25BC-3.3A^2-4.55B^2-7.05C^2 \quad (2)$$



(a) Interaction between conveyor belt speed and fore-aft tilt angle



(b) Interaction between lateral offset distance and fore-aft tilt angle



(c) Interaction between conveyor belt speed and lateral offset distance

Fig. 8 - The influence of various factors on seedling loading success rate

Note: A denotes the conveyor belt speed, B denotes the lateral offset, and C denotes the fore-aft tilt angle. In (a), B was fixed at 0 mm; in (b), A was fixed at 0.3 m/s; and in (c), C was fixed at −10°. The response surfaces and contour plots were generated from the quadratic regression model of the seedling loading success rate and represent the model-predicted success rate under the combined variation of two factors.

The contour plots and response surface analyses of various factors affecting the rice seedling loading success rate were performed using MATLAB (Fig. 8). In Fig. 8a, when the lateral offset distance is 0 mm, the success rate exhibits a "first increase, then decrease" trend with increasing conveyor belt speed and fore-aft tilt angle. Moreover, fluctuations in success rate caused by changes in conveyor belt speed are more pronounced, indicating that conveyor belt speed has a stronger influence on the response variable than the fore-aft tilt angle. In Fig. 8b, when the conveyor belt speed is fixed at 0.3 m/s, the combined effects of lateral offset distance and fore-aft tilt angle on the success rate follow a "large first, then small" trend. The magnitude of variation caused by changes in lateral offset distance is more substantial, suggesting its greater impact relative to the tilt angle. In Fig. 8c, when the fore-aft tilt angle is −10°, the combined effect of conveyor belt speed and lateral offset distance still follows the "large first, then small" pattern. Additionally, significant fluctuations in the success rate are observed with changes in conveyor belt speed, reinforcing that this factor exerts a greater influence than lateral offset distance.

Based on optimization analysis conducted in Design-Expert, the optimal parameter combination for maximizing the rice seedling loading success rate was determined to be a conveyor belt speed of 0.238 m/s, a lateral offset distance of 2.261 mm, and a fore-aft tilt angle of −11.643°, yielding a predicted success rate of 93.39%. For ease of parameter adjustment, a validation experiment was conducted using rounded values: conveyor belt speed of 0.25 m/s, lateral offset distance of 2 mm, and fore-aft tilt angle of −11°. The experiment was repeated 20 times, resulting in 19 successful loadings and an actual success rate of 95%. The 95% confidence interval for the seedling loading success rate, calculated using the Wilson method, was 76.39%–99.11%. The relative error between the experimental result and the model prediction was 1.72%, confirming the accuracy of the regression model and the reliability of the optimized parameter combination.

Results of the field verification tests

The seedling-loading success rates for the individual batches are presented in Table 5. The second and third batches achieved the highest success rate of 100%, whereas the first and fifth batches had the lowest success rate of 83.3%. The mean success rate across the five batches was 90.67%, with a standard deviation of 8.64 percentage points and a range of 83.3%–100%. Based on the 150 field trials, the 95% Wilson confidence interval for the overall seedling-loading success rate was 84.94%–94.36%.

Table 5

Seedling-loading success rates obtained in the field trials

Trial batch	First	Second	Third	Fourth	Fifth
Seedling-loading success rate (%)	83.3%	100%	100%	86.7%	83.3%

Based on field observations and an analysis of the operating mechanism, the main factors contributing to the reduced seedling-loading success rate were identified as follows:

1) The lateral tilt and vertical displacement of the seedling platform significantly affected the seedling-loading success rate. Owing to uneven terrain, variations in mud depth, and other field conditions, irregular and uncontrollable torsional displacement occurred between the rice transplanter main body and the seedling platform. When the longitudinal conveying mechanism moved laterally to the end of the guide rail, its large lateral overhang, combined with the structural flexibility of the system, amplified this torsional displacement. Consequently, the conveyor outlet fell below the reference height of the seedling platform, hindering the effective delivery of the seedling mat into the target seedling-holding column.

2) Structural constraints and contact interference between the seedling mats and the seedling platform during loading adversely affected placement stability. When the seedling mats collided with the side baffles of the seedling platform, they tended to curl or become entangled with the retaining strips. Consequently, they could not settle properly at the bottom of the seedling-holding column, thereby reducing the seedling-loading success rate.

3) Lateral vibration of the rice transplanter reduced the measurement accuracy of the pull-wire displacement sensor, thereby affecting the alignment accuracy between the conveyor belt and the target seedling-holding column. This vibration caused deviations between the actual and target lateral positions of the longitudinal conveying mechanism, preventing accurate alignment with the column requiring replenishment.

Performance comparison of automatic seedling-handling systems

To evaluate the operating performance of the developed automatic seedling-loading system, representative automatic seedling-picking, feeding, and transplanting systems for which success-rate data were clearly reported were selected for comparison (Table 6). Under the optimized test conditions, the developed system achieved a seedling-loading success rate of 95.00%. This value was 6.77, 4.00, 5.00, and 0.83 percentage points higher than those reported by *Jin et al. (2018), Khadatkar et al. (2024), Han et al. (2019),* and *Chen et al. (2025)*, respectively, but 3.00 percentage points lower than that reported by *Kumar and Raheman (2012)*. The results indicate that the longitudinal conveying, lateral positioning, and seedling-shortage detection and control components operated cooperatively to achieve the automatic loading of mat-type rice seedlings. Because the studies differed in seedling type, stage of automated operation, experimental conditions, and criteria used to define success, the reported values should be interpreted only as indicators of system performance under the respective test conditions.

Table 6

Performance comparison of similar automatic seedling-handling systems

Study	Seedling type	Success rate (%)
Jin X. et al., (2018)	Pepper plug seedlings	88.23
Khadatkar A. et al., (2024)	Pepper and tomato plug seedlings	91.00
Kumar G.V.P. et al., (2012)	Vegetable paper-pot seedlings	98.00
Han L.H et al., (2019)	Vegetable plug seedlings	90.00
Chen M. et al., (2025)	Pepper plug seedlings	94.17
Present study	Mat-type rice seedlings	95.00

CONCLUSIONS

1) An automatic seedling-loading system for high-speed ride-on rice transplanters was developed. The system comprises a longitudinal conveying mechanism, a lateral drive mechanism, and a tracking mechanism. Based on an STM32 embedded platform, the control system integrates seedling-shortage detection, position acquisition, and actuator-control modules, enabling the coordinated execution of seedling-shortage detection, lateral positioning, and targeted seedling replenishment. The developed system successfully performed the automatic loading of mat-type rice seedlings.

2) Single-factor bench tests were conducted using conveyor-belt speed, lateral offset distance, and fore-aft tilt angle as the experimental factors to determine their appropriate ranges. Subsequently, a three-factor, five-level quadratic rotatable orthogonal composite design was employed, and a multifactor regression model of the seedling-loading success rate was established (R^2 = 0.9232). The overall regression model was statistically significant. Twenty verification tests were conducted using the optimized parameter settings of approximately 0.24 m/s, 2 mm, and −11°, resulting in a mean success rate of 95.00%. The overall success rate obtained in the field tests was 90.67%, demonstrating that the system could perform automatic seedling loading under actual paddy-field conditions. However, its performance was lower than that achieved under controlled bench-test conditions, indicating that complex field disturbances remain an important factor limiting stable system operation.

3) The triggering of the mechanical seedling-shortage switches was affected by the morphology of the seedling mats and their contact positions. The output signal of the pull-wire displacement sensor fluctuated owing to lateral oscillation and vibration of the rice transplanter main body. The tracking mechanism accommodated the normal lateral reciprocating and vertical movements of the seedling platform; however, its ability to compensate for irregular lateral oscillation, torsional displacement, and height variations at the ends of the guide rail remained limited. Therefore, the field adaptability of the current system requires further improvement. Future work will focus on improving the seedling-shortage detection method, vibration resistance of the position sensor, support structure at the guide-rail ends, and structural design of the tracking mechanism.

4) The field validation comprised five batches and a total of 150 automatic seedling-loading operations. These tests primarily demonstrated the short-term feasibility of the prototype under specific field conditions but were insufficient to fully assess its long-term operational reliability. Further multi-site, multi-season, and long-duration continuous-operation tests are required, with particular emphasis on evaluating wear of the mechanical connections and transmission components, conveyor-belt tension, sensor drift, motor temperature rise, and adaptability to muddy and waterlogged field conditions. In addition, the attitude of the seedling platform, vibration of the rice transplanter main body, and lateral-positioning error should be measured simultaneously to facilitate further optimization of the tracking mechanism, position-detection method, and control strategy.

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