Design and test of the progressive push-out automatic seedling-taking device for vegetable substrate block seedlings

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Abstract: Aiming at the problems of low success rate and high seedling injury rate of automatic vegetable transplanting, this study focused on cabbage substrate block seedlings and developed a progressive push-out automatic seedling device controlled by a PLC system. Based on the friction mechanical properties of seedlings-tray during seedling taking, the collision rebound theoretical analysis of substrate block seedling delivery and the finite element simulation analysis of the seedling taking mechanism were carried out to determine the conditions for stable seedling taking and delivery of the device and the working parameters of the key mechanisms. To evaluate individual parameter effects, a test bench was built, and the effective ranges of key factors were subsequently determined. Three key experimental factors, the inclination angle of the limit guide plate, the seedling separation channel width, and the seedling separation cylinder pressure, were investigated using an $L9(3^4)$ orthogonal array design with blockage rate and breakage rate as evaluation metrics. The range and variance analysis methods were employed to determine the relative significance of each factor's influence on the performance indicators. The optimal parameters were determined as: the inclination angle of the limiting guide plate was 3.5°, the width of the seedling separation channel was 50 mm, and the pressure of the seedling separation cylinder was 0.6 MPa. Under these conditions, the seedling taking effect was significantly improved: the blockage rate was 2.46%, the breakage rate was 3.18%, and the seedling taking success rate was 94.36%. The optimal parameter combination was verified by the experiment: the average blockage rate was 3.23%, the average breakage rate was 3.68%, and the average success rate was 93.09%. Compared with the orthogonal experiment, the relative success rate error was 1.27%, indicating that the device has high stability. This study will provide a reference for the design of automatic vegetable transplanters.

Keywords: transplanter, substrate block seedlings, automatic seedling taking device, PLC control system, progressive push-out
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1 Introduction

China maintains its global leadership in vegetable production, with an annual vegetable planting area exceeding 20 million hm^2 [1-3], and the total output representing 60% of worldwide vegetable production[4]. However, the mechanization level of vegetable production in China remains relatively low at approximately 40%[5], with particularly limited automation in sowing and transplanting operations that still predominantly rely on manual labor or semi-automatic equipment. Labor expenditures constitute over 50% of total vegetable production costs[6], with growing workforce shortages emerging as a critical constraint on industry development. Consequently, developing automatic seedling taking methods and technologies to realize automatic vegetable transplanting is crucial to solve the issues of large labor workload, high cost, and low efficiency in vegetable transplanting.

Automatic seedling taking constitutes the core technological component of the automatic transplanter. There are several automatic seedling taking devices, such as ejecting type, clamping type, combined type, etc.[7-9]. The seedling picking needles were used in the automatic vegetable transplanting machine manufactured by Pearson Company[10,11]. The multi-sensor and automatic control technologies were integrated to make sure every motion of seedlings was controlled. The seedling shortage detection

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was carried out during seedling picking, and flexible seedling picking technology was used to avoid damage to the stem and leaves caused by seedling picking needles.

The seedling top-out taking method was designed in the 2ZS series fully automatic vegetable plug seedling transplanter of Japan Real Industry, which was suitable for seedlings with a height of 8-12 cm and an exclusive flexible tray with 220 holes[12]. The seedling row-by-row top-out clamping method was used in Futura automatic vegetable plug seedling transplanter of FERRARI Industry[13-15]. The top-out rod and clamping claw were coordinated through PLC control cylinder. The efficiency of the seedling picking-up unit reached 8000 plants/h. The machine has good adaptability to different seedling trays, detects missing seedlings, and adjusts the distance between soil and planter.

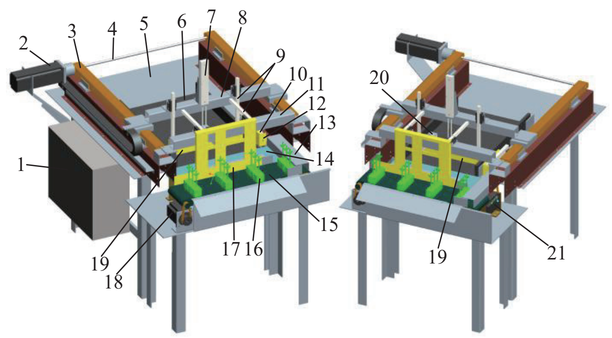
While China initiated research on automated vegetable transplanters later than other countries, it has achieved accelerated technological advancements. Pneumatic claws were used for seedlings picking-up by row, and were designed according to the characteristics of vegetable seedlings. All operations were operated by cylinder through PLC program[16-18]. A crank-slide-rod type seedling ejecting device was also designed[19]. The plug seedlings were turned to the upright direction under their own gravity after ejecting in rows. The plug seedlings were pushed into the seedling ditch by a pushing device after falling onto the seedling board. However, this seedling ejecting device was only suitable for seedlings with smaller stem crowns. An ejecting-clamping type seedling picking-up device was also designed[20,21], and the speed of seedling picking-up can be programmed to realize the process of ejecting, clamping, and dropping circularly in order.

The above automatic seedling picking-up devices are mainly designed for plug seedlings. The contact between automatic seedling picking-up devices and seedlings is rigid. The method of seedling nurturing by substrate block was proposed so as not to damage the seedlings[22-24]. The regularly shaped blocks are helpful to reduce the mechanical damage when transplanting. However, only research on semi-automatic machines for substrate block seedling separation and planting was conducted[25-28]. In this paper, a progressive push-out automatic seedling taking device for substrate block seedlings was proposed, and analysis and experiment were carried out to provide a reference for the core techniques of the substrate block seedlings automatic transplanter.

2 Materials and methods

2.1 Test prototype design

The progressive push-out automatic seedling taking device of substrate block seedling is mainly composed of the seedling taking mechanism, seedling separation mechanism, seedling feeding mechanism, lateral conveying mechanism, control system, and structural frame, as shown in Figure 1. The seedling taking mechanism is composed of a seedling taking motor, synchronous driving shaft, linear module, moving beam, guide rail, taking cylinder, and push plate. The linear modules are symmetrically arranged above the frame and connected by a synchronous drive shaft. The taking motor is installed on one side of the drive shaft. The moving beam is arranged between two slides of linear modules. The guide rail and the seedling taking cylinder are fixed on the moving beam perpendicularly, and the seedling pushing plate is installed on the seedling taking cylinder piston rod. The seedling pushing device is composed of a fixed beam, a guide rail, a seedling pushing cylinder, and a pushing plate. The guide rail and the seedling pushing cylinder are fixed on the beam and parallel to the horizontal plane. The seedling taking mechanism and the seedling separation mechanism are arranged in parallel front and back, corresponding to the horizontal conveyor belts Ⅰ and Ⅱ respectively, the surfaces of the two horizontal conveyor belts are flush, and the rotation directions are opposite. One end of horizontal conveyor belt Ⅰ is installed with seedling separation mechanism and the limiting guide plate, and one side of the limiting guide plate is set with a capacitance sensor to detect the position of block seedlings on horizontal conveyor belt Ⅰ.



a. Left axonometric drawing b. Right axonometric drawing

1. Electrical control box 2. Seedling picking motor 3. Linear module 4. Synchronized drive shafts 5. Rackmount 6. Seedling tray 7. Seedling picking cylinder 8. Moving beam 9. Guide rail 10. Seedling separation cylinder 11. Fixed beam 12. Push plate for seedlings separation 13. Limit guide plate 14. Horizontal conveyor belt Ⅰ 15. Horizontal conveyor belt Ⅱ 16. Substrate block seedlings 17. Push plate for seedlings delivery 18. Drive motor for horizontal conveyor belt Ⅱ 19. Push plate for seedlings picking 20. Seedling delivery cylinder 21. Drive motor for horizontal conveyor belt Ⅰ

Figure 1 Structure diagram of progressive push-out automatic seedling taking device

2.2 Working principle

The progressive push-out automatic seedling taking device is driven by three stepping motors and three cylinders. The stepping motors drive the linear intermittent motion of linear module and the conveyor belts, and the straight reciprocating motion of the cylinders.

The seedling tray is placed in the limiting groove of the frame (Figure 2a). The electrical control system controls the seedling picking motor and the linear module. Driven by the seedling picking motor and the linear module, the crossbeam moves to one side of the seedling tray, the seedling picking cylinder stretches, and the push plate pushes the entire tray of substrate block seedlings toward the horizontal conveyor belt Ⅰ (each time it is pushed forward, three rows of substrate block seedlings are picked up) (Figure 2b). The first three rows of substrate block seedlings are pushed onto the horizontal conveyor belt Ⅰ, and then they are intermittently conveyed toward the limit guide plate under the action of the horizontal conveyor belt Ⅰ driving motor (a capacitive sensor was installed on the side of the limit guide plate, and when the substrate block seedling signal is detected, the horizontal conveyor belt Ⅰ stops conveying) (Figure 2c). The seedling separation cylinder stretches to push the front row of substrate block seedlings onto the horizontal conveyor belt Ⅱ (Figure 2d). The row spacing is formed by the intermittent movement to the left of the horizontal conveyor belt Ⅱ (Figure 2e). When the horizontal conveyor belt Ⅱ is loaded with three rows of substrate seedlings, the seedling delivery cylinder stretches to push them towards the corresponding longitudinal conveying trough (Figure 2f). Finally, the planting is completed by the planting organization.

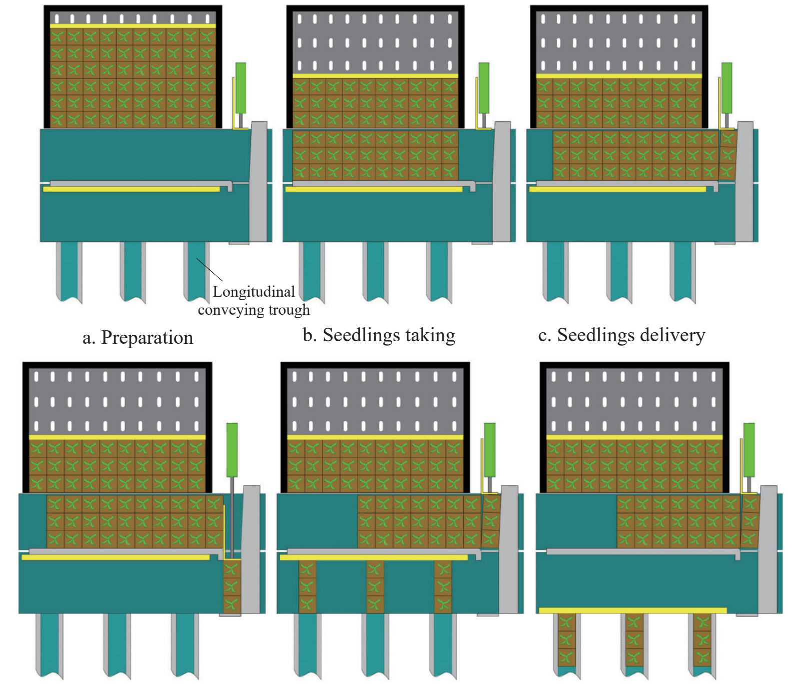


Figure 2 Working principle

2.3 Design of the key components

2.3.1 Theoretical analysis of seedlings separation mechanism

The horizontal conveyor belt Ⅰ carries the matrix -arranged substrate block seedlings to the right. When the limiting guide plate is flat (Figure 3a), a row of seedling blocks close to the limiting guide plate is subjected to the reverse thrust F_x of the guide plate at the moment of collision with the limiting guide plate, which is due to the crowding of seedling blocks and the action of the baffle. Seedling C has a shorter rebound distance after collision due to the friction between seedling F and the seedling block behind and the baffle. The rebound of seedling B is affected by the horizontal adhesion force F_{t3} to the right of seedling C and the horizontal adhesion force F_{t2} to the left of seedling A. The rebound of seedling A is affected by the horizontal adhesion force F_{t1} to the right of seedling B. Therefore, the rebound distance of seedling A is the longest, and that of seedling C is the shortest. When the seedling separating pushing plate pushes the seedlings downward, seedling E is stuck to seedling A, and seedling F is stuck to seedling B (circled in Figure 3a), making them unable to be pushed out. The rebound margin of the seedling block would be offset when the limit guide plate is set as an inclined surface (Figure 3b). The seedling push plate only influences the first row of seedling blocks (understood as a whole) to make them rotate counterclockwise around point O to form the shape of Figure 3c. Seedlings A, B, and C rotate counterclockwise around O_1, O_2, and O_3 respectively to become horizontal, which can compensate for the rebound jamming of the seedling blocks.

The collision between the seedling block and the limit guide plate was inelastic, and their impact recovery coefficient was measured to be 0.6. When there were multiple rows of seedling blocks on the conveyor belt, the rebound distance of the seedling C was minimal and negligible. When the gap between two adjacent rows of seedling blocks exceeds the rebound distance, the seedling blocks would achieve the maximum rebound distance. A force analysis was conducted on seedling block A during rebound in this scenario, as illustrated in Figure 4a. According to the law of conservation of energy[29,30]:

$$\begin{cases} \dfrac{mv_1^2}{2} = F_f l_1 + F_{t1}\Delta l \\ F_f = \mu F_N = \mu G \\ v_1 = 0.6v \end{cases} \tag{1}$$

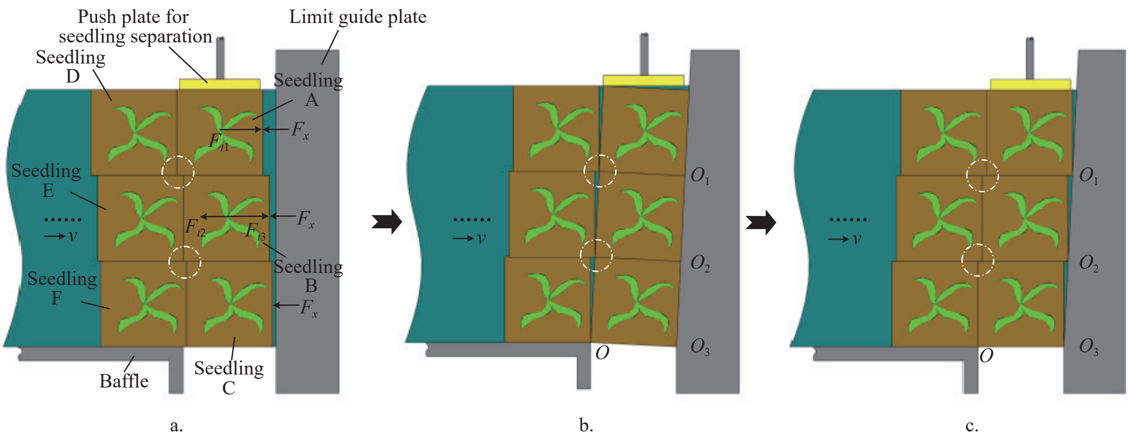
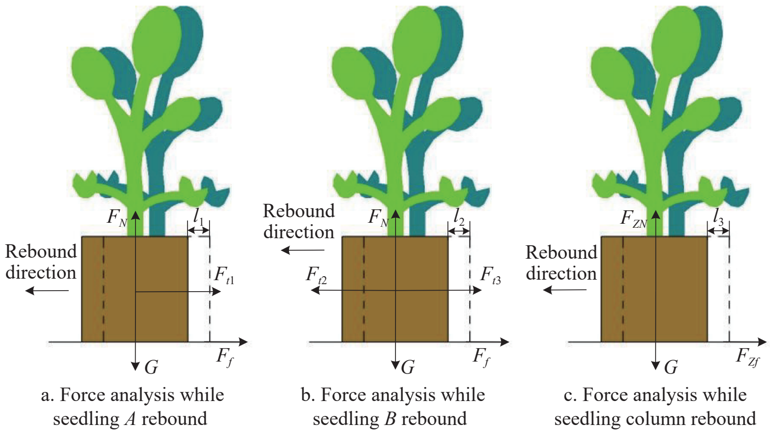


Figure 3 Analysis of forces for horizontal conveyance of substrate block seedlings



Note: G is the gravity of the seedling block, (0.98N); F_N is the force of the conveyor belt on the seedling block, N; F_f is the friction between the conveyor belt and the seedling block, N; F_{t1} is the force exerted by seedling B when seedling A rebounds, N; F_{t2} is the force exerted by seedling A on seedling B when it rebounds (N), $F_{t2}= F_{t1}$; F_{t3} is the force exerted by seedling C when seedling B rebounds, N; and G_Z is the gravity of the three seedling blocks, (2.94 N); F_{ZN} is the support force of the conveyor belt for the three seedling blocks, N; F_{Zf} is the friction between the conveyor belt and the three seedling blocks, N; l is the overall rebound distance of the three seedling blocks, mm.

Figure 4 Force analysis of seedling blocks during rebound

where, m is the mass of single seedling block (0.1 kg); v_1 is the speed of seedling A at the moment of rebound, m/s; F_f is the friction between the conveyor belt and seedling block, N; l_1 is the rebound distance of seedling A, mm; F_{t1} is the force of seedling A subjected to seedling B, namely the adhesion force between the seedling blocks, N; Δl is the relative displacement between seedling A and seedling B, mm; μ is the friction coefficient between the seedling block and the conveyor belt (0.4); G is the gravity of the seedling block (0.98 N); v is the speed of seedling A before rebound, namely the speed of conveyor belt Ⅰ (0.2 m/s).

Derive the rebounding distance of seedling A from Equation (1):

$$l_1 = \frac{0.18mv^2 - F_{t1}\Delta l}{\mu mg} \quad (2)$$

As given by Equation (2), l_1 is correlated with F_{t1} and can be calculated using Equation (3):

$$F_{t1} = C_a S \quad (3)$$

where, C_a is the tangential adhesion coefficient between seedling blocks (0.5 kPa); S is the contact area of seedling A and seedling B (2×10^{-4} m^2). Substituting the parameters in Equation (3) results in F_{t1}=0.1 N.

The force analysis of seedling B during rebound is shown in Figure 4b. According to the law of conservation of energy[29,30]:

$$\begin{cases} \dfrac{mv_2^2}{2} + F_{t2}\Delta l - F_{t3}l_2 - F_f l_2 = 0 \\ v_2 = 0.6v \end{cases} \quad (4)$$

where, v_2 is the instantaneous rebound velocity of seedling B (m/s); and l_2 is the rebound distance of seedling B (mm).

The l_2 can be calculated using Equation (4), as follows:

$$l_2 = \frac{0.18mv^2 + F_{t2}\Delta l}{F_{t3} + \mu mg} \quad (5)$$

And because l_1, l_2, Δl, F_{t2}, and F_{t3} have the following relationship:

$$\begin{cases} l_1 = l_2 + \Delta l \\ F_{t2} = F_{t3} \end{cases} \quad (6)$$

Combining Equations (1)-(6), we can get Δl=0.0064v^2, l_1=0.0443v^2, and l_2=0.0379v^2.

The calculation results in l_1=1.77 mm, l_2=1.52 mm, when v is 0.2 m/s.

After obtaining the maximum rebound distance of seedlings A and B, it was necessary to further calculate the slope of the limit guide plate:

$$\begin{cases} \theta_1 = \tan^{-1}\dfrac{l_1}{2d} \\ \theta_2 = \tan^{-1}\dfrac{l_2}{d} \\ \theta = \max(\theta_1, \theta_2) \end{cases} \quad (7)$$

where, θ_1 is the slope calculated based on the rebound distance of seedling A, (°); θ_2 is the slope calculated based on the rebound distance of seedling B, (°); d is the edge length of the seedling block (40 mm); θ is the slope of the limit guide plate, (°).

Calculated from Equation (7), θ=2.18°, that is, when the slope of the limiting guide plate was ≥2.18°, the seedling block can be prevented from getting stuck during the seedling pushing process.

When the last row of seedling blocks was delivered, the three seedling blocks collide with the limiting guide plate and rebound at the same time. At this time, the three seedling blocks were subjected to the same force and the movement process was consistent. The three seedling blocks can be regarded as a whole for force analysis. According to the law of conservation of energy[29,30]:

$$\begin{cases} \dfrac{m_Z v_Z^2}{2} = F_{Zf} l_3 \\ F_{Zf} = \mu F_{ZN} = \mu G_Z \\ v_Z = 0.6v \end{cases} \quad (8)$$

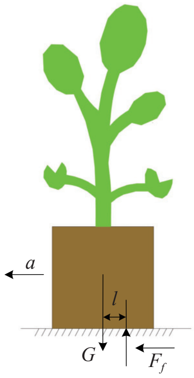
where, m_Z is the mass of three seedlings (0.3 kg); v_Z is the speed of the three seedlings rebounding at the moment (m/s); v is the speed of the three seedlings before rebounding, namely the speed of the conveyor belt Ⅰ (0.2 m/s).

The calculation yielded l_3=0.2 mm, indicating that the minimum required spacing for the seedling separation channel must be ≥40.2 mm.

2.3.2 Conditions for stable conveying after seedling separation

After the seedling blocks are pushed to the transverse conveyor belt Ⅱ in groups, the seedling blocks will fall over or slide due to the inertia when the transverse conveyor belt Ⅱ starts or stops. In order to prevent the seedling block from tipping over when being delivered on conveyor belt Ⅱ, it is necessary to analyze the force relationship of the seedling block at the moment of acceleration. As shown in Figure 5, the moment analysis of the center of mass of the seedling block was performed:

$$\begin{cases} G = F_{\mathrm{N}} \\ F_{\mathrm{f}} = ma = \mu G \\ F_{\mathrm{N}} l - \dfrac{F_{\mathrm{f}} d}{2} = 0 \end{cases} \tag{9}$$



Note: a is the acceleration of the seedling block, mm/s²; l is the distance between support force and gravity of the seedling block, mm.

Figure 5 Force analysis of seedling blocks during stable transportation

When the supporting force of the seedling block was located at the lower right corner, that is, l=d/2, the seedling block was about to flip over. The critical turning moment of the seedling block meets the following requirements:

$$F_{\mathrm{N}} \frac{d}{2} - F_{\mathrm{f}} \frac{d}{2} = 0 \tag{10}$$

According to Equation (10), F_{N}=F_{f} in an ideal state, but in reality the friction coefficient μ<1, so Equation (10) does not hold, indicating that there is no possibility of the seedlings tipping over when the horizontal conveyor belt Ⅱ is started.

Based on the above force analysis, in order to ensure that the substrate blocks reach the designated position corresponding to the planting row after seedling separation, the speed of the seedling blocks should be 0 m/s when they reach the designated position. The seedling blocks underwent acceleration followed by deceleration during the delivery process. When they reached the maximum speed, they suddenly decreased to 0 m/s. The maximum speed of the delivery process should meet the following requirements:

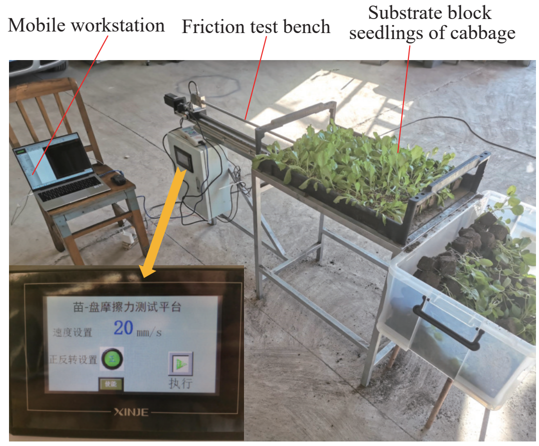
$$\begin{cases} \dfrac{v_m^2 - 0}{2a} = \dfrac{l_h}{2} \\ a = \mu g \end{cases} \tag{11}$$

where, v_{m} is the maximum transport speed of the seedling block, mm/s; l_{h} is the row distance of seedling block transportation (300 mm); g is the gravitational acceleration (9.8 m/s²).

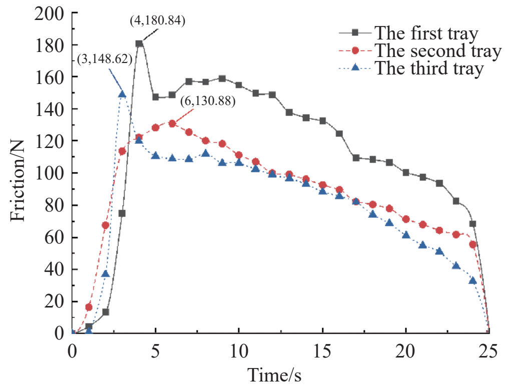
The calculated v_{m}=0.588 m/s, that is, when the conveyor belt Ⅱ speed is ≤0.588 m/s, the slippage of the substrate blocks seedlings can be avoided.

2.3.3 Determination of frictional properties between seedlings-tray

The test object was a tray full of 120 cabbage seedlings. Watering was stopped 2 d before the test, and the average moisture content of the substrate block was measured to be 17.35%. The test equipment was a self-designed seedling-tray friction test platform (Figure 6a). The whole tray of substrate block seedlings is placed on the test platform stand, and the push plate is kept in critical contact with the first row of substrate block seedlings. The test platform running speed is set to 20 mm/s, and then the loading program is executed. When all the substrate block seedlings are pushed out of the seedling tray, the proximity switch detects the position signal of the push plate, and the system unloads the push plate and resets it. The corresponding pressure peak is the maximum seedling removal friction. Three trays were randomly measured, and the maximum seedling removal friction was recorded.



a. Seedling friction test platform



b. Friction variation with time

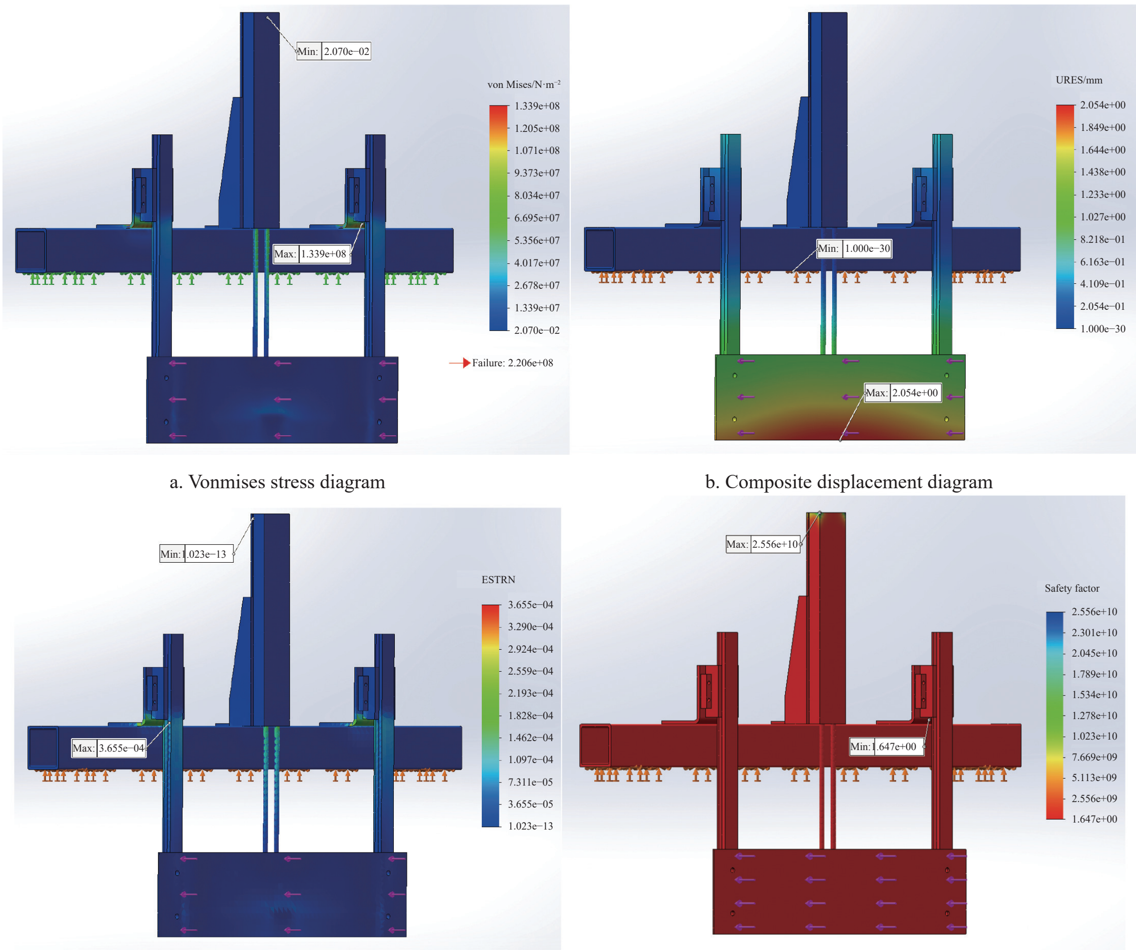
Figure 6 Frictional properties test for seedling taking

It can be found from the time-friction force variation curve (Figure 6b), when the push plate runs for 0-4 s, the friction increases sharply and approximately linearly. The substrate blocks squeezed against each other, the spatial positions were rearranged, and the resistance increased. The three plates exhibited distinct peak frictional forces during operation: 180.84 N at 4 s (first plate), 130.88 N at 6 s (second plate), and 148.62 N at 3 s (third plate), yielding an average peak friction of 153.45 N. As the push plate continues to run at a constant speed, the friction reaches its peak value and then changes slowly to zero.

2.3.4 Finite element analysis of seedlings taking device

The seedling push plate is fixed by two guide rails and stretches away from the cross beam to the bottom of the seedling tray by the cylinder piston rod. Therefore, the guide rails and piston rods connect to the seedling push plate and form a cantilever beam. The thrust received by the seedling push plate at the initial moment of contact with the substrate block is the maximum value in the seedling taking process, which affects the deformation and displacement of the seedling taking mechanism. It is necessary to perform finite element statics and modal analysis on the mechanism. SolidWorks was used to create a 3D model of the seedling taking mechanism. The material of the seedling taking cylinder was set to alloy steel, and the materials of other parts were set to ordinary carbon steel. The crossbeam of the seedling taking mechanism was fixed, and a normal load of 200 N was added to the seedling taking push plate (the maximum seedling taking thrust value of 180.84 N was measured in the experiment, calculated based on the upper limit of 10%). The model was meshed using the "standard mesh", the mesh density was set to "good", and 16 Jacobian points were selected. The model had 41 921 mesh units and 78 987 nodes.

After preprocessing the model of the seedling taking mechanism, the Vonmises stress diagram, composite displacement diagram, isostatic strain diagram, and safety factor diagram were obtained after calculating, as shown in Figure 7. The maximum stress of the seedling taking mechanism occurs at the right angle of the guide rail fixing seat, which was 1.339×10^{8} N/m^{2}. The minimum yield stress of this part was 2.206×10^{8} N/m^{2}, and the failure safety factor was low at 1.647, indicating the strength meets the requirements. The maximum strain occurs at the junction of the guide rail and the slideway, which was 3.655×10^{-4}, and the strain was relatively small. The maximum displacement occurred in the bottom middle section of the push plate, which was 2.054 mm. There was a slight deformation without breakage. Analysis showed that the reason might be that the push plate was too long and had no support in the middle, but it did not affect seedling taking.



a. Vonmises stress diagram b. Composite displacement diagram
c. Isostatic strain diagram d. Safety factor diagram

Figure 7 Finite element analysis

2.4 Automatic control system

As the most important part of the automatic seedling taking device, the automatic control system manages and coordinates the operation of each component to ensure the normal operation of the mechanical and electrical devices. As shown in Figure 8, the automatic control system consists of a PLC (Program Logic Controller), a mobile workstation, a sensor, a solenoid valve, a stepper motor, a cylinder, and other actuators.

2.4.1 Control principle

The control system adopts SIMATIC S7-200 PLC control. The mobile workstation is connected to the controller to import the program, and the seedling taking mechanism, seedling separating mechanism, seedling sending mechanism, and horizontal conveying mechanism are started and adjusted through control command signals. The energy supply relationships among the mechanisms, the signal pathway directions, and the seedling taking process are shown in Figure 9. The control signals among the parts of the seedling picking device are as follows: after the control program is written in the mobile workstation STEP7-MicroWIN SMART V2.7 software, it is transferred to the register of the PLC. The control system receives and sends signals from switches, sensors, and other judgment components to control the actuators to complete the specified actions. The motor speed is controlled by the PWM (pulse width modulation) signal and the communication control of the motor driver to realize the rotation and stop of the motor. The cylinders are equipped with solenoid valves, throttle valves, and

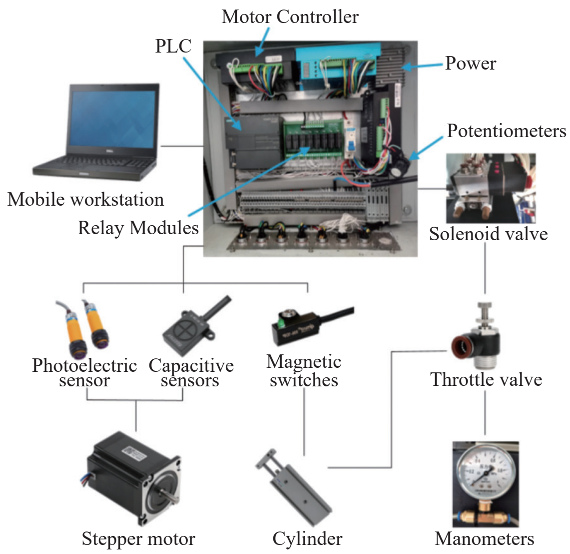


Figure 8　Structure of automatic control system

magnetic switches controlled by digital signals.

After the solenoid valve of the seedling taking cylinder receives the PLC control signal, it drives the seedling taking push plate to approach the last row of seedling blocks. The seedling taking motor driver outputs the motor control signal, indirectly driving the seedling taking push plate to provide the forward speed for the entire tray of substrate block seedlings, and pushes them progressively to the horizontal conveyor belt Ⅰ. When the capacitive sensor I detects the seedling block position signal, the seedling taking motor will stop. The motor driver of the horizontal conveyor belt Ⅰ outputs a motor control signal to drive the substrate block seedlings to be delivered to the limit guide plate. The capacitive sensor II detects the seedling block position signal and feeds it back to the control system, thereby stopping the motor of the horizontal conveyor belt Ⅰ from rotating. At this time, the solenoid valve of the seedling separation cylinder receives the control signal fed back to the control system by the capacitive sensor, and drives the seedling separation push plate to push the first row of substrate block seedlings on the horizontal conveyor belt Ⅰ to the horizontal conveyor belt Ⅱ. The motor driver of the horizontal conveyor belt Ⅱ outputs the motor control signal to intermittently deliver the substrate block seedlings (after the seedlings are pushed from the horizontal conveyor belt Ⅰ to the horizontal conveyor belt Ⅱ for three cycles). The solenoid valve of the seedling delivery cylinder receives the control signal and drives the seedling delivery push plate to push the substrate block seedlings on the horizontal conveyor belt Ⅱ to the corresponding

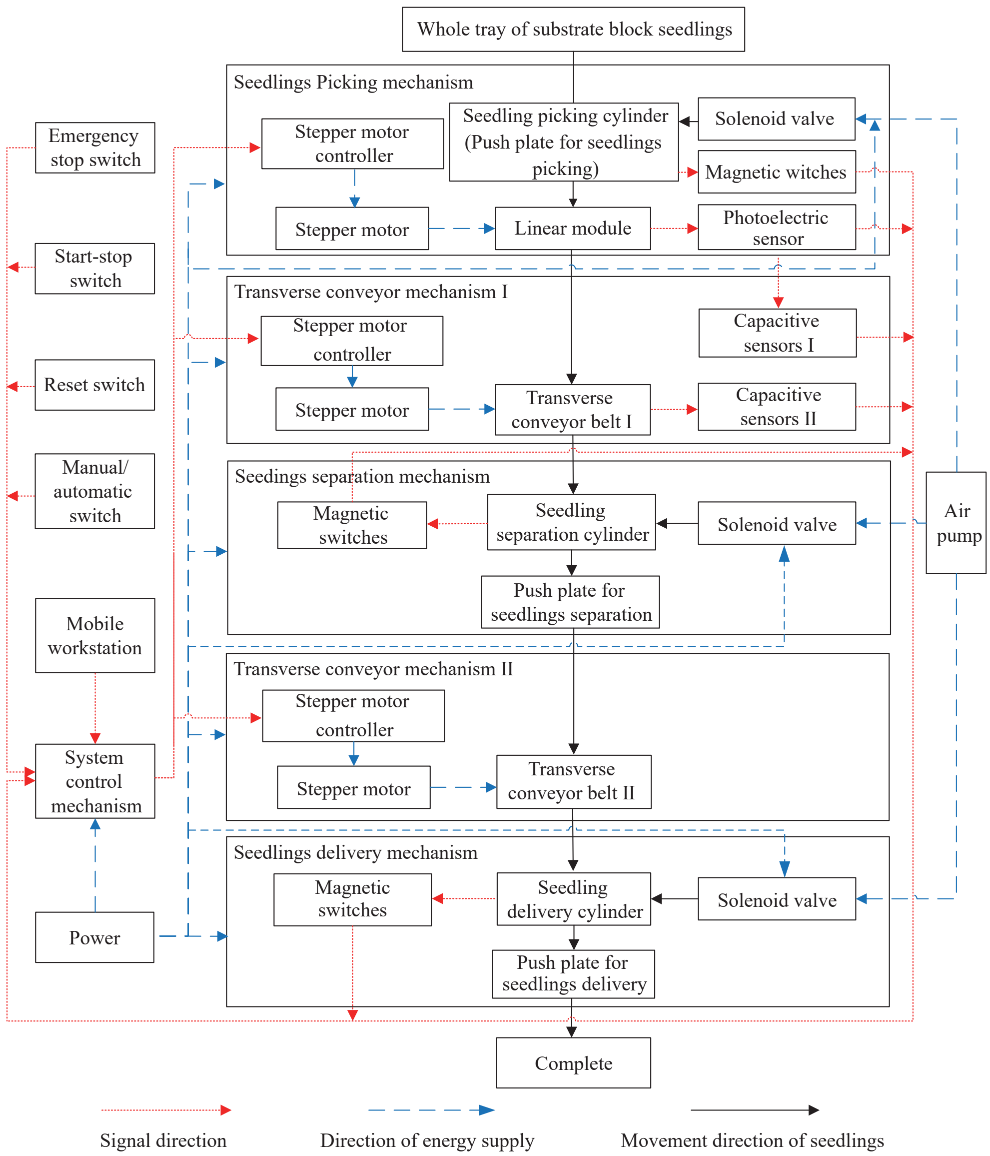


Figure 9　Control principle diagram

conveying trough. The horizontal conveyor belt Ⅰ, the seedling separation push plate, the horizontal conveyor belt Ⅱ, and the seedling delivery push plate repeat the above execution commands until the capacitive sensor I cannot detect the seedling block, and the seedling removal motor starts again. The logic nests and loops four times until all the seedlings in the tray are completely picked up.

2.4.2 Control process

The control process is implemented by PLC controller and communication parts, including: initialization, speed control, counting control, logic control, and interrupt processing. After the system is powered on, it first enters the initialization stage, which includes system initialization and motion state zero initialization. After the system is initialized, the work start button is pressed to read the preset data of the seedling work in the PLC register, and periodic work is performed according to the control signal, as shown in Figure 10. When the sensor detects an overly large deviation threshold between the actual value and the preset value or the user finds that the mechanism moves abnormally, interrupt jump 2 is executed and the stop button is pressed. The current motion mechanism stops after completing the current motion cycle, and manual reset settings are required if it is restarted. When interrupt jump 1 is executed during system operation, the system stops immediately. Under the same conditions, the interrupt level of emergency stop takes precedence over the stop command, and all system actions can be stopped in the shortest time.

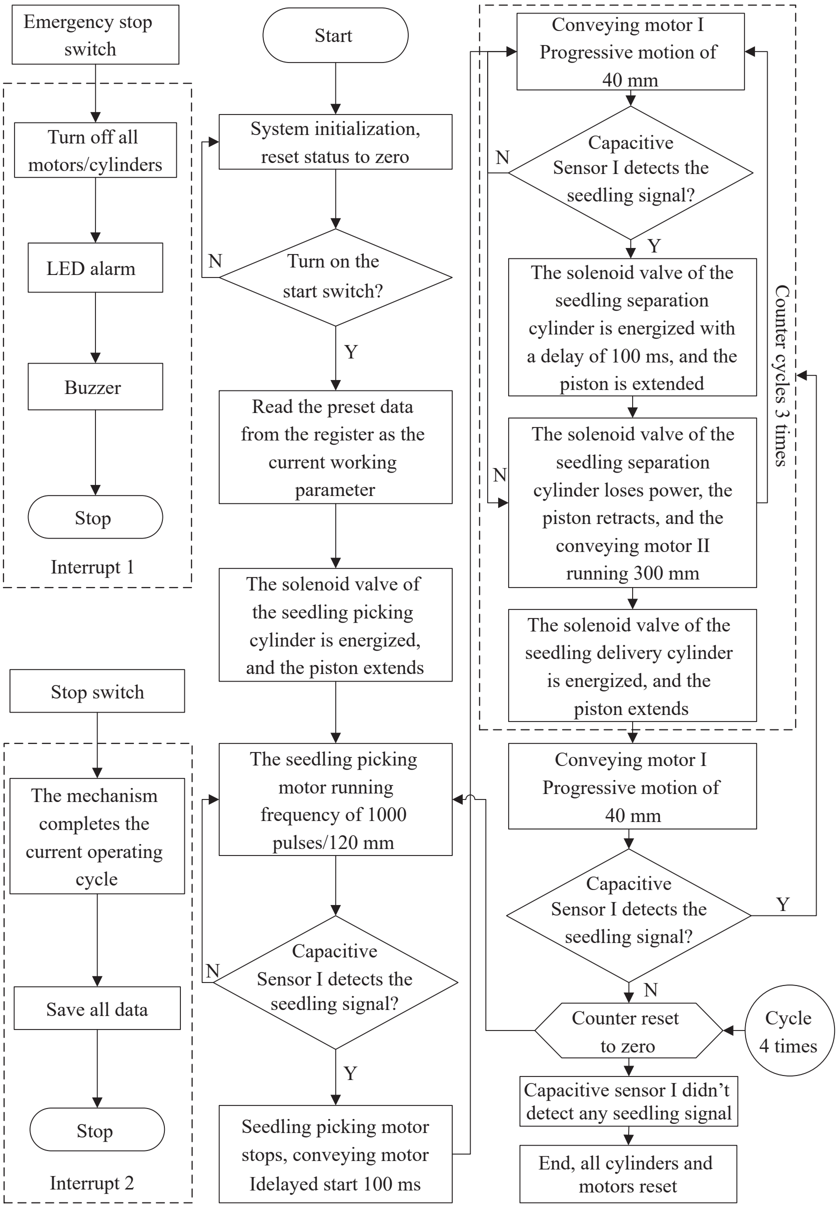


Figure 10 Control flow diagram

3 Experiment and result analysis

3.1 Experimental conditions

In order to verify the working performance of the progressive push-out automatic seedling taking device, a test bench was built to obtain the optimal combination of parameters of the device, as shown in Figure 11. The test subjects were 25-day-old cabbage substrate block seedlings with a size of 40 mm×40 mm×40 mm. There was no adhesion or root stringing between blocks. The seedlings had two leaves and one core, with an average height of about 120 mm. The seedling mass and associated tilting moment exhibited negligible influence on the uprightness of the seedling blocks and were therefore excluded from the analysis.

3.2 Test factors and evaluation indicators

According to preliminary test analysis, the main factors affecting the seedling taking performance were related to the

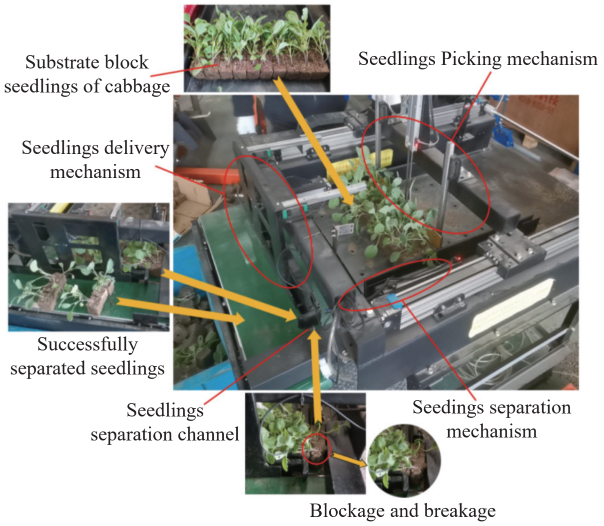


Figure 11 Automatic seedling taking device test

inclination angle of the limit guide plate, the width of the seedling separation channel, and the pressure of the seedling separation cylinder. According to the theoretical calculation results in Section 2.3, the inclination angle of the limit guide plate was 2°-4°, the width of the seedling separation channel was 40-50 mm, and the pressure of the seedling separation cylinder was 0.55-0.75 MPa. The performance test was carried out with the blockage rate, breakage rate, and success rate as evaluation indicators. The evaluation index calculation method is:

$$T = \frac{N_{DS}}{N} \times 100\% \quad (12)$$

$$E = \frac{N_{SM}}{N} \times 100\% \quad (13)$$

$$Y = (1 - T - E) \times 100\% \quad (14)$$

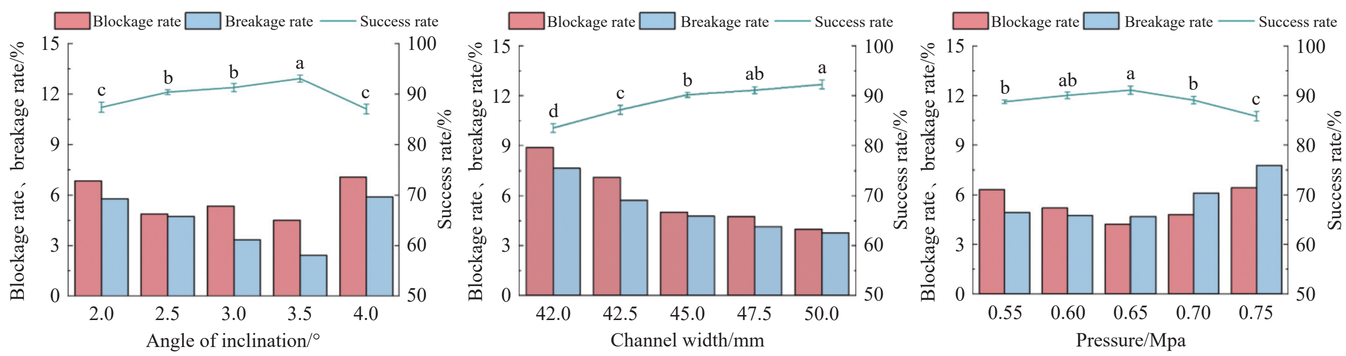
where, T is the blockage rate, %; N_{DS} is the number of blocked seedlings; N is the total number of seedlings in the test; E is the breakage rate, %; N_{SM} is the number of broken seedlings; and Y is the success rate, %.

3.3 Results and discussion

3.3.1 Single-factor test

In order to determine the level range of each factor in the orthogonal test, a single factor test was first designed. One tray of seedlings (120 plants) was selected for testing in each group of tests. When one of the factors was tested, the other two factors took the middle value to observe the influence of each factor on the blockage rate, breakage rate, and success rate.

The analysis of variance (ANOVA) was performed on the single-factor test results to compare the significant differences and standard deviations among the parameters of each factor. As shown in Figure 12a, when the inclination angle of the limiting guide plate was 3.5°, there was a significant difference in the success rate of seedling separation compared with the other four groups. When the inclination angle was between 2.5°-3.5°, the standard deviation of the success rate was lower. Within this parameter range, the blockage rate and breakage rate were relatively low, and the success rate of seedling separation was higher. As shown in Figure 12b, when the width of the seedling separation channel was between 45-50 mm, the significant difference and standard deviation of the success rate were relatively small, indicating that the wider the channel, the lower the blockage rate and breakage rate, and the higher the success rate. As shown in Figure 12c, when the cylinder pressure was 0.75 MPa, there was a significant difference in the success rate compared with the other four groups of parameters, and the standard deviation was relatively large, indicating that the greater the pressure, the more unstable the success rate; when the cylinder pressure was between 0.6-0.7 MPa, the blockage rate and breakage rate were relatively low, and the seedling separation success rate was high.



a. Inclination angle of limit guide plate b. Width of seedling separating channel c. Pressure of seedling separating cylinder

Figure 12 Single-factor test results

3.3.2 Orthogonal test

In order to obtain the optimal combination parameters of the automatic seedling taking device and verify the influence of the above three factors on the seedling taking performance, three groups of parameters with high success rates (>90%) were selected for L9(3^4) orthogonal test based on the single factor test results: the inclination angle of the limit guide plate was 2.5°-3.5°, the channel width was 45-50 mm, and the cylinder pressure was 0.6-0.7 MPa. The experimental factor levels are listed in Table 1. There were nine groups in total, each group was repeated three times, and each test was conducted on a plate of substrate seedlings. The average value of the three replications was taken to record the data.

Table 1 Factors and levels

Levels	Factors		
	Inclination angle of limit guide plate/(°)	Width of seedling separating channel/mm	Pressure of seedling separating cylinder/MPa
1	2.5	45	0.55
2	3	47.5	0.6
3	3.5	50	0.65

The test design and range analysis are listed in Table 2, and the variance analysis is listed in Table 3.

3.3.3 Analysis of test results

The results of range and variance analysis show that the inclination angle of the limit guide plate and the channel width have

Table 2 Test results of range analysis

Experiment No.	Experiment factors: Inclination angle of limit guide plate (*A*)	Width of seedling separating channel (*B*)	Pressure of seedling separating cylinder (*C*)	Blockage rate/%	Breakage rate/%
1	1	1	1	7.74	5.62
2	1	2	2	6.62	2.44
3	1	3	3	4.93	5.38
4	2	1	2	6.27	3.19
5	2	2	3	5.71	3.24
6	2	3	1	3.15	5.33
7	3	1	3	5.18	4.85
8	3	2	1	4.73	3.93
9	3	3	2	2.46	3.18
Blockage rate k_1	8.52	6.39	5.21		
Blockage rate k_2	9.16	5.69	5.11		
Blockage rate k_3	4.12	3.51	5.27		
Blockage rate Range	5.04	2.88	0.16		
Factor order：*A*>*B*>*C*					
Optimal parameter combination：*A*3*B*3*C*2					
Breakage rate k_1	4.48	4.55	4.96		
Breakage rate k_2	3.92	3.20	2.94		
Breakage rate k_3	3.99	4.63	4.49		
Breakage rate Range	0.56	1.43	2.02		
Factor order：*C*>*B*>*A*					
Optimal parameter combination：*C*2*B*2*A*2					

Note：k_1 - k_3 refers to the average sum of the factor values at each level; *R* refers to range.

a significant effect on the blockage rate, while the cylinder pressure has no significant effect on the blockage rate. The order of priority of the factors affecting the blockage rate was *A*>*B*>*C*, and the optimal solution was *A*3*B*3*C*2, that is, the inclination angle was 3.5°, the channel width was 50 mm, and the cylinder pressure was 0.6 MPa.

Two sets of better solutions were obtained from the two indicators of blockage rate and damage rate, namely, solution 1

Table 3 Variance analysis result of orthogonal test

Item	Variation source	Degrees of freedom	Sum of squares	Mean square	*F*-value	*p*-value
Blockage rate	*A*	2	8.090	4.045	38.679	0.025*
	B	2	13.541	6.771	64.742	0.015*
	C	2	0.37	0.019	0.177	0.849
	Error	2	0.209	0.105		
	Sum	8	21.877			
Breakage rate	*A*	2	0.561	0.281	8.984	0.100
	B	2	3.864	1.932	61.831	0.016*
	C	2	6.728	3.364	107.661	0.009**
	Error	2	0.062	0.031		
	Sum	8	11.215			

Note: ** very significant (p<0.01)，* significant (0.01<p<0.05)，otherwise, not significant (p>0.05).

*A*3*B*3*C*2 and solution 2 *C*2*B*2*A*2. The success rate of seedling removal in solution 1 was calculated by Equation (14) to be 94.36%. Solution 2 was used to carry out three repeated tests and the success rate of seedling removal was 90.99%. Comparing the two solutions, the success rate of seedling taking reached more than 90%, but the blockage rate of solution 2 was more than one time higher than that of solution 1. Therefore, after comprehensive consideration, the best solution was determined to be solution 1 *A*3*B*3*C*2. The best parameter combination was: inclination angle 3.5°, channel width 50 mm, cylinder pressure 0.6 MPa. At this time, the blockage rate was 2.46%, the breakage rate was 3.18%, and the success rate was 94.36%.

3.3.4 Experimental verification

In order to verify the stability of the orthogonal test parameters, the optimal parameter combination *A*3*B*3*C*2 was verified, and the test was repeated three times to take the average value, as shown in Figure 13. The test results are shown in Table 4: the average blockage rate is 3.23%, the average breakage rate is 3.68%, the average success rate is 93.09%, and the success rate error is 1.27% compared with the orthogonal test results, which meet the design requirements and verify the feasibility and accuracy of the parameter combination.

Figure 13 Experimental verification

Table 4 Verification test result

Experiment No.	Blocking rate/%	Breakage rate/%	Success rate/%
1	4.46	3.79	91.75
2	2.37	2.94	94.69
3	2.85	4.30	92.85
Average	3.23	3.68	93.09

4 Discussion

The push-out seedling removal from substrate blocks is an effective automatic seedling taking method. Compared with the automatic seedling taking device for substrate block seedlings developed by ISO Group (IG Agri Systems BV) in the Netherlands, this study has a lighter structure and simpler process; compared with similar technologies in China, there is no need to frequently fill the seedling tray with substrate blocks, which can reduce labor intensity and improve seedling taking efficiency. It is found from the experiment that the moisture content and firmness of the substrate block have a significant impact on the breakage rate, which in turn affects the success rate of seedling taking. Therefore, subsequent research needs to conduct an in-depth investigation into the molding and formulation of the substrate block. In addition, this paper explored the method of pushing the whole tray to seedlings taking. It is found that the more seedlings there are in the tray, the greater the resistance to seedling taking, which puts forward higher requirements for the strength of the seedling taking mechanism and the compressive resistance of the substrate block. Subsequent research on the single-row pushing seedling removal method could be carried out, which may be helpful in reducing the resistance to seedling taking and lowering the seedling breakage rate.

5 Conclusions

(1) An automatic seedling taking device specially used for substrate block seedling transplanter was designed, and its overall structure and working principle were explained. According to the measured friction parameters of pushing and taking of the whole tray of substrate block seedlings, seedling taking, separation, and delivery mechanisms were designed. The collision rebound and force during substrate block seedling delivery were analyzed by a theoretical analysis and finite element simulation analysis, and the working parameters of the key mechanisms and the conditions for stable transportation of substrate block seedlings were determined.

(2) An automatic control system was developed based on PLC to realize automatic logic control of seedling taking, seedling separation, and seedling delivery. A test bench was also developed. The performance test was carried out with the inclination angle of the limit guide plate, the width of the seedling separation channel, and the pressure of the seedling separation cylinder as the factors, and the blockage rate and breakage rate as the evaluation indicators. The inclination angle range of the limit guide plate was 2.5°-3.5°, the width range of the seedling separation channel was 45-50 mm, and the cylinder pressure range was 0.55-0.65 MPa. The $L9(3^4)$ orthogonal test was used to obtain the optimal parameter combination through range and variance analysis: the inclination angle of the limit guide plate was 3.5°, the width of the seedling separation channel was 50 mm, and the pressure of the seedling separation cylinder was 0.6 MPa.

(3) The optimal parameter combination was verified by experiments: the average blockage rate was 3.23%, the average breakage rate was 3.68%, and the average success rate was 93.09%. Compared with the orthogonal test, the success rate error was 1.27%, which had high stability and met the design requirements.

Credit authorship contribution statement

Zhichao Cui: Conceptualization, writing of the original draft; Jingjing Fu: Data curation; Jicheng Li: Formal analysis; Haibo Ji: Software; Changhao Wu: Visualization; Shuhe Zheng: Methodology; Tiqiong Xiao: Supervision; Yongsheng Chen: Investigation; Chenghao Zhang: Validation; Yating Yang: Writing, review, and editing; Chunsong Guan: Funding acquisition, project administration.

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