DESIGN OF AN AUTOMATIC SEEDLING FEEDING DEVICE FOR A SINGLE-DISC VEGETABLE TRANSPLANTER
/
单盘蔬菜移栽机自动育苗盘供苗装置设计

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ABSTRACT
Currently, most vegetable transplanters are semi-automatic and require manual seedling picking and feeding into the transplanting mechanism. To achieve fully automatic seedling picking and feeding, this study developed an automatic seedling feeding device for a typical single-disc vegetable transplanter. The device consists of three main functional components designed to ensure accurate and continuous seedling delivery: a seedling conveying unit, a seedling feeding unit, and a seedling guiding unit. The seedling feeding success rate was selected as the evaluation indicator, while root plug moisture content, pick-up needle angle, and seedling height were chosen as test factors. Experimental results showed that the optimal conditions - root plug moisture content of 45%, pick-up needle angle of 9°, and seedling height of 50 mm - resulted in a feeding success rate of 92.4%. These findings demonstrate that the proposed device meets the required transplanting efficiency and precision standards for vegetable transplanters. Overall, the developed seedling feeding device provides a theoretical and technical basis for advancing automation in vegetable transplanting equipment.

摘要
目前，蔬菜移栽机大多为半自动，需要人工取苗并将其送入移栽机构。为了实现蔬菜移栽机的自动取苗和送苗，本研究为一种典型的单圆盘蔬菜移栽机设计了一种自动送苗装置。该送苗装置主要有三个重要部分，即苗传输部分、苗送入部分和苗导向部分，以满足自动和精确送苗的要求。以送苗成功率为测试指标，选取苗墩含水量、取苗爪针角度和苗高作为测试因素。送苗试验结果表明，当苗墩含水量为 45%、取苗爪针角度为 9°、苗高为 50 毫米时，送苗成功率为 92.4%。试验结果表明，所设计的送苗装置能够满足移栽机的移栽效率和精度要求。本研究设计的育苗喂送装置为改进蔬菜移栽机的自动化发展奠定了理论基础。

INTRODUCTION
Seedling transplantation reduces the field growth period of vegetables and supports greenhouse-based production systems. It allows centralized management, improves land-use efficiency, and protects seedlings from stress factors such as pests, diseases, and adverse weather conditions. In addition, transplanting increases production efficiency, alleviates labor bottlenecks during peak planting periods, and provides significant economic benefits to vegetable growers *(Marchant et al., 1994; Kumar et al., 2019)*.

The development and application of vegetable transplanters have reduced the manual labor intensity in transplanting operations. Developed agricultural countries, represented by Europe, America, Japan, and South Korea, began researching seedling transplantation techniques as early as the 1920s *(Kunz et al., 2018)*.

To date, most vegetable transplanters have adopted mechatronic technology to control the entire system and perform key operations including seedling transportation, seedling guidance, hole formation, transplanting, and soil covering. *Jo et al. (2018)* developed a vegetable transplanter by analyzing and redesigning the linkage mechanism of the planting device.

Paradkar et al., (2021), designed a tray-seedling sorting transplanter, and the test showed that the success rate of transplantation on a 6×12 tray was 90.0% at a speed of 700 cycles per hour. *Han et al., (2021),* developed a high-speed seeding auto-transplanter that adopted a fully mechanical structure driven by ground wheels. *Yang et al., (2022),* designed a novel type of belt drive seedlings transmission device by considering the requirements of fully-automatic transplanters. Further, the control system of device has also realized in this investigation. The required value of 60 seedlings per minute was achieved at the frequency of 1500 Hz and corresponding success transplanting rate was also 95%. The catapult transplanter developed in Japan has many models and is suitable for various crops *(Sharma et al., 2022)*, but requires a special rigid cavity plate, and the cost is relatively higher than the semi-automatic transplanters (2ZBX-2A Vegetable transplanters) in China *(He et al., 2023)*.

According to the feeding method of the transplanter, it can be divided into semi-automatic transplanter and fully automated transplanter, which is mainly determined by whether the seedlings need to be manually picked from the seedling tray and fed into the transplanting components during the transplanting operation *(Syed et al., 2019; Manuel et al., 2021)*. At present, the commonly used transplanters in the market are mainly semi-automatic transplanters, which still require manual seedling feeding, and the planting action is completed by the planting device. However, when manually planting seedlings, due to limited human abilities, the speed and efficiency of planting are limited, which can lead to the problem of missing seedlings *(Yin et al., 2010; Francesca et al., 2019)*.

In addition, because semi-automatic vegetable transplanters require space for operators to manually feed seedlings, these machines are typically large and heavy. Fully automatic vegetable transplanters can reduce labor requirements, improve operational efficiency, and lower labor costs *(Daisuke et al., 2019)*. Therefore, developing an automatic seedling feeding device for semi-automatic transplanters is an essential step toward achieving full automation in vegetable transplanting machinery *(Ana et al., 2023; Xinwu et al., 2023)*.

However, research on automatic seedling feeding systems for vegetable transplanters is still largely in the experimental stage. *Choi et al. (2002)* developed a seedling pick-up mechanism using a path generator and pin driver. *Wen et al. (2021)* designed a traction-driven, double-row vegetable plug transplanter consisting of multiple specialized modules, including seedling feeding, combing, ejecting-type seedling extraction, plate flipping, seedling conveying, seedling separation, a double-crank five-bar planting mechanism, and empty-tray recovery. *Changjie et al. (2021)* developed a mechanical pick-up system for a high-speed automatic transplanter and evaluated it under laboratory and field conditions. The robotic arm achieved a handling capacity of 20 seedlings per minute, with a cycle time ranging from 2.5 to 3.1 seconds per seedling. The power consumption of the conveyor and robotic arm was 18 W and 16 W, respectively. Under laboratory testing, the conveying, metering, and overall efficiency of the system were 96.83%, 95.91%, and 92.86%, respectively, while field performance reached 94.70%, 93.28%, and 88.33%.

Currently, existing automatic seedling feeding devices generally suffer from low accuracy, poor versatility, complex operation, and high manufacturing cost, which limits their widespread adoption *(Mohith et al., 2019)*. Some transplanters rely on chute-type mechanisms that allow seedlings to slide into the planting unit; however, the design of such systems constrains operational efficiency and may cause mechanical damage to vegetable seedlings *(Cui et al., 2019)*. To overcome these shortcomings, certain transplanters retain seedling cups to assist with seedling feeding. In this configuration, seedlings are picked and delivered into cylindrical seedling cups during the transplanting process *(Jia et al., 2019)*. As the mechanism rotates, each cup opens upon reaching the planting position, ensuring accurate placement of seedlings into the soil.

In this study, an automatic seedling feeding device was designed for a single-disc vegetable transplanter equipped with inner and outer ring structures. The system consists of four primary components: a seedling conveying module, a seedling feeding module, a seedling guiding module, and an automatic control system. By analyzing the motion trajectory of the seedling pick-up process and conducting feeding performance tests, the structural configuration and key transplanting parameters were optimized. The final design achieves stable and coordinated seedling pick-up and feeding functions. The mechanism developed in this research is suitable for integration with various semi-automatic vegetable transplanters. The findings provide a technical basis for advancing fully automated vegetable transplanting systems.

MATERIALS AND METHODS

Overall structure and working principle

In this study, a single-disc vegetable transplanter of the FPA2 type, manufactured by Ferrari Growtech Italy *(https://ferrarigrowtech.com/en/)*, was selected as the reference machine. This model is widely used in vegetable transplanting operations across multiple regions and crop types. During field operation, the transplanter requires seedling root plugs to remain structurally stable without breakage or crumbling, and the seedling height must not exceed 180 mm.

The transplanter adopts a double-row planting configuration, where two operators manually place seedlings into the seedling cups located on both sides of the machine. When the seedling cup reaches the designated position, it opens to release the seedling into the duckbill planting mechanism, completing the transplanting process. The objective of this study was to design an automatic seedling feeding device compatible with this widely used transplanter model. A schematic representation of the proposed system is shown in Figure 1.

Fig. 1 - Single-disc vegetable transplanter equipped with the developed automatic seedling feeding device

Before implementing the automatic seedling feeding device, the original transplanter required manual seedling pickup and placement into the inner and outer circular openings of the seedling tray, as shown in Fig. 2(a). The automatic seedling feeding device developed in this study is designed to replace this manual process and achieve automated seedling pickup and feeding, as illustrated in Fig. 2(b).

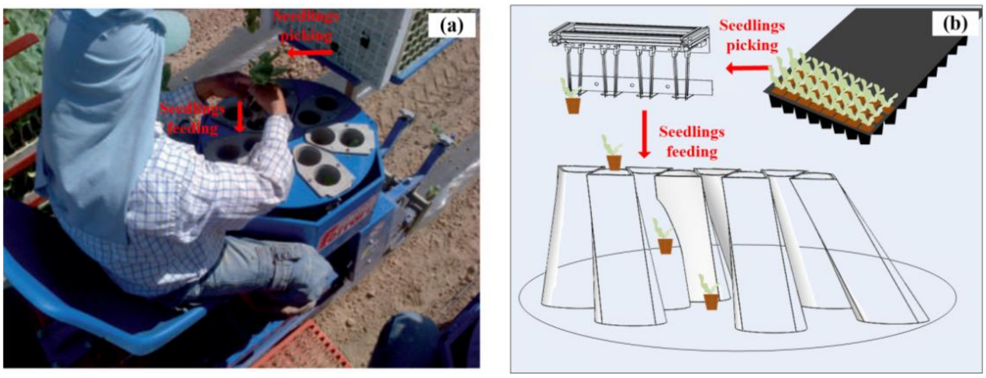

Fig. 2 - Manual and automated seedling feeding processes

(a) Manual seedling feeding. (b) Automated mechanical seedling feeding.

Based on the operating characteristics and feeding requirements of the selected transplanter, the primary function of the automatic seedling feeding device is to extract rows of seedlings from the plug tray and, with the assistance of a guiding mechanism, accurately place them into the inner and outer circular openings of the machine's seedling tray. Through the coordinated motion of the seedling cups, the automatic system ensures a transplanting effect equivalent to manual seedling feeding. Once the transplanting operation begins, the control system synchronizes and manages all components of the device to complete the automated feeding and transplanting process.

The working principle of the system can be summarized as follows: the seedling pick-up mechanism descends and grips an entire row of seedlings from the plug tray. The seedlings are then released and guided precisely into the corresponding openings on the transplanter disc. After each feeding cycle is completed, the plug tray automatically advances to the next position to ensure proper alignment for the subsequent pick-up action.

Key components and control system design

Mechanical structure of the seedling pick-up claw

The seedling pick-up claw consists of a gripper needle, an H-shaped base, a needle connector, and a fixed gripper plate. To simplify the overall mechanism and improve operational stability, the design incorporates four gripper needles, which enhance seedling holding reliability during the pick-up process. The geometric dimensions of the robotic gripper were determined based on the size and shape of the seedling root plug, with a plug-tray hole spacing of 32 mm. The root plug has an inverted quadrangular shape, and its static force distribution during gripping is illustrated in Fig. 3.

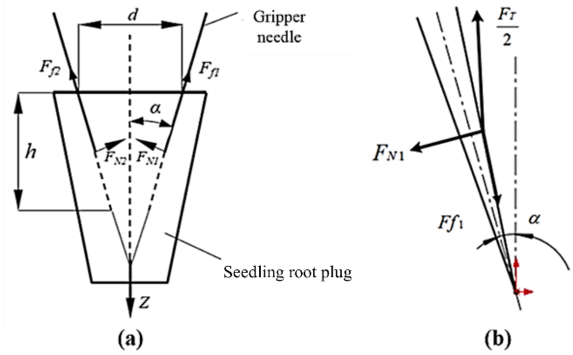

Fig. 3 - Static force analysis of the root plug and gripper needle
(a) Main forces acting on the gripper needles within the root plug.
(b) Enlarged schematic of the force analysis for a single gripper needle

During insertion, the root plug receives lateral support from the surrounding substrate inside the plug hole. As the gripper needle enters the root plug, it is subjected to a normal force F_{N1}, while a friction force F_f is generated between the needle surface and the substrate. The friction force F_f consists of two components: the soil internal friction force F_{soil} caused by contact between soil particles, and the sliding friction force F_{slide} produced by the adhesive interaction between the substrate and the needle surface. The total friction force F_f can be expressed as:

$$F_f = F_{soil} + F_{slide} = \mu(F_N + BS) \tag{1}$$

where, μ is the friction coefficient between the gripper needle and the substrate (0.7), B is the maximum adhesive force of the substrate (2.4 N at maximum based on preliminary testing), S is the contact area between the needle and the root plug (unit: cm^2). In this design, the contact area S is relatively small and its influence can be considered negligible.

Formula (1) can be further simplified as follows.

$$\begin{gathered} F_f = \mu F_N \\ F_f \cdot \cos\alpha + F_{N1} \cdot \sin\alpha = \frac{B+G}{2} \end{gathered} \tag{2}$$

After substituting F_f=μF_{N1} into formula (2), the resulting expression is:

$$F_{N1} = \frac{B+G}{2\times(\mu\cos\alpha + \sin\alpha)} \tag{3}$$

It can be concluded that the B and μ are force-related parameters. The value of B was obtained experimentally as 2.4 N. The value of μ and G remain constant under the given conditions. Therefore, the gripping force applied to the root plug is primarily determined by the entry angle *α* of the pick-up needle. The measured value of F was 5.2 N.

$$\frac{F}{\cos\alpha} = \frac{B+G}{2\times(\mu\cos\alpha + \sin\alpha)} \tag{4}$$

This equation describes the relationship between the entry angle *α* of the pick-up needle and the force applied to the root plug. Simulation results indicate that the optimal seedling pick-up performance occurs when *α* is within the range of 7° to 11°. To meet functional requirements, the clamping force applied by the pick-up claw to the root plug must remain balanced with the external forces acting on it. Therefore, the following condition must be satisfied:

$$F_N = 2[\sin\alpha \cdot (F_{N1} + F_{N2})] + \cos\alpha \cdot (F_{f1} + F_{f2})$$
$$F_{f1} = \mu F_{N1}$$
$$F_{f2} = \mu F_{N2} \tag{5}$$
$$Z \le F_Z$$

where, F_Z is the vertical pulling force applied to the root plug, expressed as, $F_Z = G + B$.

F_Z represents the total longitudinal extraction force and can be written as:

$$F_Z = 4F_{N1}(\sin\alpha + \mu\cos\alpha)$$
$$F_{N2} = \frac{F}{\cos\alpha} \tag{6}$$
$$F_Z = \frac{4F}{\cos\alpha}(\sin\alpha + \mu\cos\alpha) = 4F(\mu + \tan\alpha)$$

The average weight of the root plug G was measured as 0.1 N.

$$Z = G + B \tag{7}$$

By substituting the entry angle α of the pick-up needle into Equation (23). F_Z =17.48 N.

The fundamental driving force must satisfy the following condition:

$$P_{actual} \ge F_Z \frac{K_1 K_2}{\eta} \tag{8}$$

where, η is the working efficiency, defined as 0.9, K_1 is the working condition coefficient, defined as 1.1.

Assuming the maximum acceleration during root plug gripping is a=g, the expression becomes.

$$K_2 = 1 + \frac{a}{g} = 2 \tag{9}$$

Therefore: $P_{actual} \ge F_Z \frac{K_1 K_2}{\eta} \approx 42.8\ N$

Seedling feeding module design

The seedling feeding module is responsible for picking and placing seedlings and serves as one of the key functional components in the automatic feeding system. The structure consists of a load-bearing profile, supporting frame, sliding block, slide rail, and an electric push rod, as shown in Fig. 4.

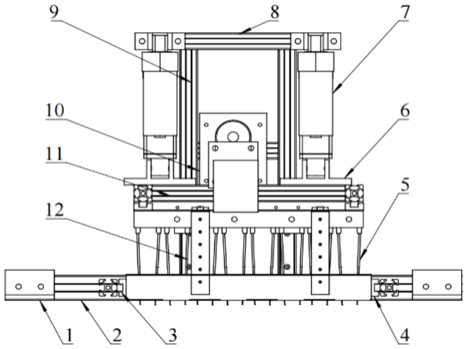

Fig. 4 - Schematic diagram of seedling feeding module

1. Profile connector; 2. Load-bearing profile; 3. Miniature slide rail; 4. Miniature sliding block; 5. Seedling pick-up claw; 6. Electric push-rod connector; 7. Electric push rod; 8. Gantry frame; 9. Supporting profile; 10. Separation device; 11. Gripper connection profile; 12. Drive sliding block

During operation, the horizontal seedling conveying unit positions the seedling feeding module at the designated pick-up and placement locations. At this stage, the control system initiates and coordinates the automatic feeding sequence. Before the system begins working, the pick-up claw remains in a retracted standby position. Once the feeding process starts, the seedling feeding module moves backward under the drive of the horizontal transmission unit until it reaches the row of seedlings. The electric push rod within the feeding module then extends, while the push rod in the vertical transmission unit retracts, allowing the pick-up claw to penetrate the root plug and complete the gripping action. Next, the push rod in the vertical transmission unit extends to lift and separate the root plug from the tray. A separation mechanism then activates, dividing the gripper needles into two rows with a spacing equivalent to one plug hole. The horizontal transmission unit then moves the feeding module forward to the designated release position. The electric push rod in the feeding module retracts, allowing the root plug to drop automatically into the seedling guiding mechanism. Finally, the push rods in both the separation mechanism and the vertical transmission unit return to their initial retracted positions, completing one full feeding cycle.

After completing the above steps, one full seedling feeding cycle is finished. The seedling feeding unit features a square structural configuration, as shown in Fig. 5.

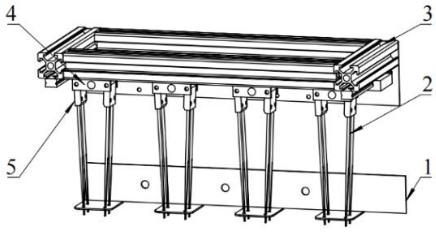

Fig. 5 - Structural diagram of the seedling pick-up claw

1. Gripper plate; 2. Gripper needle; 3. Square profile; 4. H-shaped base; 5. Needle connector

The seedling pick-up assembly consists of two rows of claw units, with four pick-up claws arranged on each row. The claws move forward and backward through the separation mechanism, and vertically through the actuation of an electric push rod. The seedling feeding structure uses a 30 mm × 30 mm aluminum profile with a wall thickness of 1.2 mm for load-bearing and support. The load-bearing profile and supporting profile measure 510 mm and 260 mm in length, respectively, and their tensile and yield strength values meet the structural design requirements. An MGN15 linear guide rail (Model MGN15, Hengdadaogui Co., Ltd., Jiangsu, China) was mounted onto the supporting profile and secured with bolts to ensure structural rigidity and smooth motion. The profile used to mount the seedling pick-up claws was a 20 mm × 20 mm European-standard aluminum profile with a wall thickness of 1.5 mm. A secondary linear guide rail (Model MCN9, Hengdadaogui Co., Ltd., Jiangsu, China) was installed beneath this profile.

Seedling guiding module

The FPA2-type vegetable transplanter is designed with a single rotating disc and transplants seedlings in two rows per ridge. The disc has a diameter of 490 mm and contains 14 seedling guiding holes, each with a diameter of 7 mm, as shown in Fig. 6(a). These holes are evenly arranged in inner and outer circular rings. A through-hole is positioned on each ring for planting, with diameters of 190 mm (inner ring) and 350 mm (outer ring). The system operates as a tractor-mounted attachment, and both the disc rotation speed and transplanting speed are determined by the rotation of the tractor's land wheel.

During operation, the feeding system picks up one full row of seedlings from the plug tray. The seedling pick-up claws transfer eight seedlings at a time, corresponding to eight consecutive positions on the disc, including the two through-holes used for planting. The disc rotates clockwise such that seedlings are positioned in the final four positions of the circular path before reaching the planting holes. The red-marked position in Fig. 6(b) indicates the seedling release point. After the pick-up device retrieves the full row of eight seedlings, the separation mechanism divides them into two rows with a spacing of 50 mm. The lower end of the guiding module aligns these two rows with the corresponding disc positions, as shown in Fig. 6(c).

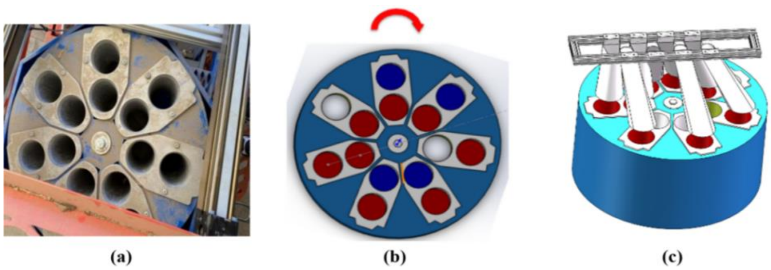

Fig. 6 - Seedling pick-up disc and alignment of the seedling guide

(a) Physical image of the seedling pick-up disc. (b) Schematic diagram of the seedling pick-up disc. (c) Alignment between the seedling guide and the disc.

With this design approach, the overall structure of the automatic seedling feeding device is shown in Fig. 7. The device features a compact and reliable layout capable of meeting the automatic seedling feeding requirements of the transplanter.

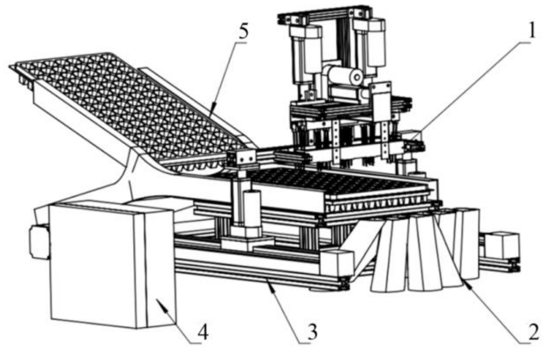

Fig. 7 - Assembly diagram of the automatic seedling feeding device

1. Seedling feeding module; 2. Seedling guiding module; 3. Horizontal seedling conveying module; 4. Control box; 5. Plug seedling tray

The automatic seedling feeding device developed in this study for a single-disc vegetable transplanter with inner and outer ring configuration consists of three main functional modules: the seedling conveying module, the seedling feeding module, and the seedling guiding module. The system is powered by a 48 V DC power supply and is capable of operating continuously for more than 20 hours. When integrated with the Ferrari Growtech FPA2 vegetable transplanter, the device achieved a transplanting capacity of approximately 2,800–3,600 seedlings per hour.

Design of Control System

The control system of the automatic seedling feeding device consists of three main functional components: the signal input module, the control center, and the actuation (motion execution) system, as shown in Fig. 8. The actuation system includes a seedling conveying control module and a seedling feeding control module. The transmission module incorporates a servo-motor-driven actuator, while the seedling feeding module uses an electric push rod to control extension and retraction of the seedling handling mechanisms. The input/output module manages system initialization and operational start commands. Under programmable logic controller (PLC) control, the servo motor drives the horizontal synchronous belt module to move the feeding mechanism forward and backward. The forward stop position corresponds to the seedling guiding unit, while the backward stop position aligns with the plug tray. Vertical lifting and lowering of the feeding mechanism are controlled by an electric cylinder. An electric push rod installed in the separation mechanism divides the mechanical claw into front and rear rows for seedling spacing. Another electric push rod located in the seedling feeding module controls the opening and closing of the pick-up claw, completing the seedling gripping and releasing actions.

The seedling pick-up and feeding control system was developed using a PLC controller (Model 6ES7 288-1ST30-0AA0, Siemens Ltd.). Hall proximity switches (Model NJK-5001A, Shanghai Hugong Co., Ltd., Shanghai, China) were installed at key positions to provide signals for controlling motor start, stop, and rotational motion, ensuring precise positioning of the seedling pick-up and feeding mechanisms. During operation, the feeding gripper descends to grasp the root plugs, then moves to the seedling guiding section to release them. In addition, a photoelectric switch (Model LJ18A-3, Zhengtaidianzi Co., Ltd., Zhejiang, China) was used to monitor step-by-step movement and confirm whether the feeding mechanism reached the designated position.

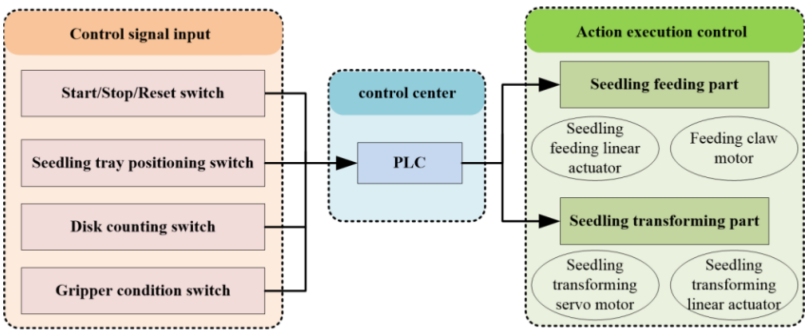

Fig. 8 - Schematic diagram of the main components of the control system

The operational logic of the seedling feeding device consists of six sequential steps, as illustrated in Fig.9.

Step 1: Before the device begins operation, the system executes a reset command to ensure all components return to their initial positions. The electric push rod in the separation mechanism retracts, merging the two rows of pick-up claws into a single row. The horizontal transmission unit positions the feeding assembly above the seedling guiding unit, while the vertical transmission mechanism returns the assembly to its initial rear position. Step 2: Once the transplanting process starts, the control system coordinates all motion components. The horizontal transmission mechanism moves the feeding assembly backward until it aligns above the first row of root plugs. Step 3: The electric push rod in the feeding module lowers the feeding gripper. The pick-up claw then closes to grip the root plug. After gripping, the vertical transmission mechanism lifts the pick-up claw to remove the seedling from the tray. Step 4: During horizontal movement, the separation mechanism activates and divides the claw into two rows with the required spacing. Step 5: Once positioned above the seedling guiding section, the electric push rod retracts to open the claw. The vertical mechanism lowers the claw, allowing the seedlings to be released into the guiding structure. Step 6: The horizontal transmission mechanism then returns the feeding assembly to the second row of the tray to begin the next pick-up cycle. The process continues sequentially until all seedlings from the tray are fed.

Fig. 9 - Main operating steps of the seedling feeding control program

RESULTS

Quadratic regression optimization test

Based on previous studies, three factors were selected for optimization: root plug moisture content, pick-up needle angle, and seedling height. A three-factor quadratic regression test was conducted, with a star-point (α-level) distance of γ = 1.682. The factor level coding scheme used in the experiment is shown in Table 1.

Table 1

Factor level coding scheme for the seedling pick-up success rate experiment

Coded value *x*	X_1 Moisture content of root plug/%	X_2 Gripper needle angle/°	X_3 Seedling height/mm
Upper star point (+1.682)	52	11	62
Upper level (+1)	45	10	55
Central level (0)	35	8	45
Lower level (-1)	25	6	35
Lower star point (-1.682)	19	5	29

Based on the factor level coding shown in Table 1, the seedling pick-up test was conducted using different parameter combinations. The experimental design and results are presented in Table 2.

Table 2

Experimental design and results of the seedling pick-up success rate

No.	Moisture content of root plug / %	Gripper needle angle / °	Seedling height / mm	Seedling pick-up success rate / %
1	25	6	35	62
2	45	6	35	72
3	25	10	35	77
4	45	10	35	82
5	25	6	55	73
6	45	6	55	92
7	25	10	55	83
8	45	10	55	92
9	19	8	45	73
10	52	8	45	90
11	35	5	45	74
12	35	11	45	90
13	35	8	29	73
14	35	8	62	80
15	35	8	45	93
16	35	8	45	86
17	35	8	45	87
18	35	8	45	88
19	35	8	45	86
20	35	8	45	85

Test result and analysis

Based on the selected test factors and evaluation indicators, an optimization experiment was conducted, and the corresponding design matrix and results are presented in Table 2. Design-Expert software was used to perform regression modeling and analyze the relationship between the three experimental factors and the response variable (seedling pick-up success rate). The significance and contribution of each factor to the response were also evaluated. Following regression analysis, a ternary quadratic regression model describing the seedling pick-up success rate was obtained, expressed as:

$$Y = -2X_1^2 - 1.82X_2^2 - 3.77X_3^2 - 2.37X_1X_2 + 0.63X_1X_3 - 1.37X_2X_3 + 5.85X_1 + 4.24X_2 + 3.72X_3 + 87.48 \quad (10)$$

At a significance level of α=0.05, the regression model underwent an analysis of variance (ANOVA) to evaluate its statistical significance and model adequacy. The ANOVA results are shown in Table 3.

Table 3

Analysis of variance (ANOVA) for seedling pick-up performance

Source of variation	Sum of squares	Degree of freedom	Mean square	F-value	P-value
Regression equation	1,229.28	9	136.59	17.76	0.0001**
X_1	463.84	1	463.84	60.30	0.0001**
X_2	245.55	1	245.55	31.92	0.0002**
X_3	188.76	1	188.76	24.54	0.0006**
X_1X_2	45.12	1	45.12	5.87	0.0359*
X_1X_3	3.13	1	3.13	0.41	0.5382

Source of variation	Sum of squares	Degree of freedom	Mean square	F-value	P-value
X_2X_3	15.12	1	15.12	1.97	0.1911
X_1^2	57.58	1	57.58	7.49	0.0210*
X_2^2	47.85	1	47.85	6.22	0.0318*
X_3^2	204.47	1	204.47	26.58	0.0004**
Residual	76.92	10	7.69		
Lack of fit	35.42	5	7.08	0.85	0.5668
Pure error	41.50	5	8.30		
Total	1306.20	19			

*Note: ** Indicates a highly significant difference at p<0.01, * indicates a significant difference at p<0.05.*

Based on the optimization results, the highest predicted seedling pick-up success rate of 92.7% was achieved when the substrate moisture content was 45%, the pick-up needle angle was 8.63°, and the seedling height was 50.2 mm. Considering equipment tolerance and practical control limitations, the experimental validation was performed using a root plug moisture content of 45%, a pick-up needle angle of 9°, and a seedling height of 50 mm. For verification, three batches of plug trays were tested, each containing 128 seedlings, for a total of 384 seedlings. Among them, 355 seedlings were successfully picked up, resulting in an actual pick-up success rate of 92.4%.

The difference between the predicted value (92.7%) and the experimental result (92.4%) was minimal, indicating strong agreement between the model and experimental conditions. These findings confirm that under the optimized operating parameters (45% moisture content, 9° needle entry angle, and 50 mm seedling height), the automatic seedling feeding device meets the operational performance requirements of the transplanter.

CONCLUSIONS

In this study, an automatic seedling feeding device was developed for a single-disc vegetable transplanter with inner and outer ring configuration, based on modifications to the semi-automatic FPA2 model produced by Ferrari Growtech. The system consists of three primary mechanical modules - seedling conveying, seedling pick-up, and seedling guiding - coordinated by a programmable logic controller (PLC)-based control system to achieve automatic and precise seedling handling. According to operational requirements and testing results, the integrated transplanter achieved a working efficiency of approximately 2,800 - 3,600 seedlings per hour, substantially improving transplanting productivity. The complete seedling feeding device weighs 15 kg, making it compact and suitable for installation on existing transplanter platforms.

A three-factor optimization experiment was conducted to evaluate key operational parameters, and analysis of variance confirmed the significance of the regression model. The optimized parameter combination was verified through field testing. The final validation demonstrated a seedling pick-up success rate of 92.7%, closely matching the predicted performance. Under the practical operating parameters, root plug moisture content of 45%, pick-up needle angle of 9°, and seedling height of 50 mm, the device achieved a seedling feeding success rate of 92.4%.

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REFERENCES

[1] Ana, L. A. R., et al. Vegetation Indices for Predicting the Growth and Harvest Rate of Lettuce. (2023). *Agriculture*, 13(5), 1091.

[2] Changjie, H., Xianwei, H., Jing, Z., Jia, Y., Honglei, L. (2021). Design and testing of the mechanical picking function of a high-speed seedling auto-transplanter. *Artificial Intelligence in Agriculture*, 5, 64-71.

[3] Choi, W. C., Kim, D. C., Ryu, I. H., Kim, K. U. (2002). Development of a Seedling Pick-Up Device for Vegetable Transplanters. *Transactions of The Asae*, 45(1), 13-19.
[4] Cui, C., Chen, Z., Xu, D., Yang, X., Fu, Y. (2019). Research Status and Development Trend of Whole Row Acupoint Plate Seedling Transplanting Machine. *Xinjiang Agricultural Mechanization*, 4, 20-23.
[5] Daisuke, M., Tohru, Y. (2019). Factors that Affect Nonmarket Fruit and Vegetable Receptions: Analyses of Two Cross-Sectional Surveys in Gunma, Japan. *Agriculture*, 9(11), 230.
[6] Francesca, D. C., Beniamino, L. M. M., Massimiliano, R., Pietro S. (2019). Yield and Quality of Faba Bean Genotypes as a Vegetable for Fresh Consumption: A Comparison between Italian Landraces and Commercial Varieties. *Agriculture*, 9(12), 253.
[7] Han, C., Hu, X., Zhang, J., You, J., Li, H. (2021). Design and testing of the mechanical picking function of a high-speed seedling auto-transplanter. *Artificial Intelligence in Agriculture*, 5, 64–71.
[8] He, T., Li, H., Shi, S., Liu, X., Liu, H., Shi, Y.g, Jiao, W., Zhou, J. (2023). Preliminary Results Detailing the Effect of the Cultivation System of Mulched Ridge with Double Row on Solanaceous Vegetables Obtained by Using the 2ZBX-2A Vegetable Transplanter. *Applied Sciences*, 13(2),1092-1092.
[9] Jia, B., Ye, M., Zhai, X., Han, L., Lv, J. (2019). Design and Tests of Cam-link Combination Pick-up Device for Vegetable Transplanters. *Journal of Agricultural Mechanization Research*, 6, 78-82.
[10] Jo, J. S., Okyere, F. G., Jo, J. M., Kim, H. T. (2018). A Study on Improving the Performance of the Planting Device of a Vegetable Transplanter. *Journal of Biosystems Engineering*. 43(3), 202-210.
[11] Kumar, G.V. P., Raheman, (2011). H. Development of a walk-behind type hand tractor powered vegetable transplanter for paper pot seedlings. *Biosystems Engineering*, 110, 189-197.
[12] Kunz, G., Perondi, E., & Machado, José. (2018). A design strategy for obtaining reliable controllers for critical mechanical systems. *Mechatronics*.
[13] Manuel, P. R., David, C. S. (2021). Development of a precision 3-row synchronised transplanter. *Biosystems Engineering*, 206, 67-78.
[14] Marchant, J. A., Tillett, R. D. (1994). Software and transplanter system design for high-speed grading of agricultural produce. *Mechatronics*, 4(3): 281-293.
[15] Mohith, S., Karanth, P. N., Kulkarni, S. M. (2019). Recent trends in mechanical micropumps and their applications: A review. *Mechatronics*, 60:34-55.
[16] Paradkar, V., Raheman, H., Rahul, K. (2021). Development of a metering mechanism with serial robotic arm for handling paper pot seedlings in a vegetable transplanter. *Artificial Intelligence in Agriculture*, 5(5),52-63.
[17] Sharma, A., Khar, S. (2022). Current developments in vegetable transplanters in developing countries: a comprehensive review. *International Journal of Vegetable Science*, 28 (5), 417-440.
[18] Syed, T. N., Jizhan, L., Xin, Z., Shengyi, Z., Yan, Y., Mohamed, S. H. A., Lakhiar, I. A. (2019). Seedling-lump integrated non-destructive monitoring for automatic transplanting with Intel RealSense depth camera. *Artificial Intelligence in Agriculture*, 3, 18-32.
[19] Wen, Y., Zhang, J., Tian, J., Duan, D., Li, X. (2021). Design of a traction double-row fully automatic transplanter for vegetable plug seedlings. *Computers and Electronics in Agriculture*, 182, 106017.
[20] Xinwu, D., Zhihao, Y., Xin, J., Pengfei, L., Kaihang, G. (2023). Design and Experiment of Automatic Adjustable Transplanting End-Effector Based on Double-Cam. *Agriculture,* 13(5), 987.
[21] Yang, T., Yang, M., Yao, S., Shi, Q., Liu, J. (2022). Research and Development of Transplanting Machine. *Agricultural Equipment & Vehicle Engineering*, 60(7):15-19.
[22] Yin, J., Liu, Y., Xie, Y. (2010). Visual optimization design of manipulator for transplanting rice seedlings. 2010 *International Conference on Mechanic Automation and Control Engineering*, 1, 483–486.