DESIGN AND EXPERIMENT OF AN INTEGRATED AUTOMATIC TRANSPLANTING SYSTEM WITH A FLEXIBLE END-EFFECTOR FOR PLUG SEEDLINGS
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基于柔性末端执行器的钵苗全自动移栽系统的设计与试验

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ABSTRACT
Automatic transplanting of plug seedlings is critical for improving agricultural efficiency. However, existing systems often suffer from functional fragmentation and use rigid end-effectors prone to damaging seedlings. This study presents a fully integrated automatic transplanting system that uniquely combines multi-tray storage and conveying, precise step-moving, manipulator-based picking and placing with a novel flexible end-effector, and automatic tray collection. In experiments using pepper seedlings, conducted over repeated trials (n=5) with 576 seedlings per trial, the integrated system achieved a picking success rate of 93.24% and a damage rate of 1.43%, with a maximum conveying positioning deviation of 1.79 mm. Compared with previously reported transplanting systems, the proposed system achieves a superior success rate while delivering a substantially lower seedling damage rate. This research provides a practical, highly integrated solution for small-to-medium scale nurseries.

摘要
全自动穴盘苗移栽对于提高农业效率至关重要。然而，现有系统常存在功能碎片化问题，且使用易损伤幼苗的刚性末端执行器。本研究提出了一种全自动移栽系统，创新地集成了多盘存储与输送、精确步进定位、基于机械手的移栽（配备新型柔性末端执行器）以及空盘自动收集。在以辣椒幼苗为对象的重复试验中（n=5，每次576株），该集成系统的取苗成功率达93.24%，损伤率为1.43%，最大输送定位偏差为1.79 mm。与已有文献报道的移栽系统相比，本系统在达到更优异的取苗成功率的同时，实现了更低的幼苗损伤率。本研究提供了一种实用、高度集成的解决方案，适用于中小型苗圃。

INTRODUCTION
Seedling transplanting techniques are extensively used in the cultivation of major crops such as vegetables and rapeseed in China *(Liu et al., 2023)*. Compared with direct seeding, transplanting can shorten the field growth period of crops, enhance their resistance to natural disasters, and significantly increase yield per unit area *(Sharma and Khar, 2022)*. As labor shortages and rising costs become more pronounced, the development of efficient and reliable automatic transplanting machines is crucial *(Yang et al., 2020)*.

Currently, seedling transplanting in China still predominantly relies on semi-automatic transplanters *(Han et al., 2019; Jin et al., 2021)*. Their operational efficiency and quality are limited by the speed of manual seedling picking, resulting in low productivity, operator fatigue, and inconsistent plant spacing *(Wen et al., 2021; Zhang et al., 2024)*. To overcome these bottlenecks, developing fully automatic transplanting mechanisms has become a key research focus *(Khadatkar et al., 2021; Liu et al., 2022)*.

In European and American countries, fully automatic transplanters have reached an advanced level, such as the FUTURA from Ferrari and the GR-2700 from Visser *(Shao et al., 2021)*. However, such machines are typically large, costly, and designed for standardized trays, making them difficult to adapt to the small-to-medium scale and diversified operation modes in China *(Tian et al., 2022)*.

Chinese researchers have focused on the core seedling picking device, developing various technical approaches. *Shang et al. (2026)* developed an automatic seedling picking and placing manipulator for tobacco

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seedling transplanting machines, and conducted kinematics analysis and optimization. While their study did not address the integration of the manipulator with upstream seedling feeding and downstream tray handling, leaving the overall workflow discontinuous. *Jin et al. (2018)* designed a single-row automatic transplanting device for tomato plug seedlings, although the device demonstrated feasibility, the use of rigid picking fingers caused noticeable damage to seedling roots during clamping.

Han et al. (2023) developed a simplified automatic transplanting device equipped with a multi-needle gripper. However, the multi-needle design exerted concentrated stress on the substrate surface, leading to local breakage of the soil plug in approximately 2.69% of the seedlings tested. *Ye et al. (2020)* proposed a rotary seedling pick-up mechanism that improved picking speed, yet the rotating motion generated considerable inertial forces that compromised positioning accuracy at higher operating speeds. *Zhou et al. (2024)* combined pneumatic and mechanical technologies to design a dual-row seedling pick-up transplanter, but the complex pneumatic circuit and multiple actuators increased system cost and maintenance complexity.

In terms of functional integration, *Zhao et al. (2022)* designed a multi-functional transplanting system integrating sorting, transplanting, and replanting. Despite its innovative integration, the system relied on a vision module that significantly increased processing time, reducing overall throughput. *Zhu et al. (2025)* put forward automated equipment for vegetable seedling transplanting, which enables intermittent seedling feeding, precise seedling picking and rapid seedling planting. Nevertheless, their system still employed rigid end-effectors without passive compliance, and the upstream/downstream tray logistics were not fully automated.

A critical review of the existing literature indicates that several key challenges and research gaps persist. Firstly, most seedling pick-up mechanisms utilize rigid fingers that can damage the root system *(Bai et al., 2022)*. This issue is particularly acute in the designs of *Jin et al. (2018)*, *Han et al. (2023)*, and *Zhu et al. (2025)*, where concentrated clamping forces directly injured seedlings. Secondly, mechanisms with multiple simultaneously operating end-effectors can generate significant inertial impact, affecting precision and stability, as observed in the rotary mechanism of *Ye et al. (2020)* and the pneumatic system of *Zhou et al. (2024)*. Thirdly, and most critically, at the system level, existing research often focuses narrowly on picking and placing, neglecting upstream processes of tray storage and conveying, and downstream empty tray collection. This functional fragmentation limits overall automation and operational continuity.

To address these challenges, the present study puts forward the following innovations: (1) A novel flexible end-effector with a passive compliance mechanism is developed, integrating a spring-buffering and hinge-sliding composite structure that effectively decouples actuation force from clamping force, thereby reducing clamping impact and minimizing seedling injury. (2) An integrated automatic transplanting system is established, combining multi-tray storage and conveying, step-by-step positioning, manipulator-based picking and placing, and automatic tray collection. Our integrated design achieves a continuous and fully automated process from full-tray input to empty-tray stacking, eliminating intermediate manual interventions.

The overarching objective of this study is to provide a practical, highly integrated, and low-damage automatic transplanting solution suitable for small-to-medium scale nurseries in China. Through the integrated design and flexible end-effector, this research offers a feasible technical pathway for automated plug seedling transplanting, and serves as an important reference for developing next-generation automatic transplanting equipment.

MATERIALS AND METHODS

Overall Design of the Integrated Automatic Transplanting System

The automatic transplanting system consists of a frame, plug trays, a multi-tray storage and conveying unit, a tray step-moving unit, a seedling picking and placing unit, and a tray collecting unit (Fig. 1). The key technical specifications of the developed automatic transplanting system are summarized in Table 1.

The system workflow is as follows: eight 72-cell plug trays (cell center distance 42 mm) are placed on the storage unit. A geared motor drives them vertically to the picking station. An electric push rod pushes the tray onto the step-moving unit, which uses a dual-axis linear module to move the tray step by step (42 mm each time) along an S-shaped path. After the tray step-moving unit completes precise tray positioning, a cam in the seedling picking and placing unit ejects the seedling from the tray. Subsequently, a manipulator equipped with the flexible end-effector completes the seedling picking, lifting, transferring, and releasing operations. When all seedlings in one tray are transplanted, the empty tray is pushed to the collection unit, where it is lifted by cams and supported by electric push rods for stacking. Simultaneously, the multi-tray storage and conveying unit pushes the next tray filled with seedlings onto the step-moving unit, allowing the seedling picking and placing unit to begin a new transplanting cycle, achieving continuous operation.

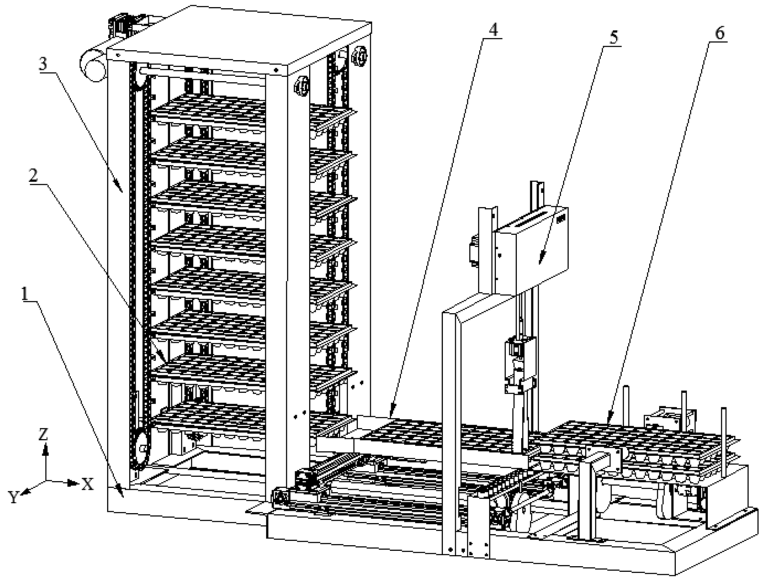


Fig. 1 - Overall structure of the integrated automatic transplanting system
1 - Frame; 2 - Plug tray; 3 - Multi-tray storage and conveying unit; 4 - Tray step-moving unit; 5 - Seedling picking and placing unit; 6 - Tray collecting unit

Table 1

Key technical specifications of the integrated automatic transplanting system

Parameter	Value / Specification
Overall dimensions (L × W × H)	2140 × 705 × 1265 mm
Total weight	273 kg
Total installed power	approximately 1.0 kW
Power supply	220V AC
Manipulator X/Y repeatability	±0.03 mm
Manipulator Z repeatability	±0.2 mm
Minimum motion cycle	0.8 s
Maximum operating speed	approximately 600 mm/s
Rated load (at min. cycle)	200 g
Transplanting efficiency	60 plants/min/row

Design of the Seedling Picking and Placing Unit

The seedling picking and placing unit mainly consists of a manipulator device and a seedling ejection device. The ejecting device pushes the seedling out of the tray, and the manipulator device then picks, transports, and releases the ejected seedling.

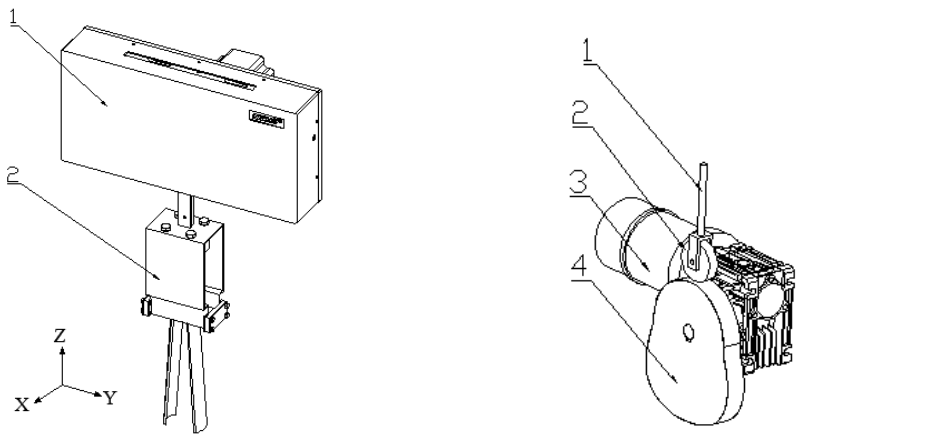


Fig. 2 - Seedling picking and placing unit

(a) Manipulator device
1 - Manipulator controller; 2 - Flexible end-effector

(b) The seedling ejection device
1 - Ejector rod; 2 - Roller; 3 - Geared motor; 4 - Cam

The manipulator device is primarily composed of a manipulator controller and a flexible end-effector (Fig. 2a). The flexible end-effector, which can perform clamping and splaying motions, is mainly responsible for seedling picking and releasing. The manipulator controller drives the flexible end-effector to lift, translate, and lower, thereby transporting the seedling.

The seedling ejection device mainly consists of a geared motor, a cam, an ejector rod, and a roller (Fig. 2b). When the geared motor is not working, the cam's near-dwell section contacts the roller. When the geared motor runs, the cam enters the lift phase, causing the roller to raise the ejector rod, which pushes the seedling out through the ventilation hole at the bottom of the tray cell. As the manipulator device picks the seedling, the geared motor continues to rotate, and then the ejector rod descends back to its initial position, waiting to eject the next seedling.

The complete picking and placing sequence (descending → gripping → lifting → releasing) is illustrated in Fig. 3. In process (a), the manipulator moves to the initial picking position while the end-effector remains open and the ejector rod stays in its lower position. In process (b), the ejecting motor rotates the cam, driving the ejector rod upward to push the seedling out of the tray cell. In process (c), the end-effector closes to grasp the ejected seedling. In process (d), the manipulator lifts the end-effector and moves rightward; simultaneously, the ejecting motor continues rotating, causing the cam to retract the ejector pin back to its initial lower position. In process (e), upon reaching the rightmost limit, the manipulator descends to its lowest position. In process (f), the end-effector opens, allowing the seedling to fall under gravity into the planter for soil insertion. After process (f), the seedling tray shifts one cell to the left, and the manipulator returns the end-effector to the initial position (a) to repeat the cycle.

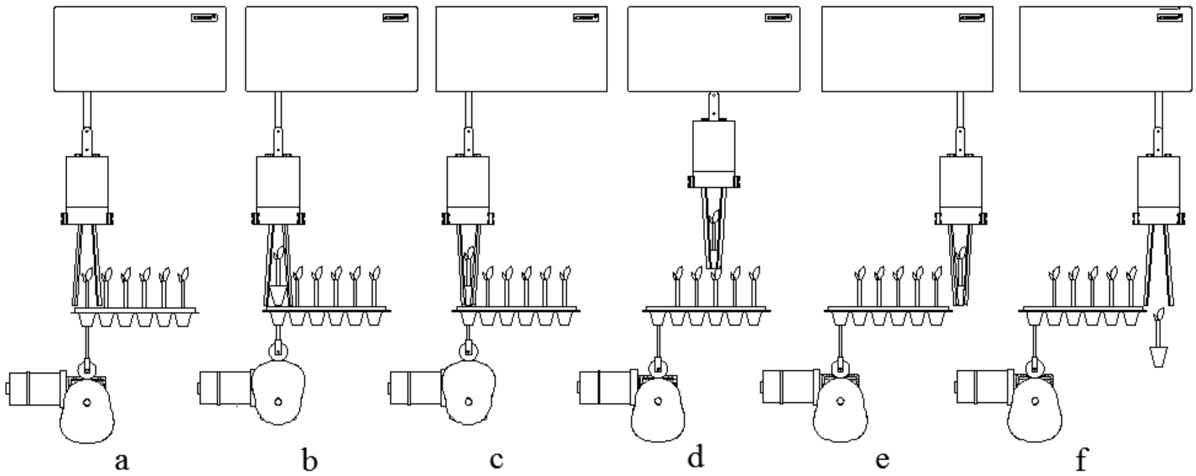


Fig. 3 - The process of picking and placing seedlings

Flexible End-Effector Design

The flexible end-effector developed in this study is of the finger-clamp type, specifically designed to pick the soil plug of the seedling, with an emphasis on flexibility. Recognizing that rigid fingers could potentially damage the delicate substrate, a spring buffer mechanism was integrated into the mechanical structure to significantly reduce the clamping impact on the soil plug, thereby minimizing the risk of root damage. The overall structure of this flexible end-effector is illustrated in Fig. 4.

The finger material was 20# stainless steel with a density of 7.85 g/cm^3, while the cone block was made of aluminum alloy (density 2.70 g/cm^3) to reduce inertial mass. The coefficient of friction between the steel fingers and the seedling substrate was taken as μ = 0.6, based on design calculations for reliable gripping. Both the tension springs and buffer springs were fabricated from stainless steel with a shear modulus of 71000 MPa.

The working principle of this flexible end-effector is as follows: When the electric cylinder piston extends, the cone block moves downward. As the cone block descends, the bearings following its inclined surfaces cause the fingers to rotate inward around their hinge points, transitioning from an open to a clamped position. When the fingers contact and pick the soil plug of the seedling, any excessive clamping force is absorbed by the buffer springs through lateral displacement of the hinges within their supports. This spring-based design effectively decouples the actuation force from the clamping force, allowing the fingers to prevent damage to the root system, and fit variations in plug size and shape.

To substantiate the force-decoupling effect, a mechanical model was established. The clamping force F_c is governed by the buffer spring preload F_0 and its compression x_s:

$$F_c = F_0 + k_s \cdot x_s \quad (1)$$

where K_s = 2.5 N/mm is the total spring stiffness. The springs are preloaded to F_0 = 20 N/mm, and the maximum hinge displacement is limited by a mechanical slot to x_s = 6 mm, yielding a maximum clamping force of:

$$F_{c,\max} = 20 + 2.5 \times 6 = 35\text{N} \quad (2)$$

This value is deliberately designed to remain below the substrate's allowable limit. Preliminary unconfined compression tests on seedling plugs (n=10) determined a compressive strength of 0.12MPa. With an effective finger-plug contact area of 400 mm^2, the maximum permissible clamping force is:

$$F_{\text{allow}} = 0.12 \times 400 = 48\text{N} \quad (3)$$

Thus, $F_{c,\max}$ = 35 N < 48 N, confirming that the spring-buffering mechanism effectively prevents over-clamping. Without this buffering, direct actuation would produce a theoretical clamping force of approximately 68 N (calculated from the cone block geometry with α=15°), which would exceed the substrate tolerance and cause damage. This quantitative analysis validates that the design decouples actuation force from clamping force, ensuring reliable gripping with minimal seedling injury.

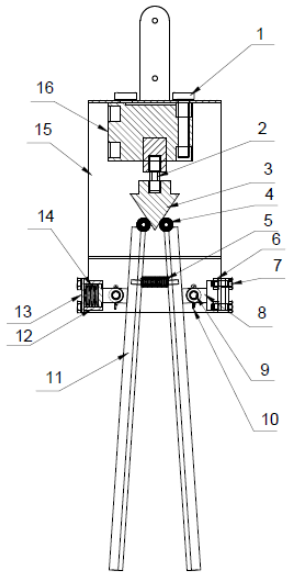


Fig. 4 - Overall structure of the flexible end-effector

1 - Hexagon bolt; 2 - Double-ended stud; 3 - Cone block; 4 - Bearing and circlip; 5 - Tension spring; 6 - Hexagon nut; 7 - Round head bolt; 8 - Hinge; 9 - Shaft pin; 10 - Cotter pin; 11 - Finger; 12 - Hinge support; 13 - Spring baffle; 14 - Buffer spring; 15 - Support frame; 16 - Electric cylinder

Seedling Ejection Device Design

The seedling ejection device employs a disk cam with a roller follower and an ejector rod (Fig. 2b). Its function is to push the plug seedling out of the tray cell through the bottom ventilation hole. Based on the seedling height and tray structure, the ejector rod stroke was set to 30 mm, which pushes the soil plug (plug height ≈ 40 mm) upward sufficiently for the end-effector fingers to grip its lower portion. The cam base circle radius (30 mm) was chosen to fit the available under-tray space while maintaining a pressure angle below 30° for smooth force transmission, as verified by ADAMS simulation (Fig. 6). The cam rotational speed (30 r/min) was synchronized with the 1.0 s manipulator cycle to ensure continuous workflow without idle waiting, and matches the tray conveying motor speed for simplified control. To ensure smooth movement with minimal impact, the lift phase was designed using a constant acceleration-deceleration motion, while the return phase adopted simple harmonic motion (cosine acceleration), achieving zero velocity at start and end points to avoid rigid impact.

With the cam rotation center as the origin, a polar coordinate system was established. The relationship between the ejector rod displacement s and the cam rotation angle δ was determined in segments (lift phase: $0 \le \delta \le \pi/2$; upper dwell: $\pi/2 \le \delta \le \pi$; return phase: $\pi \le \delta \le 3\pi/2$; lower dwell: $3\pi/2 \le \delta \le 2\pi$). Substituting the displacement expressions for each segment into the cam profile equations (4) and (5), the coordinates (x and y) of points on the theoretical cam profile were yielded:

$$x = (s_0 + s)\sin\delta + e\cos\delta \quad (4)$$

$$y = (s_0 + s)\cos\delta - e\sin\delta \quad (5)$$

where s is the ejector rod displacement, mm; δ is the cam rotation angle, °; e is the offset distance, mm; and $s_0 = \sqrt{r_0^2 - e^2}$. Since the designed cam mechanism is an in-line type, e = 0 and $s_0 = r_0$.

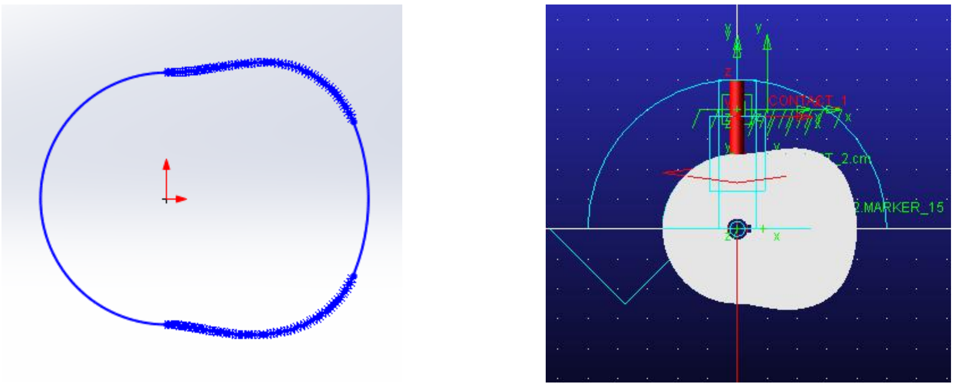
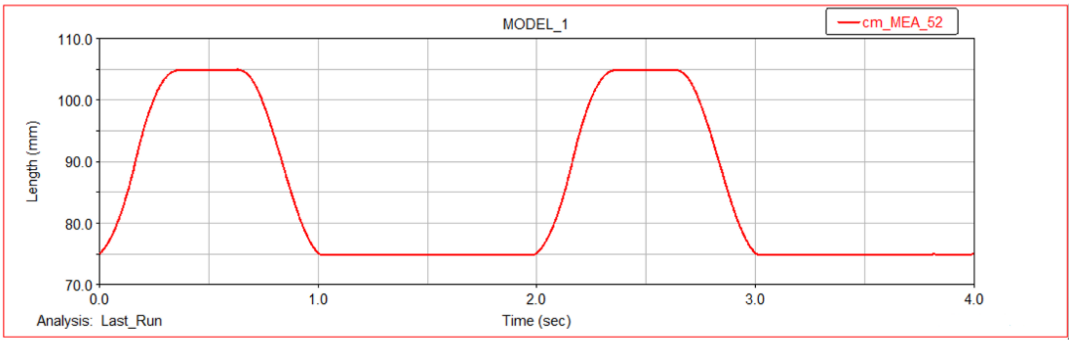


Fig. 5 - Cam design

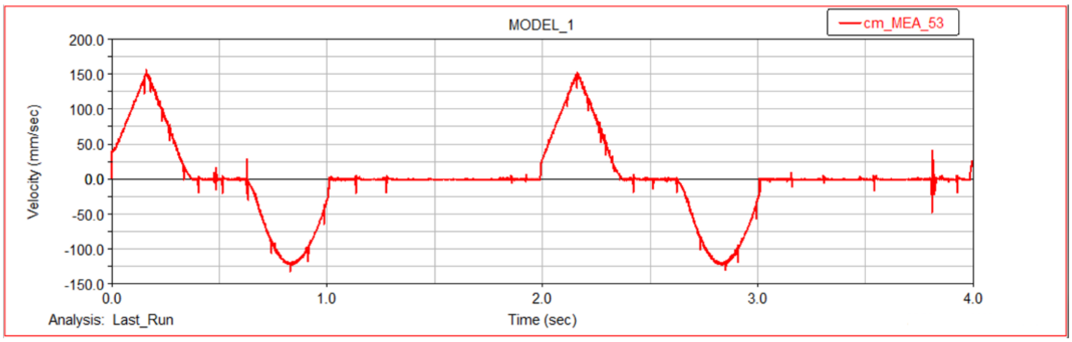
(a) Cam profile curve **(b) ADAMS simulation model**

A program was written in MATLAB software to calculate the coordinates at 1° intervals. The coordinate data were imported into SolidWorks software to generate the cam profile curve (Fig. 5a) and create a three-dimensional model of the cam.

To verify the rationality of the cam profile, the model was imported into ADAMS/View for motion simulation (Fig. 5b). A revolute joint was established between the cam and ground, and a translational joint between the ejector rod and ground. Contact forces were defined, and a driver with a rotational speed of 30 r/min was applied. Simulation results (Fig. 6) show that the displacement curve is smooth and the velocity curve is continuous without abrupt changes, confirming that the cam design meets the requirements for seedling ejection with smooth motion and no rigid impact.



(a) Displacement curve



(b) Velocity curve

Fig. 6 - Simulation results

Design of the Tray Step-Moving and Collecting Units

The tray step-moving unit (Fig.7) consists of a pallet and a dual-axis linear module that moves the tray in step increments of 42 mm (due to tray cell center distance 42 mm) with a positioning repeatability of ±0.05 mm. The tray collecting unit (Fig.8) uses a dual-cam mechanism and electric push rods to automatically stack empty trays. The cam profile was optimized to ensure the tray is lifted horizontally, following the same design methodology used for the seedling ejection device cam.

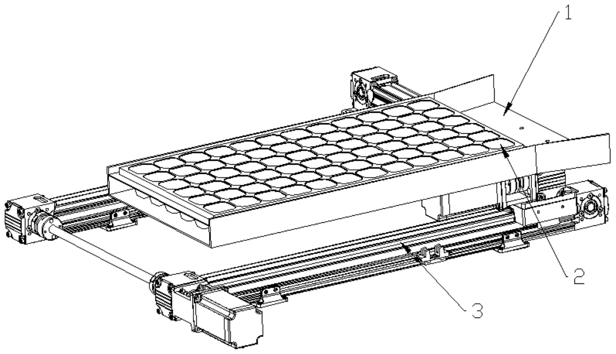


Fig. 7 - Structure of the tray step-moving unit

1 - Pallet; 2 - Tray; 3 - Linear module

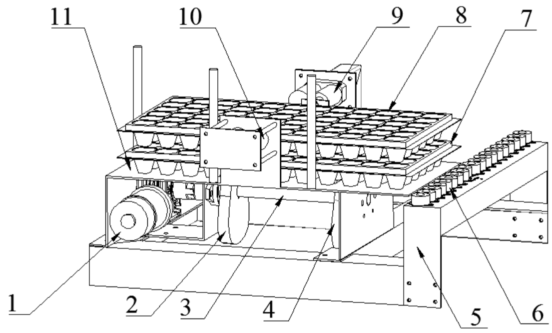


Fig. 8 - Structure of the tray collecting unit

1 - Geared motor; 2 - Cam 1; 3 - Transmission shaft; 4 - Cam 2; 5 - Universal ball support plate; 6 - Universal ball; 7 - Empty tray waiting for collection; 8 - Collected empty trays; 9 - Electric push rod 1; 10 - Electric push rod 2; 11 - Tray collection plate

Control System Design

The control system is built around a Delta DVP40ES200T Programmable Logic Controller (PLC). It controls three stepper motors (manipulator, X-axis, Y-axis), three geared motors (tray conveying, seedling ejecting, tray lifting), and nine relays (for electric push rods). The system operates in manual and automatic modes. In automatic mode, the PLC coordinates sequential actions for initialization, tray conveying and positioning, the seedling picking cycle (including step positioning, ejection, picking, transport, release, and return), and empty tray collection.

Experimental Design

Following the design methodology described above, a prototype of the integrated automatic transplanting system was developed, as shown in Fig. 9. To verify the performance of the developed system, pepper seedlings cultivated in 72-cell plug trays were used as test material (Fig. 10). The pepper seedlings had an average plant height of 150 mm, individual plant weight ranging from 20 to 50 g, and a substrate moisture content of 55%-60%.

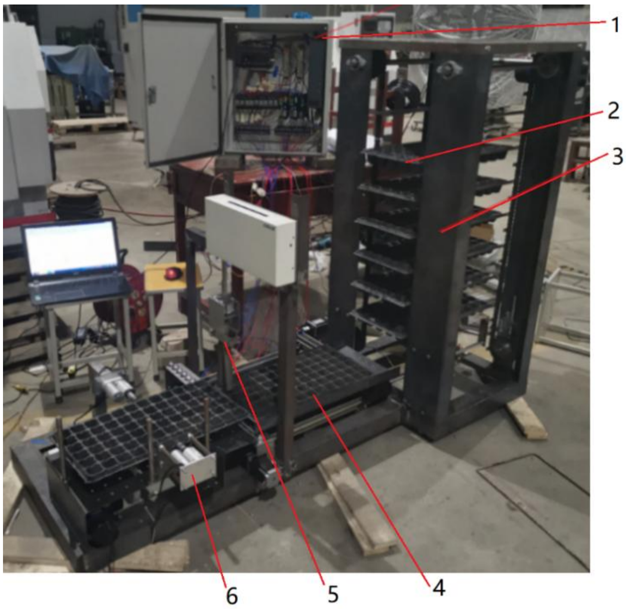


Fig. 9 - Prototype of the developed automatic transplanting system

1 - Control system; 2 - Plug tray; 3 - Multi-tray storage and conveying unit; 4 - Tray step-moving unit; 5 - Seedling picking and placing unit; 6 - Tray collecting unit

The experiments were conducted in three parts:

(1) Tray conveying accuracy test: Eight full plug trays were sequentially pushed from the storage unit to the step-moving unit. The deviation between the center of tray cell and the corresponding hole center on the pallet was measured, and the maximum and average deviation values were recorded.

(2) Standalone seedling-picking performance test: To evaluate the picking reliability of the flexible end-effector itself and eliminate potential interference from the ejecting device, seedlings were manually pre-positioned at the picking point in this test. The PLC independently controlled the manipulator and flexible end-effector to complete the full action cycle of descending, picking, lifting, translating, and releasing. Each group consisted of 72 seedlings, and the test was repeated five times. The numbers of damaged seedlings N_d, missed seedlings N_m, and successfully picked seedlings N_s were recorded.

(3) Integrated seedling-picking system performance test: The system was operated automatically at a transplanting rate of 60 plants per minute per row, corresponding to a manipulator motion cycle of 1 s (determined through preliminary debugging to ensure smooth operation). Each group consisted of 8 trays (72 seedlings per tray), and the test was repeated five times. The same indicators as above were recorded.

The seedling picking success rate S_s, damage rate S_d, and miss rate S_m were calculated using the following formulas:

$$S_s = \frac{N_s}{N_0} \times 100\% \tag{6}$$

$$S_d = \frac{N_d}{N_0} \times 100\% \tag{7}$$

$$S_m = \frac{N_m}{N_0} \times 100\% \tag{8}$$

where N_0 is the total number of seedlings, N_s is the number of successfully picked seedlings, N_d is the number of damaged seedlings, and N_m is the number of missed seedlings.

Fig. 10 - Pepper seedlings used in the experiment

Statistical Analysis

All experiments were conducted with five independent replications for each test condition. Data are presented as mean ± standard deviation (SD). To compare the seedling picking performance between standalone control and integrated system conditions, an independent-samples t-test was performed using SPSS software (version 22.0). The null hypothesis (H_0) was that there is no significant difference in the performance indicators (success rate, damage rate, and miss rate) between the two test conditions, while the alternative hypothesis (H_1) was that a significant difference exists. A two-sided *p*-value < 0.05 was considered statistically significant. In addition, 95% confidence intervals (CIs) for the mean differences between the two conditions were calculated to quantify the magnitude of the observed effects.

RESULTS

Tray Conveying Accuracy

The results of tray conveying accuracy are shown in Table 2. The deviations for the eight trays ranged from 1.12 mm to 1.79 mm, with an average deviation of 1.60 mm (SD = 0.24 mm, n = 8) and a maximum deviation of 1.79 mm. These deviations were primarily caused by vibrations during the conveying process.

Since the design tolerance for the holes on the pallet bottom was 2 mm, the maximum observed deviation of 1.79 mm remained within this tolerance. Therefore, the conveying accuracy meets the positioning requirements for seedling picking.

Table 2

Accuracy of tray conveying to the step-moving unit

Tray No.	Deviation (mm)	Maximum Deviation (mm)	Average Deviation (mm)
1	1.65	1.79	1.60 ± 0.24
2	1.63		
3	1.76		
4	1.79		
5	1.12		
6	1.39		
7	1.79		
8	1.70		

Seedling Picking Performance

(1) Standalone Control Test

Under standalone control of the manipulator device, without considering the influence of the ejecting device, the seedling picking performance indicators are shown in Table 3. The average success rate of seedling picking was 97.14%, with an average damage rate of 1.21% and an average miss rate of 1.65%. The low damage rate indicates the flexible end-effector verified reliable performance. Fig. 11 showed that the flexible end-effector securely holds the substrate without causing visible damage to the soil plug or root system, demonstrating the effectiveness of the spring-buffered finger-clamp mechanism.

Fig. 11 - Multi-angle photographs of the flexible end-effector gripping the seedling soil plug

Table 3

Seedling picking performance under separate control

Test Group	Success Rate S_s (%)	Damage Rate S_d (%)	Miss Rate S_m (%)
1	97.65	0.93	1.42
2	96.73	1.38	1.89
3	97.21	1.56	1.23
4	97.13	0.78	2.13
5	96.98	1.40	1.58
Mean ± SD	97.14 ± 0.35	1.21 ± 0.32	1.65 ± 0.35

(2) Integrated System Test

The seedling picking performance of the fully automated transplanting system is shown in Table 4. The average success rate of seedling picking was 93.24%, with an average damage rate of 1.43% and an average miss rate of 5.33%. Compared with the standalone control test, the damage rate showed no significant change, but the miss rate increased substantially, leading to a decrease in the success rate.

Observations during the experiment revealed that the primary cause of the increased miss rate was the clearance between the ejector rod and its linear bearing. The ejector rod was fitted with a linear bearing with a radial clearance of approximately 0.02 mm (standard fit tolerance). Under dynamic operation, this clearance caused a lateral deflection at the rod tip of approximately 1–3 mm, corresponding to an angular deviation of 1.5°–2.5° from the vertical axis. This deviation occasionally tilted the seedlings as they were pushed out of the tray cells, causing the flexible end-effector to miss the target and resulting in the increased miss rate.

Table 4

Seedling picking performance of the integrated system

Test Group	Success Rate S_s (%)	Damage Rate S_d (%)	Miss Rate S_m (%)
1	93.34	1.24	5.45
2	93.44	1.67	4.89
3	93.31	0.93	5.76
4	93.02	1.85	5.10
5	93.09	1.46	5.45
Mean ± SD	93.24 ± 0.18	1.43 ± 0.37	5.33 ± 0.33

Transplanting Efficiency

The transplanting efficiency was primarily influenced by the manipulator device in the seedling picking and placing unit. The movement speed of the manipulator was controlled by adjusting the input pulse frequency of its stepper motor via the PLC. Through repeated debugging trials (n = 5), it was determined that a manipulator motion cycle of 1.0 s (SD = 0.05 s) yielded the smoothest operation of the flexible end-effector, corresponding to a transplanting efficiency of 60 plants per minute per row. To further increase the efficiency, a high-speed manipulator with a shorter motion cycle would be required.

Tray Collection Performance

Observation of the tray collecting unit showed that the empty trays were stacked neatly according to the design requirements, as illustrated in Fig. 12. This confirms the reliability of the collection unit design.

Fig. 12 - Successfully collected empty trays

Discussion

Statistical comparison between the standalone control and integrated system tests revealed no significant difference in damage rate (1.21 ± 0.32% vs. 1.43 ± 0.37%; mean difference = 0.22 percentage points; 95% CI: -0.29 to 0.73; independent-samples t-test, *t* = 1.02, *p* = 0.34 > 0.05), indicating that the flexible end-effector maintained consistent clamping performance even when integrated with the ejection and conveying units. The 95% confidence interval contains zero, which further confirms the lack of statistical significance and supports the null hypothesis that the damage rate does not differ between the two conditions. However, the miss rate increased significantly in the integrated system (1.65 ± 0.35% vs. 5.33 ± 0.33%; mean difference = 3.68 percentage points; 95% CI: 2.86 to 4.50; *t* = 16.78, *p* < 0.001), which was the primary cause of the reduced overall success rate (97.14 ± 0.35% vs. 93.24 ± 0.18%; mean difference = 3.90 percentage points; 95% CI: 3.50 to 4.30; *t* = 22.04, *p* < 0.001). The confidence intervals for both miss rate and success rate do not contain zero, providing strong evidence against the null hypothesis. These statistically significant differences confirm that the ejection device, rather than the end-effector itself, was the limiting factor in system performance.

Compared with existing technologies, the main advantage of this study lies in the integration of multiple functions into a complete system, reducing manual intervention and improving operational continuity. The experimental results demonstrate that the developed automatic transplanting system performs reliably. Under standalone control, the flexible end-effector achieved a seedling picking success rate of 97.14%, which is higher than the 92.59% reported by *Jin et al. (2018)* and comparable to the 96.3% reported by *Ye et al. (2020)*. The seedling damage rate of 1.21% is lower than the 2.69% reported by *Han et al. (2023)* and 1.59% reported by *Zhou et al. (2024)*. The lower damage rate observed in this study can be attributed to the spring buffer mechanism incorporated into the finger-clamp design, which effectively reduces impact forces during clamping and accommodates variations in plug size and shape.

The transplanting efficiency of 60 plants per minute per row is higher than the 40 plants/min reported by *Han et al. (2018)* and the 48 plants/min achieved by *Jin et al. (2018)*, while it is lower than that of advanced international machines such as the Ferrari FUTURA *(Shao et al., 2021)*. Selecting a manipulator with a shorter motion cycle or increasing the number of end-effectors operating in parallel could improve efficiency, but may also increase mechanical complexity and cost. For small-to-medium scale nurseries in China, cost-effectiveness and adaptability may be more critical than achieving maximum possible speed. Tray conveying accuracy, with a maximum deviation of 1.79 mm, remained within the 2 mm design tolerance, comparable to results reported by *Yue et al. (2024)* and *Zhou et al. (2024)*.

Despite these promising results, several limitations of the present study should be acknowledged. First, the experiments were conducted exclusively with pepper seedlings, and the system's adaptability to other crop species (e.g., tomato, eggplant, or tobacco) with different plug sizes remains untested. Second, the transplanting efficiency of 60 plants/min/row, while outperforming several domestic counterparts, is lower than that of advanced international machines. Third, the clearance-induced wobble of the ejector rod (0.02 mm radial clearance resulting in approximately 1–3 mm tip deflection) remains a weak point of the current design. Fourth, all performance evaluations were conducted under relatively ideal laboratory conditions; the system's reliability under real field conditions have yet to be verified.

CONCLUSIONS

This study developed an automatic transplanting system for plug seedlings, integrating multi-tray storage and conveying, step-by-step positioning, manipulator-based picking and placing, and automatic empty tray collection. Through theoretical analysis, simulation optimization, and prototype experiments, the following conclusions were drawn:

(1) The system achieves fully automated operation from tray input to empty tray stacking, addressing functional fragmentation and reducing manual intervention.

(2) A finger-type flexible end-effector with a spring buffer mechanism was designed. Under standalone control, it achieved a picking success rate of 97.14% and a damage rate of 1.21%.

(3) Experiments with pepper seedlings showed that the integrated system achieved a success rate of 93.24% with a damage rate of 1.43%; tray conveying accuracy had a maximum deviation of 1.79 mm; and the tray collecting unit successfully stacked empty trays. The results demonstrate the feasibility of low-damage, fully automated transplanting for small-to-medium nurseries.

(4) Future work will focus on three aspects: (i) evaluating the system's adaptability to other crop species to broaden its applicability; (ii) refining the ejection mechanism by replacing linear bearings with precision guide rails to reduce wobble; (iii) integrating machine vision for seedling quality detection and exploring high-speed manipulators to further improve system performance; and (iv) evaluating the system's reliability and stability under actual field conditions, including uneven terrain and varying environmental factors.

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