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Study on the Method and Mechanism of Seedling Picking for Pepper (*Capsicum annuum* L.) Plug Seedlings

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Abstract: To better meet the requirements of mechanized transplanting of pepper plug seedlings, this study explores the seedling picking mechanism of a fully automatic pepper transplanting machine. It introduces a novel "eagle beak" type trajectory for seedling picking and designs a probe-type mechanism for pepper plug seedling retrieval. We establish a kinematic theoretical model and delineate the composition and operational principles of this probe-type mechanism. Additionally, we develop an auxiliary optimization software tailored based on Visual Basic 6.0 visual programming software for this mechanism. It employs a blend of manual fine-tuning and a "parameter guidance" optimization algorithm, enabling the determination of 11 optimal target parameters. Our comparative analysis between the theoretical model, optimization software, and high-speed camera experiments reveals a strong correlation in the motion trajectories, and the maximum error of the pose angle is 1.2°. To validate the mechanism's design, we conducted a seedling retrieval experiment. In this test, the success rates of the seedling harvesting mechanism at speeds of 30, 40, and 50 r/min were 96.4%, 94.3%, and 91.4%, respectively, thus demonstrating its practical feasibility.

Keywords: transplanting machine; seedling picking mechanism; pepper plug seedlings; non-circular gear; trajectory and attitude

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1. Introduction

Pepper, a significant vegetable and spice, is also a crucial industrial raw material for extracting substances like Capsaicin and Capsanthin. It thrives in temperate, tropical, and subtropical regions globally [1,2]. Current agricultural trends favor the transplanting technology of pepper seedlings. Transplanting cultivated pepper plug seedlings into fields mitigates adverse weather impacts, such as droughts and floods. This practice extends the effective growth period, enhances seedling pest resistance, and consequently boosts pepper yields. Pepper seedlings are primarily transplanted using two methods: manual planting and mechanical transplanting. Manual planting, despite its labor-intensive and time-consuming nature, demands significant labor, leading to higher costs [3–5]. In contrast, mechanical transplanting, recognized for its time and labor efficiency, reduces production costs [6] and significantly enhances transplanting efficiency. Thus, research on pepper transplantation methods and mechanisms is crucial for advancing pepper cultivation levels and improving the quality and technical standards of China's transplanting equipment [7,8].

The seedling picking mechanism is a pivotal component of a fully automatic pepper transplanting machine. This mechanism has been extensively studied worldwide [9–12]. Currently, seedling picking mechanisms can be mainly divided into four types, namely: stem clamping type, top out type, air blowing type, and insertion clamping type [13]. For the stem clamping seedling picking mechanism, Wang Xiu et al. designed a stem clamping automatic seedling picking device for vegetable transplanting robots [14]. The seedling picking device undergoes whole-row seedling picking, equidistant seedling splitting, and precise seedling dropping, achieving automated seedling picking and dropping operations. This type of seedling retrieval mechanism has high seedling retrieval efficiency, but the success rate of seedling retrieval is easily affected by the growth position of the seedlings, which has high requirements for seedling cultivation and unstable work results. For the top out seedling picking mechanism, Wen Yongshuang et al. designed a vegetable hole tray seedling insertion and top out seedling picking device, which mainly consists of a feeding mechanism, an insertion and top out mechanism, a flipping mechanism, a seedling feeding mechanism, a sorting plate, a seedling hopper, and so on [15]. The top out seedling retrieval system has a simple structure and high seedling retrieval efficiency. However, due to the different bonding forces between the bowl seedling and the hole tray, the thrown bowl seedling has problems such as rolling, uncontrollable seedling trajectory, and poor consistency in seedling placement. For the air-blown seedling picking mechanism, Yuan Ting et al. designed a vegetable transplanting machine with an air-blown vibration composite seedling picking mechanism, which mainly consists of an air-blown device, a vibration device, and a chain structure seedling feeding device [16]. During the working process, the vibrating plate in the vibration device undergoes simple harmonic motion, driving the cavity plate to vibrate up and down, achieving the separation of the soil bowl and the inner wall of the cavity plate. When the hole tray moves above the planter, the soil bowl falls into the planter under the action of blowing the trachea, completing the planting work. The air-blown seedling picking mechanism has a simple structure, minimal damage to the hole tray seedlings, and high seedling picking efficiency. However, it requires specific hole trays and is not suitable for large-scale promotion and use. For the insertion clamping seedling picking mechanism, Yin Daqing et al. designed a vegetable bowl seedling picking mechanism with a protruding and pushing bowl [17]. The seedling picking mechanism consists of a non-circular planetary gear system and a seedling picking end actuator. The seedling picking end actuator can simultaneously achieve seedling picking and pushing actions. However, the structure of the seedling retrieval end-effector is relatively complex and has low reliability. When the rotation speed of the seedling retrieval mechanism is higher than 40 r/min, the success rate of seedling retrieval is significantly reduced, making it unable to adapt to high-speed seedling retrieval. Wang Mengmeng et al. introduced a "V"-shaped seedling claw, effectively reducing shed seedlings during picking, with a 94.4% success rate [18]. Gao Guohua and the team improved the seedling extractor, designing an inclined version to minimize seedling damage during the hole tray transplanting process. The angled action of the seedling needle significantly reduced pressure damage to the seedlings [19].

Therefore, compared with other types of seedling picking mechanisms, the probing seedling picking mechanism has advantages such as stable and reliable seedling picking, minimal damage, good adaptability, high transplanting efficiency, and the ability to effectively ensure the integrity of the seedling bowl substrate. To meet the trajectory and posture requirements of transplanting pepper plug seedlings, this article proposes a probing-type seedling picking method for pepper plug seedlings and designs a probing-type seedling picking mechanism based on the planting agronomy of pepper plug seedlings. This mechanism works smoothly and reliably, with superior performance, and can meet the needs of fully automatic and mechanized transplanting of pepper seedlings [20].

2. Materials and Methods

2.1. Design of the Seedling Picking Mechanism

This study aims to design a seedling picking mechanism capable of efficiently completing the tasks of picking, transporting, and releasing seedlings. Drawing inspiration from manual seedling picking methods, we conducted mechanized path planning for seedling picking. In manual picking, the arm acts like a 2R open-chain mechanism, with the shoulder as a fixed joint and the elbow driving the hand to perform picking, conveying, and releasing actions. By harnessing the unequal speed transmission characteristics of non-circular gear planetary gear trains, we achieved the "eagle beak"-shaped trajectory needed for efficient pepper transplantation. The probing method, involving insertion into the soil bowl, effectively prevents damage to chili stems during the picking process, a common issue with clamping stem mechanisms. Figure 1 illustrates the manual seedling picking process.

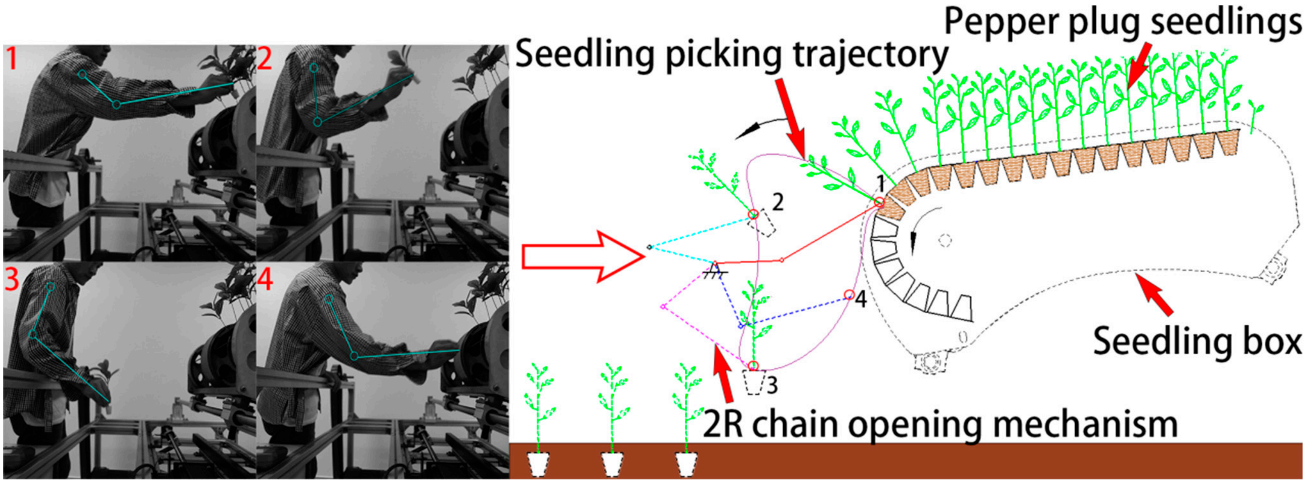


Figure 1. Simulated manual seedling picking trajectory.

The 2R open-chain mechanism, often constrained by rod or slide mechanisms, limits the solution domain and design flexibility, frequently failing to meet practical engineering requirements. However, when constrained by a non-circular gear train, the 2R mechanism enables unequal speed transmission between the crank and rocker. This configuration offers a broader, feasible solution domain and precise replication of specific trajectories and attitudes. In our study, we adopted a two-stage non-circular gear transmission constraint for the 2R mechanism, resulting in a single degree of freedom. This meets the actual pose constraints during operation. We transformed the crank in the 2R mechanism into a non-circular gear planetary gear system and the swing rod into a seedling end-effector. Combining these elements, we devised the exploratory pepper plug seedling picking mechanism presented here. The design requirements for this probing-type pepper plug seedling picking device include: a trajectory that meets transplanting needs; high picking efficiency; robust stability; minimal damage to the seedlings; and a high degree of transplanting upright accuracy. The mechanism accurately positions the seedling needle into the hole tray, ensuring complete soil entry for the root of the pepper seedling. The force and angle of insertion are carefully controlled to avoid damage. This seedling picking mechanism, capable of one full rotation, rapidly completes six seedling picking actions, significantly enhancing production efficiency.

2.2. Composition and Working Principles of the Mechanism

The pepper plug seedling picking mechanism comprises a non-circular gear planetary gear train and a seedling picking end actuator, as depicted in Figure 2. When operational, power is transmitted through the drive shaft to the transmission box. This shaft is rigidly connected to the upper transmission bevel gear, which meshes with the lower transmission bevel gear fixed to the sun shaft. The interlocking of these gears transmits power to the sun shaft. The sun shaft's end is secured to the gearbox housing, causing it to rotate counterclockwise uniformly. The non-circular gear planetary gear system features five non-circular gears. The sun gear, anchored to the frame, rotates relative to the gearbox housing and engages with intermediate gears I and II. These intermediate gears, in turn, mesh with planetary gears I and II, setting the stage for rotation. The seedling end actuator, affixed to the planetary gear, accomplishes circular motion in sync with the gearbox housing while also rotating unevenly relative to it.

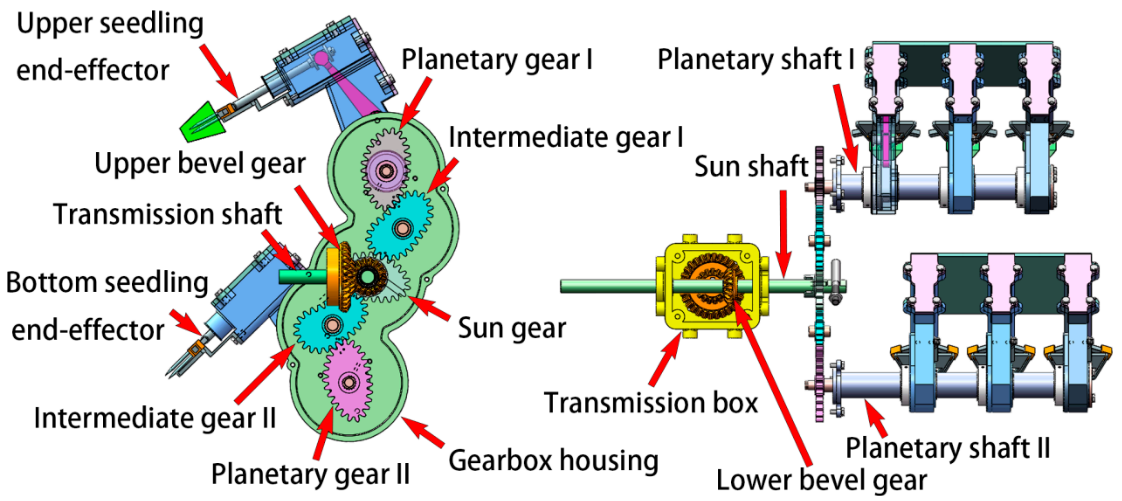


Figure 2. Schematic diagram of the seedling picking mechanism for pepper plug seedlings.

The seedling end-effector primarily includes components like the picking arm shell, shift fork, cam, and spring guide rod, as shown in Figure 3. The picking arm shell is solidly connected to the planetary shaft via a positioning plate. Meanwhile, the cam maintains a relatively stationary position with the gearbox shell, and the seedling needle is securely attached to the slider. During operation, the picking arm shell rotates around the cam. The shift fork's upper end forms a high-pair connection with the connecting block, driving the spring guide rod to reciprocate linearly within the picking arm shell. The shift fork's lower end is linked to the cam through a high-pair. Influenced by the cam, the shift fork and the seedling arm housing perform uneven rotation relative to the gearbox housing. Concurrently, guided by the cam contour, it oscillates back and forth around the fork shaft within the seedling picking arm shell.

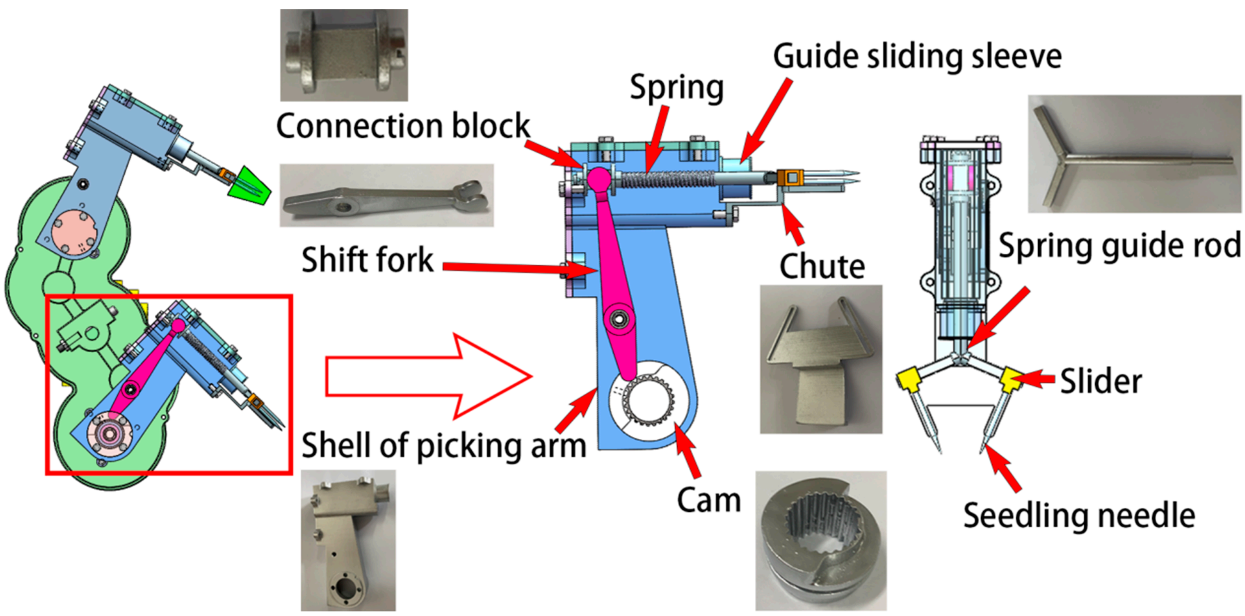


Figure 3. Seedling retrieval end-effector.

During seedling picking, the actuator at the seedling picking end rotates clockwise with the planetary shaft relative to the gearbox. In this phase, the shift fork also rotates clockwise, causing the spring to compress. This action linearly moves the seedling needle along its tilt direction, allowing it to penetrate the pepper seedling pot substrate along the plug's inner wall. By utilizing the taper of the seedling needle for clamping, the mechanism efficiently extracts the pepper seedling from the plug, as illustrated in Figure 4.

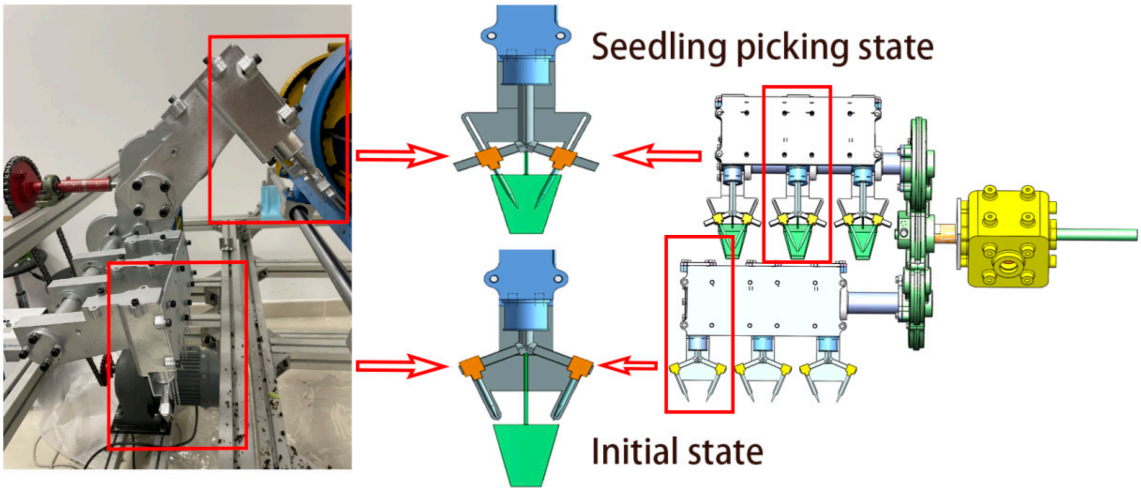


Figure 4. Schematic diagram of the end-effector's operation in seedling picking.

During the seedling release phase, the spring reverts from its compressed state to its natural state, resetting the seedling needle to its initial position. Subsequently, the pepper plug seedlings are ejected to complete a seedling picking cycle. Throughout this cycle, the seedling picking end actuator, driven by the non-circular gear planetary gear train, combines the reciprocating linear motion of the seedling needle with the picking arm's path trajectory. This creates the complex trajectory and attitude necessary for efficient pepper transplantation.

2.3. Kinematic Analysis

In our kinematic analysis, we designate the rotation center of the planet carrier as the coordinate origin, as depicted in Figure 5. Utilizing the rotation angle of the planetary carrier as a known variable, we analyze and derive the rotation angles and key coordinates of each non-circular gear.

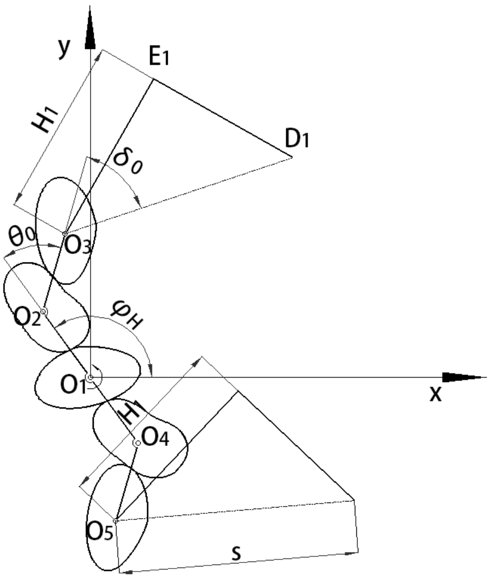


Figure 5. Kinematic model of the seedling picking mechanism.

During the mechanism's operation, the sun gear remains stationary relative to the frame, while the planet carrier (gearbox) rotates counterclockwise uniformly. Counterclockwise rotation is denoted as positive, and clockwise rotation is denoted as negative. When the planet carrier turns through the angle φ, the angle of each non-circular gear relative to the planet carrier is denoted as, and their absolute angles as $\beta_i(\varphi)$ where i = 1, 2, and 3, corresponding to the sun gear, intermediate gear, and planetary gear, respectively.

Planet carrier turning angle φ:

$$\varphi = \omega \cdot t, \tag{1}$$

the absolute angle of rotation of the planet carrier $\varphi_H(\varphi)$:

$$\varphi_H(\varphi) = \varphi_{H0} + \varphi, \tag{2}$$

relative rotation angle $\beta_1(\varphi)$ of the sun gear clockwise to the planet carrier:

$$\beta_1(\varphi) = -\varphi, \tag{3}$$

the absolute rotation angle of the sun gear $\varphi_1(\varphi)$:

$$\varphi_1(\varphi) = \varphi_{H0}. \tag{4}$$

The polar radial direction of the sun gear pitch curve is denoted as $r_1(\varphi)$. Assuming the center distance between two meshing gears as the polar coordinate radius of the intermediate gear pitch curve is determined to be $r_2(x) = a - r_1(x)$, and that of the planetary gear pitch curve is $r_3 = a - r_2(x)$.

The intermediate gear I rotates counterclockwise relative to the planet carrier, with a relative angle of $\beta_2(\varphi)$:

$$\beta_2(\varphi) = \int_0^{-\varphi} \frac{r_1(x)}{|O_1O_2| - r_1(x)} dx, \tag{5}$$

the absolute rotation angle $\varphi_2(\varphi)$ of intermediate gear I:

$$\varphi_2(\varphi) = \varphi_H(\varphi) + \beta_2(\varphi), \tag{6}$$

the planetary gear I rotates clockwise relative to the planet carrier with the relative rotation angle $\beta_3(\varphi)$:

$$\beta_3(\varphi) = \int_{\theta_0}^{\beta_2(\varphi)+\theta_0} \frac{r_2(x)}{|O_2O_3| - r_2(x)} dx, \tag{7}$$

the absolute angle of rotation $\varphi_3(\varphi)$ of planetary gear I:

$$\varphi_3(\varphi) = \varphi_H(\varphi) + \theta_0 - \varphi_{30} - \beta_3(\varphi). \tag{8}$$

Among them, ω represents the rotational angular velocity of the planetary carrier, and t represents the motion time. Where $\varphi_{30} = \int_0^{\theta_0} \frac{r_2(2\pi - x)}{|O_2O_3| - r_2(2\pi - x)} dx$ is the initial angle of rotation of the planetary gear relative to the planet carrier due to the presence of the planet carrier inflection. The existence of the corner enhances the controllability of the seedling picking mechanism's optimization, facilitating easier achievement of the complex trajectory and attitude necessary for efficient pepper transplanting.

The coordinates of the rotation center of each non-circular gear are expressed by x_{oi} and y_{oi}, and the coordinates of the rotation center of the sun gear are:

$$\begin{cases} x_{o1}(\varphi) = 0 \\ y_{o1}(\varphi) = 0 \end{cases}, \tag{9}$$

the coordinates of the rotation center of intermediate gear I is:

$$\begin{cases} x_{o2}(\varphi) = |O_1O_2| \cdot \cos(\varphi_{H0} + \varphi) \\ y_{o2}(\varphi) = |O_1O_2| \cdot \sin(\varphi_{H0} + \varphi) \end{cases}, \tag{10}$$

the coordinates of the center of rotation of the planetary gear I are:

$$\begin{cases} x_{o3}(\varphi) = x_{o2}(\varphi) + |O_2O_3| \cos(\varphi_{H0} + \varphi + \theta_0) \\ y_{o3}(\varphi) = y_{o2}(\varphi) + |O_2O_3| \sin(\varphi_{H0} + \varphi + \theta_0) \end{cases}, \tag{11}$$

the coordinates of the upper pickup end-effector tip point D_1 are:

$$\begin{cases} x_{D1}(\varphi) = x_{o3}(\varphi) + S \cdot \cos[\varphi + \theta_0 + \beta_3(\varphi) + \delta_0] \\ y_{D1}(\varphi) = y_{o3}(\varphi) + S \cdot \sin[\varphi + \theta_0 + \beta_3(\varphi) + \delta_0] \end{cases}, \tag{12}$$

the coordinates of the inflection point E_1 of the end-effector of the upper pickup are:

$$\begin{cases} x_{E1}(\varphi) = x_{o3}(\varphi) + H_1 \cos[\varphi + \theta_0 + \beta_3(\varphi) + \delta_0 + \gamma] \\ y_{E1}(\varphi) = y_{o3}(\varphi) + H_1 \sin[\varphi + \theta_0 + \beta_3(\varphi) + \delta_0 + \gamma] \end{cases} \tag{13}$$

where S represents the distance between the tip point D_1 of the seedling pickup end-effector and the rotation center of the planetary gear.

H_1 denotes the distance between the inflection point E_1 of the seedling pickup end-effector and the rotation center of the planetary gear, while:

$$\gamma = \arctan\frac{\sqrt{S^2 - H_1^2}}{H_1}$$

represents an intermediate variable.

The non-circular gears' planetary gear system is symmetrically arranged at the center. Having calculated the coordinates for the relative planet carrier angle, absolute angle, and gear rotation center of intermediate gear I and planetary gear I, we can establish the kinematic model for intermediate gear II and planetary gear II. This is achieved by considering only the phase angle difference, given that the phase angles of the upper and lower non-circular gears differ by 180°. The same principle applies to calculating the coordinates of the lower seedling end-effector tip point and its inflection point, as their phase angles also differ by 180°.

2.4. Trajectory and Attitude Analysis

2.4.1. Relative Motion Trajectory Analysis

To minimize damage to the seedling's root system during clamping to the seedling pot substrate, this study replicates the "hawk's beak"-shaped static trajectory of manual seedling picking. The relative motion trajectory is illustrated in Figure 6. Here, the thick black solid line indicates the trajectory of the seedling end-effector moving at varying speeds with the non-circular gear planetary gear system. The thin magenta solid line represents the motion trajectory of the extended seedling needle tip.

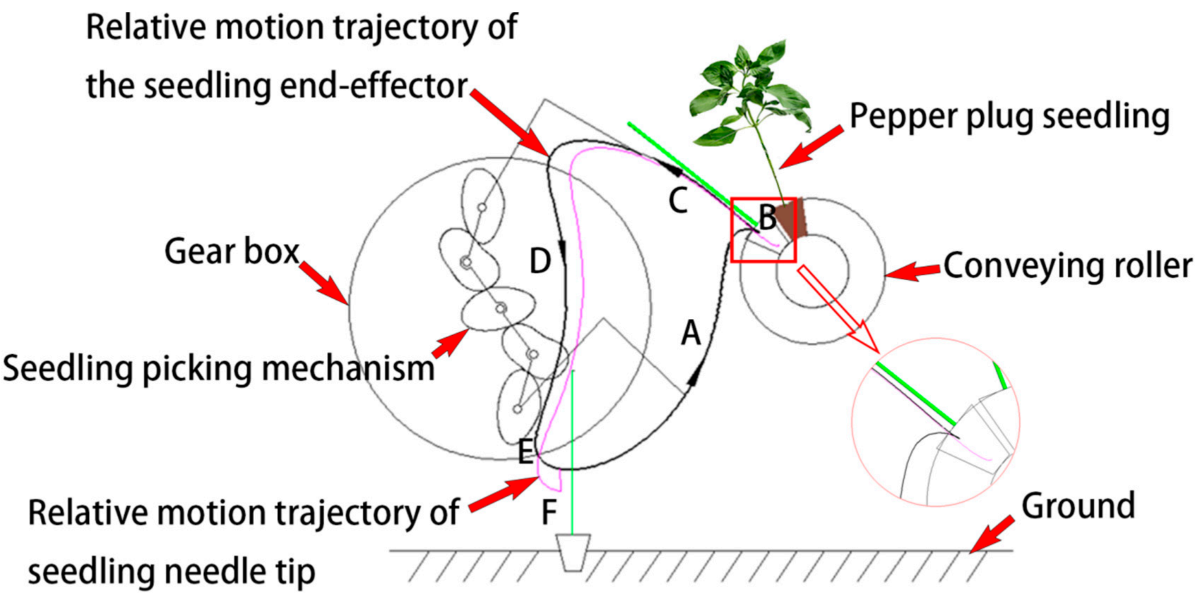


Figure 6. Relative motion trajectory diagram.

In the initial state, each non-circular gear and seedling end actuator are positioned according to their optimized initial phase angles. Throughout the operation of the seedling picking mechanism, the gearbox rotates counterclockwise, propelling the seedling picking end-effector, which is driven by the non-circular gear planetary gear train. This mechanism allows for four consecutive working stages—seedling picking, conveying, releasing, and returning—within a single working cycle:

(1) Seedling Picking Stage: In the ABC section of the figure, as the seedling end-effector transitions from point A to B, it positions itself above the root of the pepper plug. Concurrently, the lower end of the shift fork ascends from the lowest to the highest point of the cam contour line. The upper end of the shift fork, propelling the spring guide rod, induces a linear motion in the seedling needle relative to the seedling arm shell, resulting in its instantaneous extension. The trajectories of the seedling needle and the seedling arm shell nearly align, minimizing rotation of the picking arm and ensuring minimal disturbance to the seedling pot substrate. The BC segment is near-linear, longer than the plug's depth, and almost parallel to the growth direction of the plug seedling, allowing smooth removal of the plug seedling and reduced root damage;

(2) Conveying Stage: In the CDE segment of the figure, the seedling needle remains extended, with the shift fork and the seedling arm shell relatively stationary. The pepper plug seedling, along with the seedling needle, gradually separates from the plug in its growth direction and is then transported to the seedling placement position (point E) via the non-circular gear planetary gear system;

(3) Seedling Releasing Stage: In the EF segment of the figure, the shift fork departs from the cam's highest contour point, with its upper end fixed to the spring guide rod. The spring transitions from compression to its natural state, guiding the shift fork to the cam contour's lowest point. Upon reaching point F, the seedling needle retracts rapidly under the shift fork's influence, allowing the plug seedlings to drop vertically. This action significantly ensures the perpendicularity of the plug seedlings post-planting;

(4) Returning Stage: In the FA segment of the figure, the seedling needle remains retracted, and the seedling end actuator, driven by the non-circular gear planetary gear train, returns to its initial position. This reset occurs before point A, preparing the mechanism for the subsequent seedling retrieval action in the next work cycle.

2.4.2. Absolute Motion Trajectory Analysis

The absolute motion of the seedling picking mechanism involves the forward motion of the transplanting machine. This mechanism operates in two concurrent ways: it follows the movement of the transplanting machine and simultaneously rotates relative to it. The integration of these two movements produces the absolute motion trajectory relative to the ground, as shown in Figure 7. After completing the seedling picking action, the mechanism moves forward along with the transplanting machine. During this movement, the seedling picking end actuator must avoid contact with the previously transplanted and planted pepper plug seedlings. A higher intersection point between the absolute motion trajectory of the mechanism and the pepper plug seedlings is preferable, as it significantly reduces the likelihood of disturbing the planted seedlings. In this study, the designed penetration pepper plug seedling picking mechanism's absolute motion trajectory intersects 50 mm above the ground at the pepper plug seedling. This height ensures that the picking mechanism remains clear of the pepper plug seedling's main stem segment during movement. Considering that the branches and leaves of the pepper plug seedling exhibit high toughness, the mechanism is unlikely to knock down the already planted seedlings even in the event of a collision.

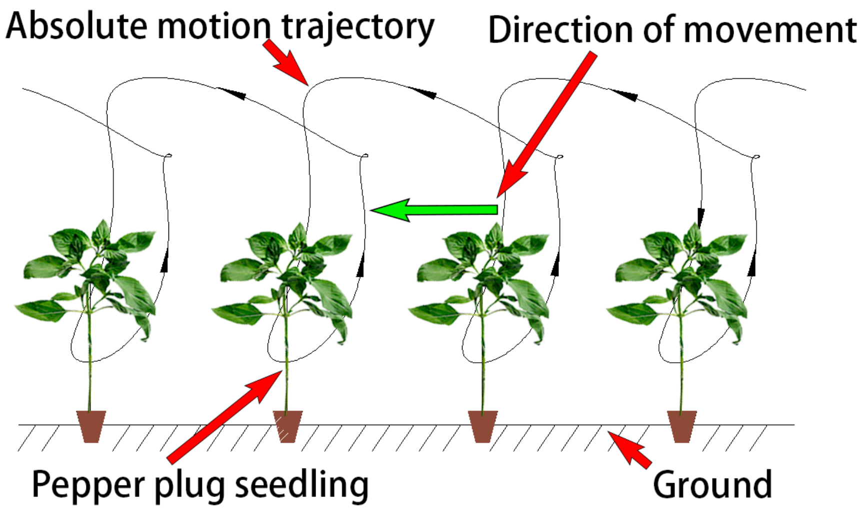


Figure 7. Absolute motion trajectory diagram.

2.5. Optimization and Analysis of the Seedling Picking Mechanism

2.5.1. Optimization Design, Software Development, and Parameter Optimization

Leveraging the kinematic model of the probing-type pepper plug seedling picking mechanism, we developed an optimization design software for this mechanism, as illustrated in Figure 8. To align with the agronomic requirements of transplanting pepper plug seedlings and the structural features of the seedling picking mechanism, we identified 11 optimization objectives, listed in Table 1.

Utilizing the optimization design software developed for the seedling picking mechanism, we acquired a set of mechanism parameters that fulfill the requirements for transplanting pepper plug seedlings, as depicted in Table 2.

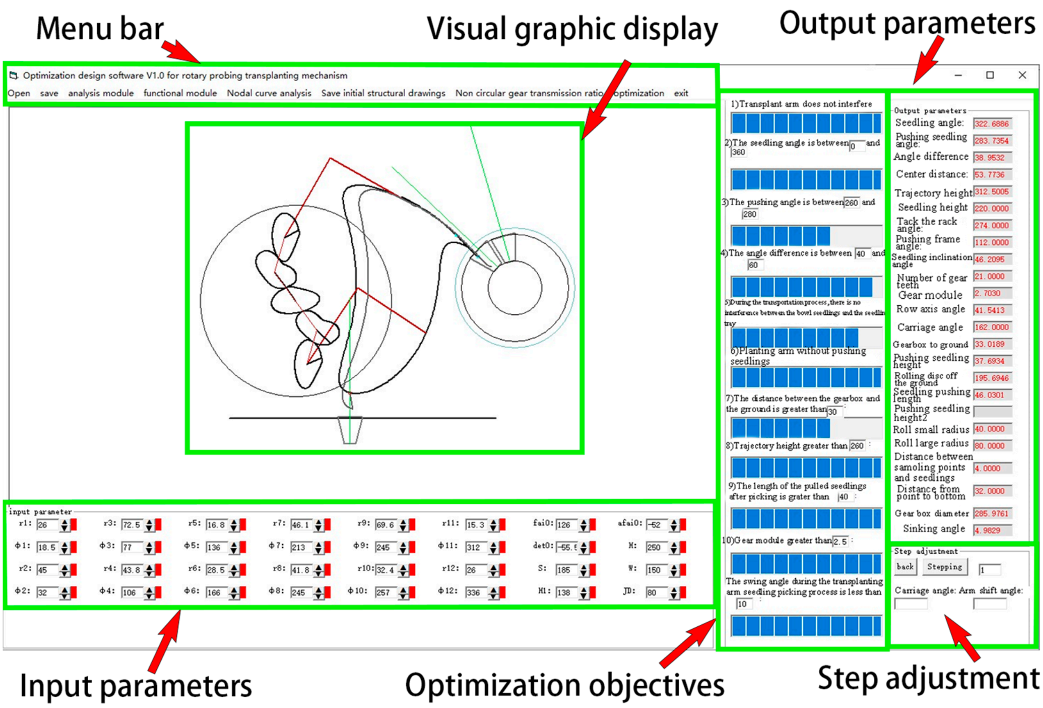


Figure 8. Optimization design software of the seedling picking mechanism.

Table 1. Optimization objectives.

Serial Number	Optimization Objectives	Parameter Requirements
1	Picking seedling angle θ_1	$300^\circ < \theta_1 < 340^\circ$
2	Pepper seedling angle θ_2	$260^\circ < \theta_2 < 280^\circ$
3	Angle difference θ_3	$40^\circ < \theta_3 < 60^\circ$
4	Height of the gearbox from the ground h_1	$30\text{ mm} < h_1$
5	Height of seedling trajectory h_2	$260\text{ mm} < h_2$
6	Pulling length h_3	$40\text{ mm} < h_3$
7	Module m of non-circular gears	2.5 mm < m
8	Seedling picking end actuator seedling picking swing angle θ_4	$\theta_4 < 10^\circ$
9	No interference in seedling end-effector	Meet the conditions
10	No interference between pepper plug seedlings and hole plates during transportation	Meet the conditions
11	Seedling end actuator does not push seedlings	Meet the conditions

Among the parameters, (r_i and θ_i) represent the control points of the non-circular gear pitch curve. fai_0 is the initial angle of the planet carrier, while det_0 is the initial angle of the seedling end-effector. S denotes the distance between the rotation center of the planetary gear and the tipping point of the seedling needle. H_1 is the distance between the inflection point of the seedling end-effector and the rotation center of the planetary gear. $afai_0$ is the inflection angle of the planet carrier of the seedling extraction mechanism, and H represents the planting distance of the pepper plug seedling.

Table 2. Summary of institutional parameters.

Parameter Symbols	Specific Values	Parameter Symbols	Specific Values
r_1	28.4	θ_1	18.5
r_2	45	θ_2	32
r_3	98	θ_3	77
r_4	46	θ_4	106
r_5	33	θ_5	136
r_6	22.5	θ_6	166
r_7	64.1	θ_7	213
r_8	32.8	θ_8	245
r_9	64.6	θ_9	245
r_{10}	53.4	θ_{10}	257
r_{11}	25	θ_{11}	312
r_{12}	26.8	θ_{12}	336
fai_0	126	det_0	−55.5
S	185	H_1	138
$afai_0$	−52	H	250

2.5.2. Parameter Response Law Analysis

To expedite and enhance the efficiency of optimizing the seedling picking mechanism, we analyzed the response of each parameter to the mechanism's optimization objectives. We selected key parameters such as the control parameter of the first value point of the non-circular gear, the initial mounting angles of the planet carrier and the seedling picking end-effector, the inflection angle of the planet carrier, and the structural size parameter of the end-effector. Their influence laws on the trajectory of the seedling picking mechanism were examined. Figure 9 illustrates the response law analysis of some parameters to the optimization objective of the seedling picking mechanism:

(1) Response Law of r_1 to the Optimization Objective of the Seedling Picking Mechanism

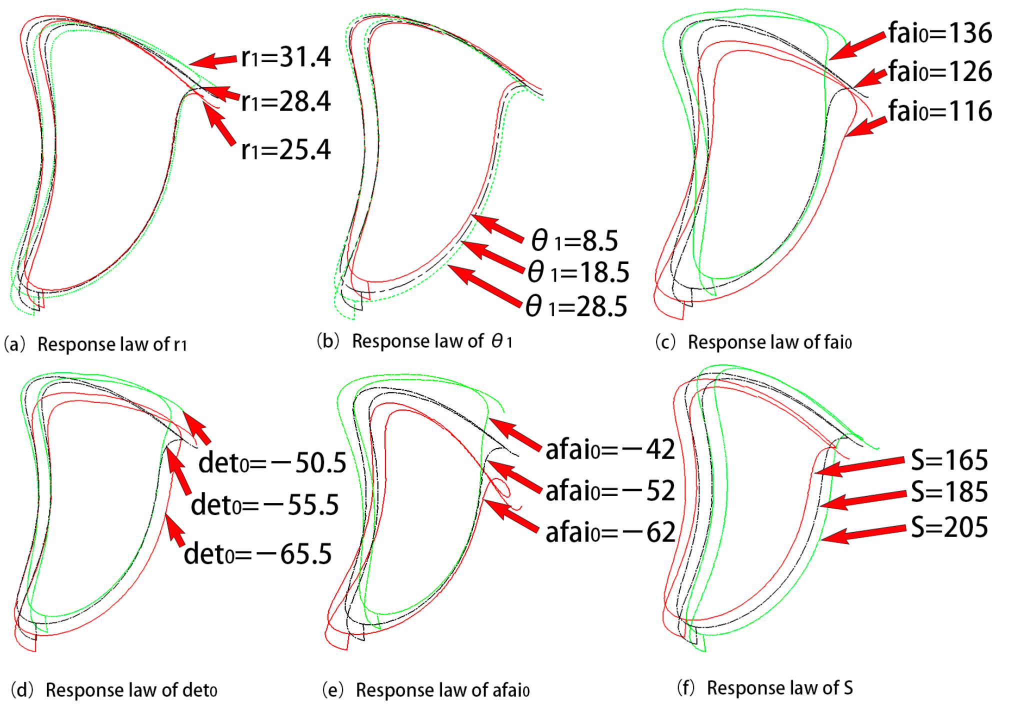


Figure 9. Analysis of the response law of some parameters to the optimization objectives of the seedling picking mechanism.

r_1 is the radial direction of the first value point of the non-circular gear pitch curve. As illustrated in Figure 9a, an increase in r_1 size results in the upward movement of the seedling picking point, an increase in the seedling picking angle, a downward shift of the seedling releasing point, a decrease in the seedling releasing angle, an increase in the angle difference, and a decrease in the trajectory height. When the seedling needle penetrates the hole plate, the swing angle of the seedling picking end actuator escalates, potentially damaging the soil bowl;

(2) Response Law of θ_1 to the Optimization Objective of the Seedling Picking Mechanism

θ_1 is the polar angle of the first value point of the non-circular gear pitch curve. As depicted in Figure 9b, with an increase in θ_1, the seedling picking point moves downward, the seedling picking angle rises, the seedling releasing point descends, the seedling releasing angle diminishes, the angle difference enlarges, and the trajectory height increases. The swing angle of the seedling picking end actuator also increases when inserting the seedling needle into the hole plate;

(3) Response Law of fai_0 to the Optimization Objective of the Seedling Picking Mechanism

fai_0 is the initial mounting angle of the star rack in the probing-type pepper hole tray seedling picking mechanism. Figure 9c shows that as fai_0 increases, the seedling picking trajectory rotates counterclockwise, the seedling picking point elevates, and the linear motion distance in the seedling picking section shortens. Excessively large fai_0 may result in difficulties in smoothly removing the plug seedlings;

(4) Response Law of det_0 to the Optimization Objective of the Seedling Picking Mechanism

det_0 is the initial installation angle of the seedling end-effector. As depicted in Figure 9d, an increase in this angle leads to a notable upward movement of the seedling picking point within the mechanism. The seedling picking angle rises, the seedling releasing point and angle both increase, and the trajectory height grows. However, a higher gearbox position results in an increased likelihood of collision with the ground during the seedling picking mechanism's rotational movement;

(5) Response Law of $afai_0$ to the Optimization Objective of the Seedling Picking Mechanism

$afai_0$, representing the corner angle of the planetary carrier, affects the seedling picking mechanism as shown in Figure 9e. An increase in $afai_0$ causes the seedling picking trajectory to rotate counterclockwise and the seedling picking point to ascend. Consequently, both the seedling picking and releasing angles enlarge, and the trajectory height diminishes. During the seedling placement stage, this effect may cause the plug seedling to tilt and land improperly, compromising the upright positioning of the pepper plug seedling;

(6) Response Law of S to the Optimization Objective of the Seedling Picking Mechanism

S, the distance between the rotation center of the planetary gear and the tip of the seedling needle, impacts the mechanism, as illustrated in Figure 9f. As S increases, the seedling picking point elevates, the seedling picking angle grows, and the linear motion distance of the seedling picking end actuator in the seedling picking section varies, becoming both shorter and longer. The seedling releasing point descends, the seedling releasing angle enlarges, the trajectory height increases, and the gearbox's height from the ground also rises. This change potentially causes interference between the upper and lower seedling picking end actuators.

3. Test

3.1. Virtual Test

Utilizing the optimized mechanism parameters, we established a virtual prototype of the pepper plug seedling picking mechanism and conducted a virtual simulation test, as depicted in Figure 10. Virtual simulation can be used to verify whether there is interference in the rotation motion of the seedling picking arm and to obtain the relative and absolute motion trajectories of the seedling picking mechanism. Upon comparison, the work trajectory and attitude derived from the virtual simulation were closely aligned with the results from the optimization design software. This concordance verifies the accuracy of the kinematic analysis, optimization design software, and virtual simulation.

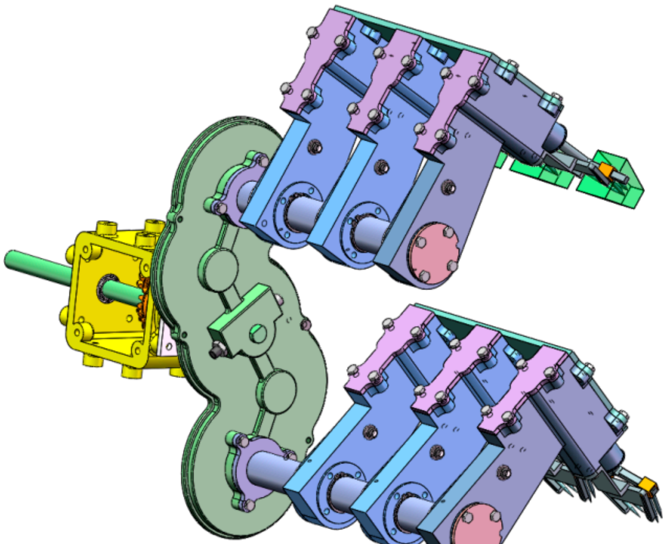
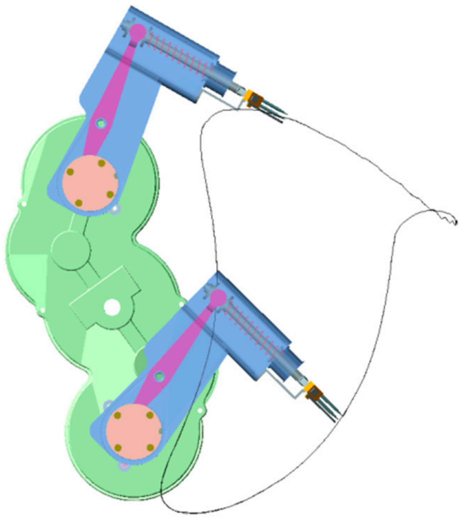


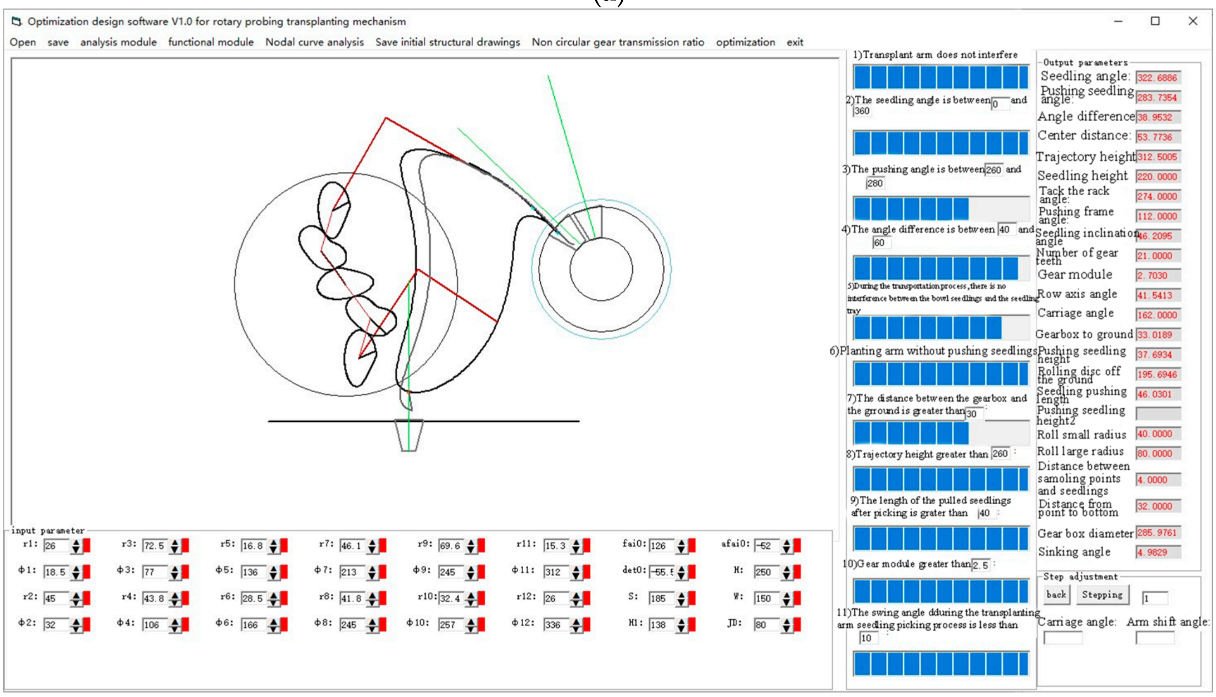
Figure 10. A virtual prototype model of the seedling picking mechanism.

In the relative motion simulation, we imposed appropriate constraints between the components of the seedling picking mechanism. A rotating drive was added to the rotational pair between the left shell of the gearbox and the ground, serving as the power source for the mechanism. The relative motion trajectory of the virtual prototype of the probing-type pepper plug seedling picking mechanism is illustrated in Figure 11a. This trajectory is contrasted with the auxiliary optimization design software's output, shown in Figure 11b. The angles between the posture and horizontal direction of the seedling picking mechanism at four critical positions—when the seedling needle starts to extend, is fully extended, begins to retract, and is fully retracted—are recorded as 328.42°, 325.2°, 276.8°, and 277.32°, respectively, in the optimization software. This relative motion simulation intuitively assesses potential interference during the mechanism's rotation, the correctness of non-circular gear engagement, and the accuracy of the seedling picking end actuator's posture at key points. As Figure 11 demonstrates, the theoretical model trajectory of the mechanism's relative motion closely matches the simulation trajectory.

The absolute motion trajectory of the virtual prototype model of the probing pepper plug seedling picking mechanism is shown in Figure 12a. This is compared with the absolute motion trajectory optimized in the auxiliary optimization design software for the pepper plug seedling picking mechanism, presented in Figure 12b. Through this comparison, we find that the theoretical trajectory of the absolute motion of the seedling picking mechanism essentially mirrors the simulation trajectory.

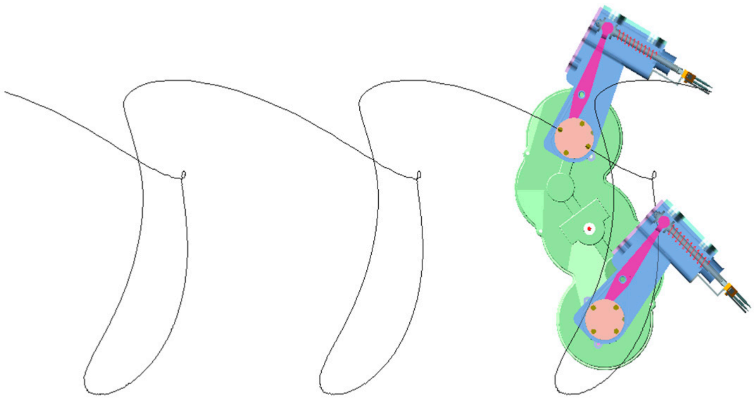


(**a**)

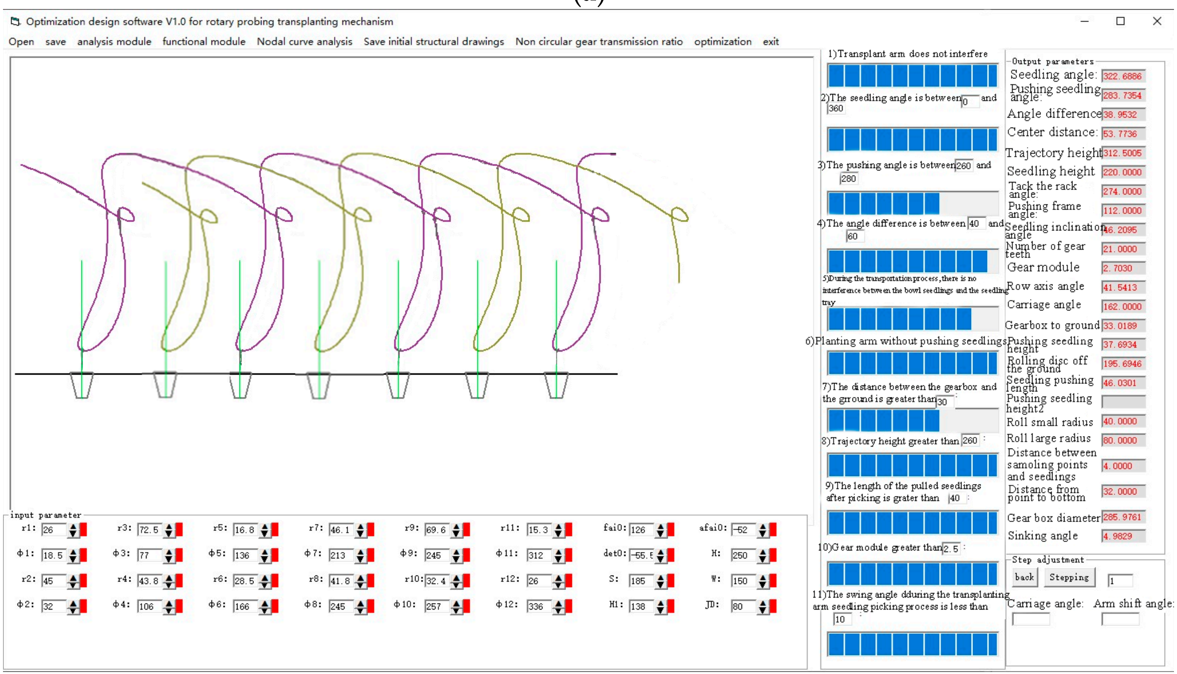


(**b**)

Figure 11. Comparison of the relative motion trajectory results. (**a**) Virtual prototype model relative motion trajectory. (**b**) Theoretical model relative motion trajectory.



(**a**)



(**b**)

Figure 12. Comparison of absolute motion trajectory results. (**a**) Absolute motion trajectory of a virtual prototype. (**b**) Absolute motion trajectory of kinematic models.

3.2. High-Speed Camera Test

For the high-speed camera test of the pepper plug seedling picking mechanism, we selected the I-SPEED3 high-speed camera and set the shooting frame rate to 60 Hz/s. We assembled the physical prototype of the mechanism onto the test bench according to the initial angle of the gearbox and set the gearbox's rotation speed to 50 rotations per minute (r/min). During a rotation cycle, the I-SPEED3 camera captured the mechanism's attitude at four key positions: when the seedling needle starts to extend, is fully extended, begins to retract, and is fully retracted, as illustrated in Figure 13. The captured angles between these four key positions and the horizontal direction were 328.5°, 325.33°, 278.03°, and 277.51°, respectively.

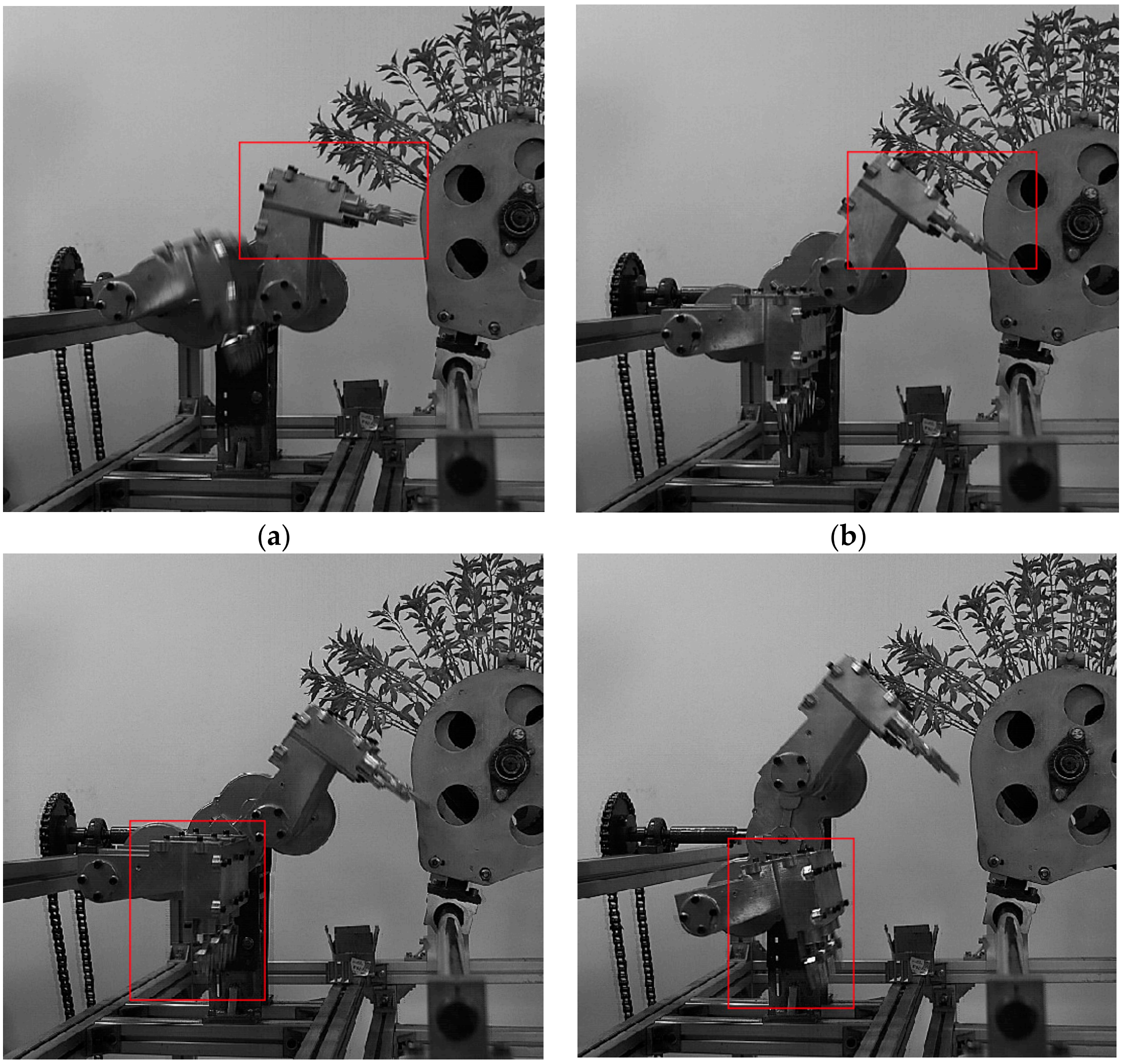
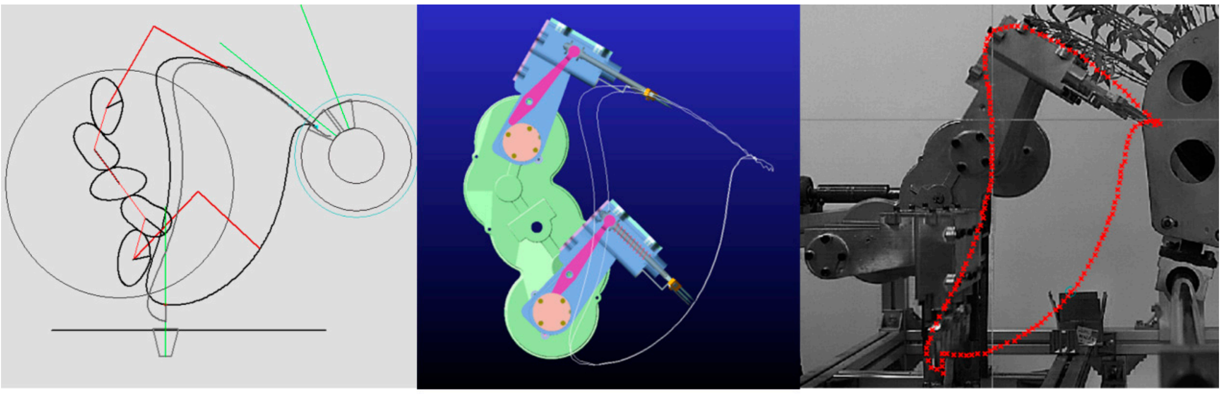

(**a**) (**b**) (**c**) (**d**)

Figure 13. Attitude of key positions of the seedling picking mechanism. (**a**) The seedling needle starts to probe out. (**b**) The seeding needle is fully probed. (**c**) The seeding needle starts to retract. (**d**) The seeding needle is fully retracted.

Using the I-SPEED3 Suite high-speed camera (iX-Cameras, Rochford, UK) analysis software to track the tip points of the pepper plug seedling picking mechanism, we determined the positions of the seedling needles' tip points throughout the rotation. This enabled us to plot the relative motion trajectory of the seedling needle tip, as shown in Figure 14c. We compared this with the theoretical model's relative motion trajectory in Figure 14a and the virtual prototype model's trajectory in Figure 14b. As Figure 14 indicates, the three relative motion trajectories are essentially consistent, confirming the accuracy of the physical prototype model, theoretical model, and virtual prototype model.



(a) Relative motion trajectory of the theoretical model (b) Relative motion trajectory of the virtual prototype (c) High-speed camera relative motion trajectory

Figure 14. Comparison of the relative motion trajectory of the seedling picking mechanism.

3.3. Seedling Picking Test

We conducted a seedling picking test of the pepper plug seedling picking mechanism on a specially constructed test bench, shown in Figure 15. We selected Emperor 336 peppers with a seedling age of 57 days and an average seedling height of 158.6 mm as the experimental subjects, and we utilized a 72-hole plastic plug. During the test, we adjusted the seedling picking mechanism to its initial position, aligning the end actuator of the seedling picking mechanism with the holes in the plug. The rotation speed of the seedling picking mechanism was set to 30–50 r/min.

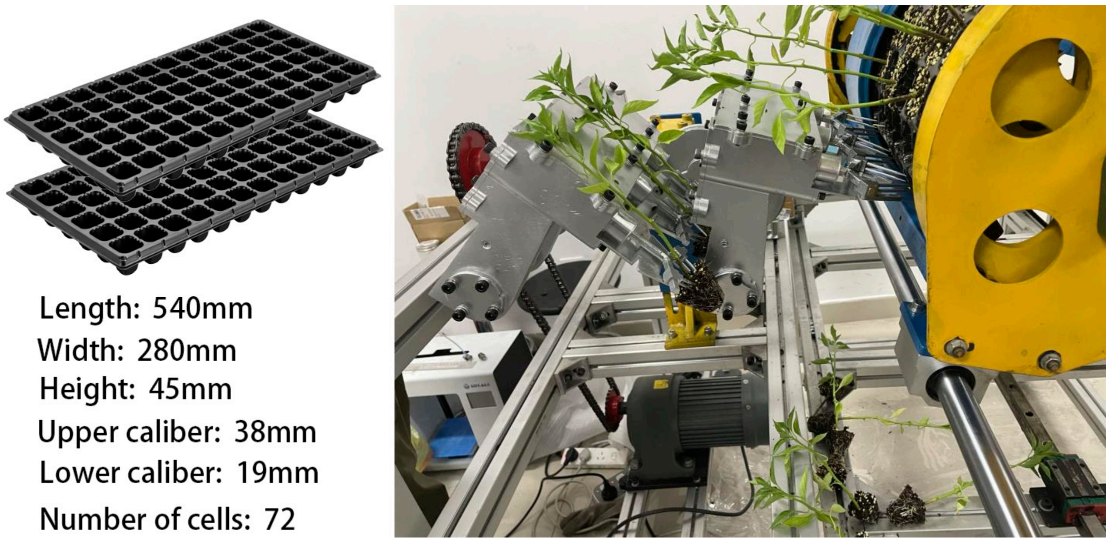


Figure 15. Seedling picking test by seedling picking mechanism.

We analyzed a rotational motion and used a digital laser goniometer to measure the angle between the seedling needle and the horizontal direction of the seedling picking mechanism in four states: when the seedling needle starts to extend, is fully extended, begins to retract, and is fully retracted. As depicted in Figure 16, the angles measured in the seedling experiment by the digital laser goniometer were 31.21° (328.79°), 35.05° (324.95°), 83.11° (276.89°), and 83.81° (276.19°) in the four respective states.

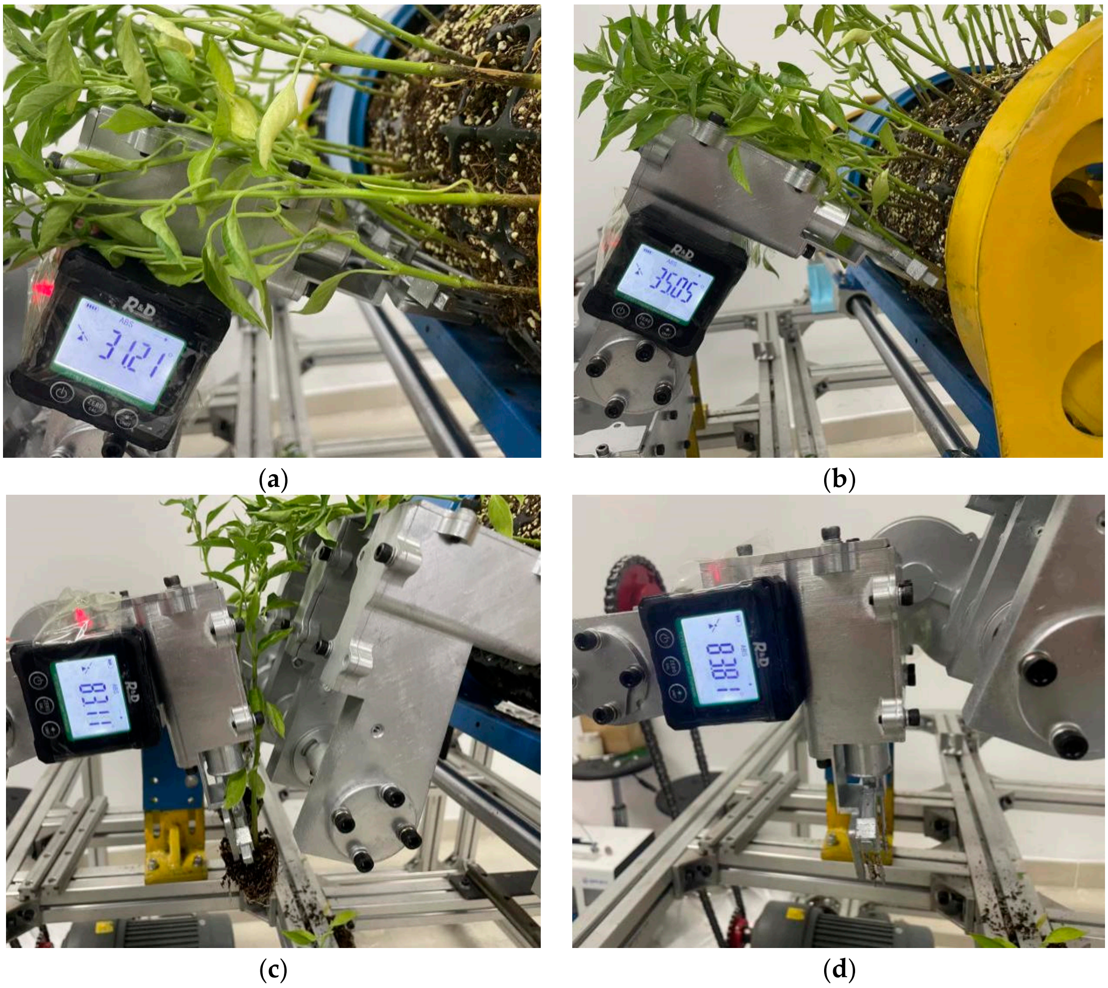


Figure 16. An angle analysis diagram of the seedling picking test. (**a**) Start poking out. (**b**) Fully protrude. (**c**) Start retracting. (**d**) Full recovery.

We organized and summarized the angles between the seedling needle and the horizontal direction recorded in the optimization software, high-speed camera experiment, and seedling picking test under four states: the seedling needle starting to extend, fully extending, starting to retract, and fully retracting. Table 3 presents a comparison of these angles. By comparison, it was found that the maximum error angle of the four key positions occurred when the seedling needle began to retract, with an angle error of 1.2°. This error does not affect the accuracy of actual pepper plug seedling picking or the verticality of the seedlings, which meet the design requirements of exploratory pepper plug seedlings.

Table 3. Comparison of the angles of the seedling picking mechanism.

	Start Poking Out/°	**Fully Protrude/°**	**Start Retracting/°**	**Full Recovery/°**
Optimize software	328.4	325.2	276.8	277.3
High-speed test	328.5	325.3	278	277.5
Seeding picking test	328.8	325	276.9	276.2
Maximum angle error	+0.4	−0.2	+1.2	−1.1

We conducted a seedling picking test using pepper plug seedlings to verify the effectiveness of the pepper plug seedling picking mechanism. The test parameters were set to take 140 seedlings from each group, and the speed of the seedling picking mechanism was set to 30 r/min, 40 r/min, and 50 r/min. The results of seedling picking are shown in Table 4.

Table 4. Seedling pinking test.

Speed r/min	Total Number of Plants/Plant	Number of Successful Seedlings Taken/Plant	Success Rate/%
30	140	135	96.4
40	140	132	94.3
50	140	128	91.4

As the speed of seedling retrieval increases, the efficiency of seedling retrieval is significantly improved, but the success rate of seedling retrieval also decreases. The main reason is that as the speed of the seedling picking mechanism increases, the centrifugal force and the vibration caused by gear rotation also increase, which affects the stability of the seedling picking. To further ascertain the mechanism's reliability, dynamic analysis is necessary to evaluate the forces and vibrations among various non-circular gears. Due to time constraints, only bench tests were conducted. Future work includes developing a complete machine for transplanting pepper plug seedlings, conducting field experiments, and analyzing the overall working performance of the pepper transplanting machine.

4. Conclusions

(1) This study introduced a novel seedling picking method and designed a pepper plug seedling picking mechanism that incorporates a non-circular gear planetary gear train. This design successfully replicates an "eagle beak"-shaped motion trajectory, enabling sequential completion of seedling picking, conveying, releasing, and resetting actions;

(2) Utilizing self-developed software for optimizing the design of the probing-type pepper plug seedling picking mechanism, this article analyzed the impact of various mechanism parameters on transplanting performance. A set of mechanism parameters was optimized to ensure the transplanting arm adheres to the trajectory and attitude required for pepper plug seedlings;

(3) The operation of the seedling picking mechanism was captured on a test bench using a high-speed camera, providing actual working trajectories and attitudes of the physical prototype at key positions. The seedling picking mechanism underwent a bench test, during which the angle between the seedling needle and the horizontal direction was measured in four states: the seedling needle beginning to protrude, fully protruding, starting to retract, and fully retracting. The trajectory and pose of the optimized design software, high-speed camera experiment, and seedling picking experiment were compared, and the motion trajectory was consistent. The maximum error in pose angle was 1.2°;

(4) The seedling picking experiment of the probing-type pepper plug seedling picking mechanism was completed on the experimental platform. The success rates of the seedling picking mechanism were 96.4%, 94.3%, and 91.4% at speeds of 30, 40, and 50 r/min. The seedling picking effectiveness fulfills the transplanting requirements for pepper plug seedlings, demonstrating practical application value.

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and editing, M.Z. and J.Y. (Jianjun Yin); visualization, M.Z., H.S., Z.W., T.X., G.W. and J.Y. (Jianjun Yin); supervision, M.Z. and J.Y. (Jianjun Yin); project administration, M.Z. and J.Y. (Jianjun Yin); funding acquisition, M.Z. and J.Y. (Jianjun Yin). All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to our laboratory's privacy and data protection.

Conflicts of Interest: The authors declare no conflict of interest.

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