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Exploring the Optimal Design for and Experimentation on a Bowl-based Mechanism for Transplanting Potted Strawberry Seedlings

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Abstract: To improve the mechanization of strawberry planting integration and the efficiency of fetching and transplanting seedlings, an integrated transplanting mechanism with protruding, fetching and planting is designed. This new device can realize rapid fetching and pushing bowl movements. The working principle of the slewing mechanism is analyzed, a kinematics model of the mechanism is established, and the optimization goal is established. Visual auxiliary analysis software is developed, optimized parameters are established, and the corresponding theoretical trajectory is provided. A three-dimensional model is established and a virtual simulation design analysis is performed to obtain a simulation trajectory. Three-dimensional printing technology is used to manufacture the test prototype, and the actual working trajectory of the test prototype is extracted using high-speed photography technology, which verifies the consistency of the actual trajectory with the theoretical and simulated trajectories. A prototype transplanting experiment is performed, showing that the success rate of seedling extraction is 91.2% and the rate of excellent planting is 82.8%, which meet the requirements for integrated strawberry harvesting, planting and transplanting and verify the correctness and feasibility of the mechanism design.

Keywords: Potted strawberry seedlings; potted seedling transplanting; integrated planting mechanism; protruding and pushing bowl type; parameter optimization.

1 Introduction

Taxonomically, strawberry belongs to the Rosaceae family and is a perennial evergreen plant. With the rapid development of China's economy, the demand for strawberries continues to increase [1-2], coupled with the rising labor cost, so research on strawberry transplanting machinery has practical meaning. Transplanting machinery is divided into semiautomatic and fully automatic machinery [3]. At present, there are no reports on automatic transplanting equipment for potted strawberry seedlings [4]. A semiautomatic transplanter with artificial seedlings is adopted, which is labor intensive and inefficient. The world's large-scale automatic transplanting models of potted vegetable seedlings include the Australian Williames automatic transplanter and Futura series automatic transplanter produced by Ferrari in Italy [5]. Generally, machine, electricity, gas and liquid integration is adopted, which has a high degree of automation, but the size is large, the structure is complicated, and the price is high, which is not suitable for China's national conditions [6]. Small automatic vegetable seedling transplanting machines, such as a transplanting machine produced by Yanmar Company in Japan, rely on two sets of mechanisms to complete seedling removal and planting

actions[7-8], which is reliable but low in efficiency. High-efficiency, low-cost, lightweight and simplified automatic potted seedling transplanting machinery is still lacking worldwide [9].

In recent years, much research has been done on fully automated potted seedling transplanting in China. The transplanting mechanism is the core component of potted seedling transplanters. The principle of removing potted seedlings from pots can be divided into three stages: clamping the seedlings, taking the pot and ejecting the seedlings. To avoid seedling damage, a bowl-type transplanting mechanism is suitable for transplanting potted strawberry seedlings. Such devices include the rotary transplanting mechanism composed of a noncircular gear and a crank-rocker mechanism designed by Sun Liang et al., [10] the vegetable seedling transplanting mechanism composed of three eccentric circles and incomplete noncircular gears designed by Yu Gaohong et al. [11-12], Ye Bingliang et al. [13-14], and Zhou Meifang et al., [15-16] the rotary hole-piercing pot seedling transplanting mechanism designed by Zhou Maile et al., [17] and the pole-non-circular gear potted strawberry seedling transplanting mechanism designed by Xu Chunlin et al. [18] All of the above use the planting arm to drive an

"eagle-beak" trajectory formed by a needle point into the soil, clamp the seedling, and remove the seedling.

To improve the efficiency of seedling retrieval and planting, this paper designs an integrated transplanting mechanism with protrusion, picking and planting. It takes the seedlings by reversing the seedling needles and clamping the soil bowl, that is, the planetary carrier rotates in the direction opposite to the soil, and the seedling needles are inserted into the soil bowl under the leaves of the seedlings, such that the leaves and stems are not damaged. A "one" shape was used instead of the "eagle beak" to collect the seedling, a spring was used to make the seedling needle quickly penetrate the soil, and the time of entering the soil was reduced, thereby reducing the damage caused by the seedling needle to the root system of the seedling due to the lateral movement of the seedling box. In addition, since there is no sudden change in the theoretical trajectory of the seedling tip point of the transplanting mechanism, a higher rotational speed is allowed. To complete seedling removal more quickly to meet the needs of high-speed planting, a double cam structure is adopted on the basis of the original research results [6]. When the seedling needle is retracted, spring force is used to quickly complete the pushing action of the seedling, which reduces the time of seedling removal and improves the accuracy of planting.

1.1 Trajectory analysis

The seedling-grasping component is used to take seedling, and the seedling-pushing board pushes the seedling to ensure that it is completely removed, and at the same time, the two planting arms do not interfere with each other or with the seedling tray. To achieve rapid seedling extraction, precise seedling pushing, combined with the existing seedling taking mechanism, an integrated mechanism is proposed, and its track analysis is shown in Figure 1. The dashed line is the trajectory of a point in front of the seedling-pushing board, the thick solid line is the actual trajectory of the seedling needle point, and the thin solid line is the theoretical trajectory of the seedling needle tip under the assumption that the seedling needle does not completely protrude. The mechanical structure must complete the 4 consecutive stages of taking seedlings, holding the seedlings, pushing the seedlings, and returning the seedlings in one cycle. Seedling taking stage: in section ABC, when the seedling needle on the planting arm reaches

point A, it quickly protrudes, the seedling needle is inserted into the soil bowl, and the soil bowl is clamped at point B. At the same time, the seedling needle makes the soil bowl contact the planting arm. The seedling tray is separated, reaching point C, and the soil bowl completely leaves the seedling tray. Clamping stage: in the CD section, the relative positions of the potted seedling and the seedling needle remain unchanged. The stage of pushing seedlings: in the DE section, at point D, the seedling-pushing shifting-yoke starts to move, and the seedling-pushing board quickly pushes the bowl under the action of the spring. At the same time, the seedling-taking shifting-yoke starts to move, and the seedling needles are retracted. Under this action, the potted seedlings fall into the soil hole approximately vertically. Recovery stage: in the EA section, the seedling-pushing board slowly returns to its original position, compressing the spring. At this stage, the seedling needle and the seedling-pushing board are completely reset, so the seedling-pushing board does not interfere with the seedling tray, which meets the design requirements.

Fig. 1 Trajectory of the integrated transplanting mechanism

1.2 Working principle

The transplanting mechanism is composed of a planetary gear train and planting arms, as shown in Figure 2. The planetary gear train is composed of left and right housings, planetary gears (1 and 5), a sun gear (3), intermediate gears (2 and 4) and so on. The planting arm part is composed of a cam (13), a seedling-taking shifting-yoke (14), a seedling-pushing shifting-yoke (16), a planting arm shell (19), a seedling needle (20), a pushing and pulling seat plate (23), a connecting rod (24), a pushing bowl (21), a pushing bowl slider (22), and a taking bowl

slide (26) consisting of a spring seat, which cooperates with the spring seat on the planting arm shell. The planting arm shell is provided with a slideway, and the pushing bowl slider (22) and taking bowl slider (26) can slide on it, as shown in Figure 2(c).

The working principle of the planetary gear system is as follows: the sun shaft (8) transmits power and drives the gearbox housing (18) to rotate at a uniform speed; the sun gear (3) is fixed to the flange, and the planetary gears (1 and 5) and intermediate gears (2 and 4) follow the shell body rotation. The planting arm shell rotates at unequal speeds with the planetary axes (6 and 10).

The working principle of the planting arm is as follows: the cam (13) is fixed to the gearbox housing. The planting arm shell is fixed to the limit plates at the ends of the planetary axes (6 and 10). The seedling-taking shifting yoke (14) and seedling-pushing shifting yoke (16) rotate around the fork shafts (15 and 17, respectively). The cam (13) drives the shifting-yokes (14 and 16) to swing, which drives the sliders (26 and 22). This completes the seedling collection and seedling pushing operations.

(c) Working principle diagram of the transplanting arm planetary gear (1, 5), intermediate gears (2, 4), sun gear (3), planetary axes (7, 9), sun axle (8), first part of the planting arm (11), second part of the planting arm (12), cam (13), seedling-taking shifting-yoke (14), seedling-taking shifting-yoke axle (15), seedling-pushing shifting-yoke (16), seedling-pushing shifting-yoke axle (17), gearbox housing (18), planting arm (19), seedling needle (20), seedling-pushing board (21), push bowl slider (22), push-pull seat plate (23), connecting rod (24), compression springs (25, 27), and seedling-taking bowl slider (26)

Fig. 2 Working principle diagram of the seedling planting mechanism

2 Kinematic model of the mechanism

2.1 Noncircular gear pitch curve forming method

In this paper, Lagrangian interpolation is used to obtain the noncircular gear pitch curve. To avoid the Runge phenomenon^[19], too many interpolation points are not used, so a total of 6 interpolation points are selected. In the polar coordinate system, the first and sixth interpolation points coincide to ensure the sealing of noncircular gears.

Lagrange interpolation formula in a polar coordinate system:

$$L_n(r) = \sum_{i=0}^n \varphi_i l_i(r) \quad (1)$$

$$l_i(r) = \prod_{\substack{j=0 \\ j \neq i}}^n \frac{r - r_j}{r_i - r_j} \quad (2)$$

where:

$l_i(r)$ — Lagrange function

r_i — The radial of each point on the nodal curve, mm

φ_i — The polar angle corresponding to the radial, °

2.2 Kinematic model establishment

The movement diagram of the noncircular planetary gear train is shown in Figure 3, and the symbols of the transplanting mechanism are described in Table 1 [20-22].

Fig. 3 Schematic of the noncircular planetary gear train

Since the mechanism is symmetrical around the center of the sun gear, only one side of the mechanism is used for analysis. The sun gear is fixed on the frame, and the planet carrier (gearbox housing) rotates counterclockwise at a constant speed (counterclockwise rotation is recorded as positive, and clockwise rotation is negative).

Tab. 1 Symbol description of transplanting organization

Symbol	Description
$r_1 (\theta)$	Sun gear pitch curve radius
$r_2 (\theta)$	Intermediate gear pitch curve radius
φ_{H0}	The initial installation angle of the planet carrier
θ_0	Planet carrier corner
δ_0	The angle between the planting arm and the planet carrier before the seedling needle protrudes
$\delta_0 + \theta$	The angle between the planting arm and the planet carrier after the seedling needles are protruded
a	Center distance between two adjacent noncircular gears
b	Length of the first planting arm
c	The distance from the rotation center of the planetary gear to the tip of the seedling needle
d	The distance from the rotation center of the planetary gear to the tip of the seedling needle after the seedling needle protrudes

In the transplanting process, the planet carrier rotates counterclockwise at a uniform speed, and the sun gear is fixed when the planet carrier rotates through φ .

The absolute rotation angle of the planet carrier relative to the frame is:

$$\varphi_H(\varphi) = \varphi_{H_0} + \varphi \quad (3)$$

The relative and absolute rotation angles of the sun gear are:

$$\begin{cases} \beta_1(\varphi) = -\varphi \\ \varphi_1(\varphi) = \varphi_{H_0} \end{cases} \quad (4)$$

The relative and absolute rotation angles of the intermediate gear are:

$$\begin{cases} \beta_2(\varphi) = \sum_{i=0}^{\varphi-1} \frac{r_1(\beta_1(i))}{a - r_1(\beta_1(i))} (\beta_1(i+1) - \beta_1(i)) \\ \varphi_2(\varphi) = \varphi_H(\varphi) + \beta_2(\varphi) \end{cases} \quad (5)$$

The relative and absolute rotation angles of the planetary gear are:

$$\begin{cases} \beta_3(\varphi) = \sum_{i=0}^{\varphi-1} \frac{r_2(\beta_2(i))}{a - r_2(\beta_2(i))} (\beta_2(i+1) - \beta_2(i)) \\ \varphi_3(\varphi) = \varphi_H(\varphi) - \varphi_{30} - \beta_3(\varphi) \end{cases} \quad (6)$$

To compensate for the corners of the planet carrier, the rotation angle of the planetary gear is:

$$\varphi_{30} = \int_0^{\theta_0} \frac{r_2(2\pi - x)}{a - r_2(2\pi - x)} dx \quad (7)$$

The coordinates of the center of rotation of the sun gear are:

$$x_1(\varphi) = y_1(\varphi) = 0 \quad (8)$$

The coordinates of the center of rotation of the intermediate gear are:

$$\begin{cases} x_2(\varphi) = a \cdot \cos(\varphi_H(\varphi)) \\ y_2(\varphi) = a \cdot \sin(\varphi_H(\varphi)) \end{cases} \quad (9)$$

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

$$\begin{cases} x_3(\varphi) = a \cdot \cos(\varphi_H(\varphi) + \theta_0) + x_2(\varphi) \\ y_3(\varphi) = a \cdot \sin(\varphi_H(\varphi) + \theta_0) + y_2(\varphi) \end{cases} \quad (10)$$

The coordinates of point E at the end of the planting arm in the first part are:

$$\begin{cases} x_E(\varphi) = b \cdot \cos(\varphi_H(\varphi) + \theta_0 + \varphi_1 - \beta_3(\varphi)) + x_3(\varphi) \\ y_E(\varphi) = b \cdot \sin(\varphi_H(\varphi) + \theta_0 + \varphi_1 - \beta_3(\varphi)) + y_3(\varphi) \end{cases} \quad (11)$$

The coordinates of the point at the end of the planting arm in the second part are discussed in three situations.

(1) Before the needle sticks out, the F coordinates of the end point of the planting arm in the second part are:

$$\begin{cases} x_F(\varphi) = c \cdot \cos(\varphi_H(\varphi) + \theta_0 + \delta_0 - \beta_3(\varphi)) + x_3(\varphi) \\ y_F(\varphi) = c \cdot \sin(\varphi_H(\varphi) + \theta_0 + \delta_0 - \beta_3(\varphi)) + y_3(\varphi) \end{cases} \quad (12)$$

(2) After the needle sticks out, the F' coordinates of the end point of the planting arm in the second parts are:

$$\begin{cases} x_{F'}(\varphi) = d \cdot \cos(\varphi_H(\varphi) + \theta_0 + \delta_0 - \beta_3(\varphi) + \theta) + x_3(\varphi) \\ y_{F'}(\varphi) = d \cdot \sin(\varphi_H(\varphi) + \theta_0 + \delta_0 - \beta_3(\varphi) + \theta) + y_3(\varphi) \end{cases} \quad (13)$$

(3) When the seedling needle protrude, a schematic diagram of establishing the transplanting arm with integrated taking and planting planetary gear train was created, as shown in Figure 4, and the symbol description of the planting arm structure is provided in Table 2. Taking point D as the origin, a rectangular coordinate system is established. Since the front and rear seedling needles are symmetrical, only one side is taken for analysis.

Tab. 2 Symbol description of the transplanting arm structure

Symbol	Description
l_1	Length of the upper section of the seedling-taking shifting-yoke
l_2	The y distance between the upper end of the seedling-taking shifting-yoke and the hinge point of the seedling needle
$l_{NT}-l_3$	The x direction distance between the upper end of the seedling-taking shifting-yoke and the hinge point of the seedling needle
θ_I	Seedling needle angle
l_9	Seedling needle length
l_8	The distance in the x direction from hinge point C of the seedling-taking shifting-yoke to hinge point N of the seedling-taking shifting-yoke
l_7	The distance in the y direction from hinge point C of the seedling-taking shifting-yoke to hinge point N of the seedling-taking shifting-yoke
l_4	Length of the upper section of the seedling-taking shifting-yoke
l_{10}	Length of the lower section of the seedling-taking shifting-yoke
l_5	The x-direction distance between the upper end of the push bowl fork and the intersection point of the push bowl and seedling needle on the same plane
l_6	The y distance between the upper end of the push bowl fork and the intersection of the push bowl and the seedling needle on the same plane
β	The angle between the upper section of the seedling-taking shifting-yoke and the x-axis
λ	The angle between the upper section of the seedling-taking shifting-yoke and the x-axis
β_1	The middle angle of the seedling-taking shifting-yoke
β_2	The middle angle of the seedling-taking shifting-yoke

Fig. 4 Schematic diagram of the end effector for seedling planting

The coordinates of the hinge point of the seedling-taking shifting-yoke are:

$$\begin{cases} x_D(\varphi) = x_3(\varphi) - l_{11} \\ y_D(\varphi) = y_3(\varphi) \end{cases} \quad (14)$$

The coordinates of the hinge point of the seedling-taking shifting-yoke are:

$$\begin{cases} x_C(\varphi) = x_D(\varphi) + l_8 \\ y_C(\varphi) = y_D(\varphi) + l_7 \end{cases} \quad (15)$$

The coordinates of the upper end point of the seedling-taking shifting-yoke are:

$$\begin{cases} x_N(\varphi) = x_C(\varphi) + l_1 \cdot \cos \lambda \\ y_N(\varphi) = y_C(\varphi) + l_1 \cdot \sin \lambda \end{cases} \quad (16)$$

The coordinates of the hinge point of the seedling needle are:

$$\begin{cases} x_I(\varphi) = x_N(\varphi) + l_{NT} - l_3 \\ y_I(\varphi) = y_N(\varphi) + l_2 \end{cases} \quad (17)$$

In the process of seedling needle protrusion, the coordinates of the tip point of the second part of the planting arm are:

$$\begin{cases} x_{F_1}(\varphi) = x_I(\varphi) - l_9 \cdot \cos \theta_I \\ y_{F_1}(\varphi) = y_I(\varphi) - l_9 \cdot \sin \theta_I \end{cases} \quad (18)$$

The coordinates of the upper end point G of the seedling-taking shifting-yoke are:

$$\begin{cases} x_G(\varphi) = x_D(\varphi) + l_4 \cdot \cos \beta \\ y_G(\varphi) = y_D(\varphi) + l_4 \cdot \sin \beta \end{cases} \quad (19)$$

The coordinates of point H on the seedling-taking plate on the same plane as the seedling needle are:

$$\begin{cases} x_H(\varphi) = x_G(\varphi) - l_5 \\ y_H(\varphi) = y_G(\varphi) + l_6 \end{cases} \quad (20)$$

2.3 Kinematic modeling of the cam mechanism

The design of the cam has always been the greatest challenge of the transfer mechanism. The cam pressure angle is too large, which will cause a self-locking phenomenon, but the angle of the cam lift section cannot be too large, and the difficulty of matching the two cam contour lines is also a design difficulty. As shown in Figure 5, the cam has two layers of profiles, the seedling-taking profile and the seedling-pushing profile. The seedling removal stage proceeds as follows: start to take the seedlings at point g, stop the movement of the seedling-taking shifting-yoke at point h, and reach the limit position, at which point the cam angle should be less than 12° in the seedling removal phase. The clamping phase is in the 'he' phase of the cam seedling taking profile. The seedling-pushing phase proceeds as follows: start pushing the seedlings at point b, start to move the seedling-pushing shifting-yoke, and finish pushing the seedlings at point a. The cam angle should be less than 13° in the stage of pushing seedlings. When the seedling-pushing shifting-yoke reaches point b of the cam seedling-pushing profile, the seedling-taking shifting-yoke is also moving, and the seedling needles are slowly retracted. Under the combined action of the two, the pot seedlings fall approximately vertically into the soil hole. The recovery stage proceeds as follows: the seedling-pushing board slowly returns to its original position, the seedling needle is slowly retracted, and the spring is compressed, corresponding to the ad stage of the cam seedling-pushing profile and the ef stage of the cam seedling taking-profile, such that the seedling-pushing board will not interfere with the seedling tray, the seedling needle is completely retracted, and the design requirements are met.

Fig. 5 Schematic diagram of the double-profile cam

As shown in Figure 6, the state of the seedling-taking shifting-yoke and the seedling-pushing shifting-yoke occurs in two extreme positions. When the distance between the top of the seedling-taking shifting-yoke and the seedling-pushing shifting-yoke in the extreme position is the shortest, it is in a state of holding the soil bowl. When the distance between the top of the seedling-pushing shifting-yoke and the top of the seedling-taking shifting-yoke is the longest, it is the state after the bowl is pushed. Knowing the coordinates of points Q, G, S, N, D, and C, the minor radius of the cam $R_1=14$ mm, and the length and included angle of the upper and lower sections of the seedling-taking shifting-yoke and seedling-pushing shifting-yoke are taken. To obtain the size of the major diameter of the cam, a rectangular coordinate system is established with the center of the cam circle as the origin. Point J is the contact point of the small diameter of the seedling-taking shifting-yoke and the seedling-taking-profile cam, and point L is the contact point of the major diameter of the seedling-taking shifting-yoke and the seedling-taking-profile cam. Point K is the contact point of the small diameter of the seedling-pushing shifting-yoke and the seedling-pushing profile cam, and point P is the contact point of the large diameter of the seedling-pushing shifting-yoke and the seedling-pushing profile cam.

Fig. 6 Schematic diagram of cam fork modeling

Through geometric relationships [23], (x_p, y_p) and R_3 can be obtained simultaneously:

$$\arctan \frac{y_p - y_D}{x_p - x_D} = \arctan \frac{y_G - y_D}{x_G - x_D} + \quad (21)$$

$$2\pi - \beta_1$$

$$x_p = x_D + l_{10} \cdot \cos(2\pi - \beta_1 + \beta) \quad (22)$$

$$R_3 = \sqrt{(x_o - x_p)^2 + (y_o - y_p)^2} \quad (23)$$

According to formulas (21) ~ (23), R_2 can be obtained in the same way:

$$R_2 = \sqrt{(x_o - x_L)^2 + (y_o - y_L)^2} \quad (24)$$

where: R_2 —The large-diameter radius of the profile cam of seedling pushing, mm
 R_3 —The large-diameter radius of the profile cam of seedling taking, mm

2.4 Design of the pressure angle of the cam mechanism

The acute angle between the direction of the rotational speed of the shift fork around the shift fork shaft and the direction of the positive pressure F received by the shift fork is the pressure angle α , and the pressure angle is less than 45° as required^[24]. According to the reversal method, the cam rotation center O is the center of the circle, and OC is the radius to draw a circle. This circle is the trajectory circle of the swing center in the reversal motion. With CL as the radius, a point on the cam contour line's lift section is the center of the arc, and the intersection point with the trajectory circle Point $C1$ and points $C2$, $D1$, and $D2$ are the same. The schematic diagram is shown in Figure 7. The force analysis of taking the bowl fork as the research object is:

$$\sum F_x = 0, \sum F_y = 0, \sum M_D = 0 \quad (25)$$

Fig. 7 Reversal method to find the cam pressure angle

$$\sum F_x = F_s - F_R \cdot \cos \varphi_2 + F \cdot \cos\left(\frac{\pi}{2} - (\alpha + \varphi_3 + \beta_1 - \beta)\right) = 0 \quad (26)$$

$$\sum F_y = F_R \cdot \sin \varphi_2 - F \cdot \sin\left(\frac{\pi}{2} - (\alpha + \varphi_3 + \beta_1 - \beta)\right) = 0 \quad (27)$$

$$\sum M_D = F_s \cdot l_4 \cdot \sin \beta - F \cdot \cos(\alpha + \varphi_3) \cdot l_9 - M_2 = 0 \quad (28)$$

where: F_s —Spring force, N
 F_R —Force from the hinge point of the shifting-yoke to the shifting-yoke, N
 F —The force of the cam on the shifting-yoke, N
 φ_2, φ_3 —Friction angle, rad
 M_2 —Moment of inertia, N·mm
 J_2 —Moment of inertia of the fork
 α_4 —Fork angular acceleration, rad/s²

We get:

$$F = 1 / \left(\frac{l_9 \cdot \cos(\alpha + \varphi_3) + M_2}{l_4 \cdot \sin \beta} + \frac{\cos \eta}{\tan \varphi_2} + \sin \eta \right) \quad (29)$$

$$\eta = \alpha + \varphi_3 + \beta_1 - \beta \quad (30)$$

$$M_2 = J_2 \alpha_4 \quad (31)$$

Under the same other conditions, when η is greater than 90° , the greater the pressure angle is, the smaller the denominator, and the greater the force F . If it is so large that the denominator in the formula is zero, F will increase to infinity, and the mechanism will self-lock.

The pressure angles ($\alpha_1, \alpha_2, \alpha_3, \alpha_4$) of the cam lift section are measured, and it can be concluded that these pressure angles are all less than the maximum pressure angle of 45° . To meet this condition, the lift section of the contour line of the seedling-taking-profile cam is divided into two sections, as shown in Figure 6. The dividing point is at point k , and the slope of the second section is smaller than that of the first section; the lift section of the contour line of the seedling pushing profile cam is also divided into two sections. The dividing point is at point c , and the slope of the second section is smaller than that of the first section.

3 Mechanism multiobjective optimization and simulation

3.1 Target optimization

According to the agronomic requirements of potted strawberry seedling transplanting, the movement interference, angle change, and trajectory shape of the transplanting mechanism involve 7 optimization goals:

① The seedling taking angle is between 310° and 320° ② The angle of seedling pushing is between 260° and 280° to ensure the erect nature of the seedlings. □ The angle difference between seedling taking and seedling pushing is 40° . □ The distance between the gearbox and the seedling feeding point is greater than 0 to avoid interference between the gearbox body and the planting mechanism. ⑤ The track height is greater than 260 mm. □ When seedlings are taken, the swing angle of the planting arm is $0^\circ \sim 5^\circ$ to avoid interference between the gearbox body and the planting mechanism. □ The two planting arms do not interfere to avoid collision between the two planting arms during seedling retrieval.

3.2 Optimization design software

The gear pitch curve parameters include $\varphi_1=0^\circ$, $\varphi_2=48.9^\circ$, $\varphi_3=107.1^\circ$, $\varphi_4=230.1^\circ$, $\varphi_5=268.6^\circ$, $\varphi_6=360^\circ$, $r_1=24.1 \text{ mm}=r_6$, $r_2=29.7 \text{ mm}$, $r_3=20.2 \text{ mm}$, $r_4=22.3 \text{ mm}$, and $r_5=22 \text{ mm}$. The structural parameters include $\varphi_{H0}=149^\circ$, $\theta_0=-68^\circ$, $\delta_0=-56^\circ$, $x_g=245 \text{ mm}$, $y_g=110 \text{ mm}$, $\gamma=55^\circ$, $H_1=144 \text{ mm}$, and $S=168 \text{ mm}$, as shown in Figure 8.

Fig. 8 Optimization of the main interface of the integrated picking and planting mechanism

The transmission ratio curve corresponding to the transplanting mechanism under these parameters is shown in Figure 9. As the rotational angle of the planet carrier changes, the transmission ratio curve between the gears presents a complicated changing trend, with multiple crests and troughs appearing at the same time. Looking at the transmission ratio curves under this set of parameters, the transplanting mechanism conforms to the unequal speed transmission law required for potted seedling transplanting [17].

Fig. 9 Transmission ratio relationship between gears

According to the optimized structural parameters, the virtual design of the mechanism is completed, and motion simulation is carried out. In a working cycle (the planet carrier rotates 360° from the initial position), when the planet carrier rotates 89° , the seedling starts to be pushed, and the seedling needles begin to retract. When the planet carrier rotates through 102° , the potted seedling is pushed out under the combined action of the seedling-pushing board protruding out and the seedling needle retracting. When the planet carrier rotates 211° , the seedling-pushing board retracts to the initial position. The seedlings are taken when the planet carrier rotates to 257° .

3.3 3D modeling simulation analysis

Figure 10 (a) is the Visual Basic optimized relative trajectory, and (b) is the Visual Basic optimized absolute trajectory. Figure 11(a) shows the simulated relative motion trajectory, and Figure (b) shows the simulated absolute motion trajectory. The optimized absolute trajectory and the relative trajectory are basically similar to the simulated trajectory, and the swing angle of the planting arm in the relative trajectory is small. When the absolute trajectory pushes the seedlings in the vertical direction, the uprightness of the seedlings is guaranteed to be met upon request, and the next step of prototype manufacturing can be carried out.

Fig. 10 Visual Basic optimized trajectory graph

Fig. 11 Motion simulation trajectory

As shown in Figure 12, the solid line is the movement of the seedling-pushing board relative to the end shell, the movement stroke is 20 mm, and the left side of the wave crest is steeper in one cycle, which means that the spring is released and the seedling-pushing board moves quickly, and the right side of the wave crest is relatively smooth. This represents the slow compression of the spring, where the seedling-pushing board slowly retracts and shows the next cycle of movement. The dotted line is the movement curve of the seedling needle relative to the end shell. The movement stroke is 40 mm, the left side of the wave crest is relatively smooth, the right side of the wave crest is relatively steep, and there is a short stay in the middle of the wave crest. One cycle of movement will not cause interference. It can be seen from the figure that in the process of pushing the seedlings, the seedling-taking shifting-yoke and the seedling-pushing shifting-yoke move together to push the seedlings quickly. The rightmost point of each wave crest on the dotted line is on the right side of the point where the solid line is flat, which means that the seedling-pushing board is fully retracted before the next cycle of operations will be carried out, and the seedling-pushing board will not interfere with the removal of the potted seedlings.

Fig. 12 The relationship between relative movement stroke and time of the pushing bowl and seedling needle

4 Prototype test

4.1 High-speed photography bench test

Using 3D printed molding technology, the material is PLA^[25], which completes the physical prototype assembly. To verify the actual work trajectory of the organization, a high-speed camera was used on the platform to capture multiple key position states, as shown in Figure 13: (a) initial position, (b) starting position of the seedling needle, (c) clamping position of the seedling needle, (d) potted seedling pushing start position, (e) potted seedling pushing end position, (f) retract position of the seedling needle, and (g) retraction position of the seedling-pushing board.

(a) Initial position

(b) Seedling needles began to stick out

(c) Seedling pin clamped the seedling

(d) The bowl started to stick out

(e) The bowl was pushed fully out

(f) The seedling needle retracted into place

(g) The bowl was pushed back into place

Fig. 13 Each key position

The seedling needles are retracted first, and then the planet carrier is rotated through an angle. The seedling-pushing board is fully retracted, the planet carrier is rotated another angle to start taking seedlings, and the seedling needles quickly protrude without interference, which meets the design requirements. The trajectory of the seedling needle point is shown in Figure 14.

Fig. 14 Trajectory of seedling needle point

4.2 Prototype soil tank test

The mass ratio of the original soil to the substrate is 0.4:1, the seedling tray has 72 holes, the soil depth in the soil trough is 120 mm, and the dimensions of the pot hole are as follows: top 40 mm×40 mm, bottom 15 mm×15 mm, and depth 40 mm. Standards for planting seedlings are as follows: well-developed root system, more than 20 first-level roots, short petiole, approximately 15 cm long, 2~3 mm thick, 5~7 mature leaves, new stems more than 0.8 mm thick, seedling weight above 20 g, and no diseases or insect pests. The bench rotation speed is 40 r/min, the theoretical seedling speed is 80 plants/branch/row, the plant spacing is 200 mm, and the soil trough is moved at a speed of 0.27 m/s. As shown in Figure 15, the existing benches of the research group are used for experiments [26]. According to the JB/T 10291-2013 Dryland Planting Machinery Industry Standard issued by the Ministry of Industry and Information Technology of the People's Republic of China. After processing the test data, the success rate of seedling retrieval was 91.2%, and the rate of excellent planting was 82.8%. The results proved that the technology can better meet the planting requirements.

Fig. 15 Planting bench test with seedlings

Acknowledgments

(1) According to the agronomic requirements of strawberry transplanting, an integrated seedling planting and seedling transplanting mechanism for mechanized transplanting of potted strawberry seedlings is proposed, which can quickly reach out and extract the seedlings in a "waist"-shaped track and quickly push out the seedlings to form a "one horizon line"-shaped trajectory.

A set of mechanisms completes the three actions of seedling retrieval, transportation and planting in sequence. The working principle of the mechanism is analyzed, and a mechanistic kinematics model is established.

(2) The optimized design software of the strawberry seedling taking and seedling planting integrated transplanting mechanism is compiled, and computation is used to obtain a set of mechanism parameters and motion trajectories that meet the design requirements: the initial installation angle of the planet carrier is 149°, and the corner of the planet carrier is -68°. The initial installation angle of the planting arm is -56°.

(3) Through virtual prototype simulation and high-speed photography experiments, the simulated trajectory and actual motion trajectory of the transplanting mechanism are obtained. A comparative analysis shows that the theoretical trajectory, the simulated trajectory and the actual motion trajectory are basically the same, thus verifying the bowl-based integrated seedling taking and seedling planting device. The correctness and feasibility of the planting mechanism design are confirmed.

(4) In the prototype planting test, the success rate of seedling extraction was 91.2%, the seedling extraction efficiency was

80 plants/min, and the excellent planting rate was 82.8%, which satisfies the requirements of erection and transplanting and verifies the practicability of the mechanism.

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Figures

Figure 1

Trajectory of the integrated transplanting mechanism

Figure 3

Schematic of the noncircular planetary gear train

Figure 4

Schematic diagram of the end effector for seedling planting

Figure 5

Schematic diagram of the double-profile cam

Figure 6

Schematic diagram of cam fork modeling

Reversal method to find the cam pressure angle

Transmission ratio relationship between gears

Figure 10

Visual Basic optimized trajectory graph

(a) Motion simulation of the relative motion trajectory

(b) Motion simulation of the absolute motion trajectory

Figure 11

Motion simulation trajectory

Figure 12

The relationship between relative movement stroke and time of the pushing bowl and seedling needle

(a) Initial position

(b) Seedling needles began to stick out

(c) Seedling pin clamped the seedling

(d) The bowl started to stick out

(e) The bowl was pushed fully out

(f) The seedling needle retracted into place

(g) The bowl was pushed back into place

Figure 13

Each key position

Figure 14

Trajectory of seedling needle point

Figure 15

Planting bench test with seedlings