Design and experimental research on the sweet potato seedling transplanting mechanism of the planetary gear train with deformed elliptical gear transmission

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Abstract: Aiming at the lack of suitable machines for sweet potato seedling transplanting in China, and according to the agronomic requirements for the horizontal insertion method of sweet potato seedling, a new sweet potato seedling transplanting mechanism of planetary gear train was proposed based on the non-uniform transmission of deformed elliptical gear. The working principle of the transplanting mechanism was analyzed, and the kinematics modeling and analysis of the mechanism were carried out. The study established the numerical objectives of the transplanting mechanism and applied the theory of membership function to establish a mathematical model for the parameter-guided optimization design of the transplanting mechanism. The parameter-guided optimization design software was developed to obtain a set of optimal mechanism parameters that satisfied the motion trajectory of sweet potato transplanting and the posture of the transplanting arm. Based on the optimized parameters, the structure of the transplanting mechanism was designed, and a virtual prototype of the mechanism was created, whereby a virtual motion simulation of the transplanting mechanism was conducted to verify the correctness of the kinematics model and design of the mechanism. The high-speed photographic kinematics test of the mechanism prototype and sweet potato seedling transplanting tests were conducted to test the mechanism's kinematic characteristics and transplanting performance. The test results show that the test trajectory of the mechanism and test posture of the transplanting arm are almost consistent with the theoretical and simulation trajectory, meeting the agronomic requirements of the horizontal insertion method of sweet potato seedling; And when the rotary speed of the mechanism are 20 r/min and 30 r/min, the average success ratios of sweet potato seedlings transplanting are 90% and 82%, respectively, which prove the application feasibility of the mechanism in the practical machines.

Keywords: sweet potato seedling transplanter, transplanting mechanism, deformed elliptical gear transmission, kinematics analysis, membership function, optimization design
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1 Introduction

In China, sweet potato is the fourth largest food crop after rice, wheat, and maize. China is the world's largest sweet potato producer, with the total annual planted area and total production of sweet potatoes stable at about 5.3 million hm^2 and 85 million t, and the total production accounts for about 79% of the world[1-3]. Sweet potato seedling transplanting is the significant process of sweet potato cultivation, which still exists some problems such as transplanting mainly by people of low efficiency, high labor intensity, and high costs, as well as lack of suitable transplanting machines and low mechanization level[4,5]. Therefore, it becomes the research hotspot in the field of agricultural machinery in China to carry out research on sweet potato seedling transplanting mechanisms to promote the development of sweet potato seedling transplanting machines and the modernization of the sweet potato industry.

Developed countries in Europe, USA and Japan studied and applied sweet potato seedling transplanting machines earlier[6,7]. The sweet potato seedling transplanting machines produced by Marschnik in the USA and Ferrari in Italy[8], all use a chain-clamp transplanting mechanism. This type of transplanting mechanism uses chains drive with seedling clamps evenly distributed on the chain to achieve sweet potato seedling transplanting and a slideway to control the opening and closing of the clamps, which has high efficiency and is suitable for transplanting sweet potato seedlings in large plain areas. However, the slide is prone to wear and tear, and the machines are expensive. The linkage-type sweet potato seedling transplanting machine developed by Iseki corporation in Japan[9]

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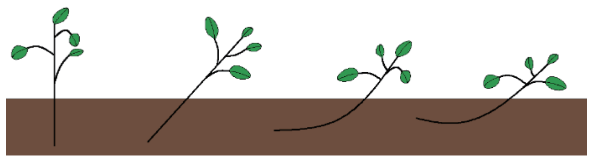
uses a crank-rocker mechanism to achieve sweet potato seedling transplanting, which has a simple structure and is suitable for small-field seedling transplanting operation, but the price of the machine is also high. Some sweet potato seedling transplanter prototypes have been developed in China recently. The sweet potato seedling transplanting machine designed by Liu et el.[10] controls the position and posture of the mechanical arm for transplanting operation through a single-chip microcomputer, which is also of higher price, making it difficult to promote the application. Zhu et al.[11] designed a sweet potato seedling transplanting mechanism consisting of four-bar linkage, gear train, cylinder, etc., but the whole structure is more complex and the movement of the four-bar linkage mechanism is not stable enough. Hebei Institute of Agricultural Mechanization developed a transplanter prototype for sweet potato seedling, which inserts seedlings horizontally into the soil by using a transplanting rod on a turntable, but the transplanting trajectory is difficult to control and the application feasibility of the mechanism should yet be verified[12].

In summary, the sweet potato seedling transplanting mechanisms at home and abroad have problems such as complex structure, high cost, or high vibration, and there is lack of sweet potato seedling transplanting machines more suitable for China. Therefore, this paper proposed a new sweet potato seedling transplanting mechanism of planetary gear train with deformed elliptical gear transmission of smooth transmission and compact structure, conducted kinematics modeling and parameter optimization, and trajectory simulation verification and mechanism prototype tests to provide a theoretical and experimental basis for the development of sweet potato seedling transplanter.

2 Design requirements for the transplanting mechanism

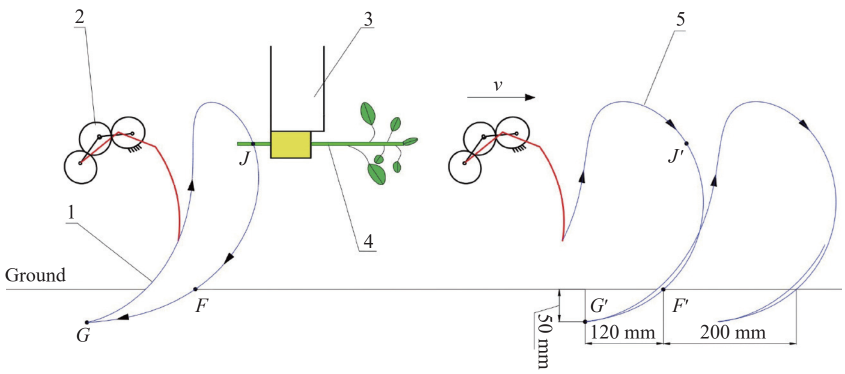
The main transplanting methods of sweet potato seedling include the straight, diagonal, horizontal, and boat-bottom insertion methods are shown in Figure 1[13]. The horizontal insertion method is suitable for transplanting sweet potato seedlings of 200-300 mm long, which not only has a large stem yield, but also produces potatoes of uniform size, and has more significant economic benefits[14], so it was chosen as the transplanting method for sweet potato seedling in this paper. The horizontal insertion method requires the roots under the soil of the transplanted sweet potato seedlings with the depth about 50 mm and horizontal length about 120 mm.



a. Straight insertion b. Diagonal insertion c. Horizontal insertion d. Boat-bottom insertion

Figure 1 Main methods of transplanting sweet potato seedling

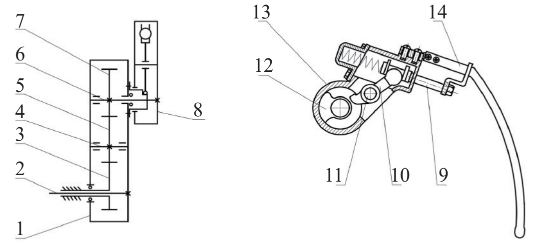
Because of the difficulty of mechanically separating sweet potato seedlings due to their soft, slender, and fragile stems[15], this study proposed a semi-automatic transplanting operation scheme in which the sweet potato seedling transplanting mechanism 2 is matched with an intermittent seedling delivery device 3 with the synchronous belt to transplant sweet potato seedling, shown in Figure 2. During the transplanting process of sweet potato seedling, the operator presses sweet potato seedlings into the flexible seedling clips on the synchronous belt of seedling delivery device, and an incomplete gear mechanism drives the synchronous belt transmission to transport sweet potato seedlings intermittently and orderly to the seedling pick-up position, then the transplanting mechanism removes the sweet potato seedling from the clip and plants it into the soil according to a specific trajectory.



1. Relative motion trajectory 2. Transplanting mechanism 3. Intermittent seedling delivery device with synchronous belt 4. Sweet potato seedling 5. Absolute motion trajectory

Figure 2 Transplanting operation scheme for horizontal insertion method of sweet potato seedling

The sweet potato seedling transplanting mechanism consists of a drive part (planetary gear train) and an executive part (transplanting arm). The key to its design is to make the end point of the transplanting arm to form a motion trajectory that meets the agronomic requirements of the horizontal insertion method of sweet potato seedling. Therefore, the relative motion trajectory 1 and absolute motion trajectory 5 of the transplanting mechanism are proposed in this paper, shown in Figure 3. The relative motion trajectory was divided into three parts: 1) The seedling pick-up and transporting section trajectory *JF*, where point *J* is the seedling pick-up point, at which the transplanting arm clamps the sweet potato seedling, and point *F* is the starting point of the transplanting arm to insert into the soil. 2) The seedling planting section trajectory *FG*, where point *G* is the seedling planting point, at which the transplanting arm's clamping jaw is quickly opened to complete the sweet potato seedling transplanting operation. In the corresponding absolute motion trajectory of this section, the horizontal distance between points *F*′ and *G*′ is about 120 mm, the vertical distance is about 50 mm and the transplanting plant distance is about 200 mm. 3) The return section trajectory *GJ*, the transplanting mechanism returns to the initial position and is ready to start the next transplanting operation.



a. Transplanting mechanism b. Transplanting arm

1. Gearbox housing (planetary carrier) 2. Drive shaft 3. Sun gear 4. Intermediate gear shaft 5. Intermediate gear 6. Planetary gear shaft 7. Planetary gear 8. Transplanting arm 9. Push rod 10. Fork 11. Fork shaft 12. Cam 13. Transplanting arm housing 14. Clamping jaw

Figure 3 Structure diagram of the transplanting mechanism

3 Kinematics analysis of the transplanting mechanism

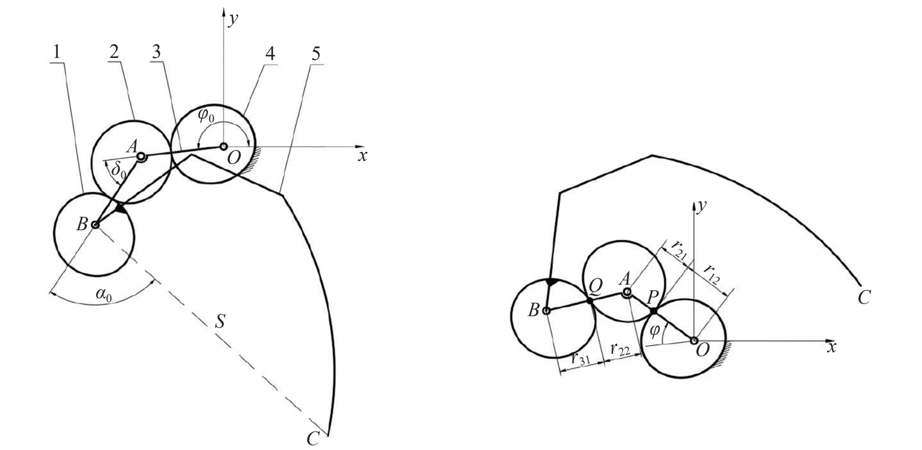
3.1 Working principle of the transplanting mechanism

According to the requirements for the motion trajectory of the sweet potato seedling transplanting mechanism, a new transplanting mechanism of planetary gear train based on deformed elliptical gear transmission was proposed, and its structure diagram is shown in Figure 3. The transplanting mechanism consists of a planetary gear train and a transplanting arm, among which planetary gear train consists of sun gear 3, intermediate gear 5, planetary gear 7, gearbox housing 1 (planetary carrier), etc. The three gears are all identical deformed elliptical gears. Sun gear 3 of the transplanting mechanism is fixed to frame through flange and hollow set on drive shaft 2 fixed to gearbox housing 1. Intermediate gear 5 is engaged with sun gear 3 and planetary gear 7, respectively. The transplanting arm consists of push rod 9, fork 10, fork shaft 11, cam 12, transplanting arm housing 13, clamping jaw 14, etc. Housing 13 and cam 12 of the transplanting arm are fixed to planetary gear shaft 6 and gearbox housing 1, respectively.

When the transplanting mechanism is in work, drive shaft 2 drives gearbox housing 1 to rotate clockwise at a uniform speed, and transplanting arm housing 13 rotate not only with the gearbox housing 1 at a clockwise uniform speed, but also with planetary gear shaft 6 at a counterclockwise variable speed. By optimizing the mechanism parameters, the end point of the transplanting arm forms a trajectory that satisfies the horizontal transplanting under the combined effect of these two movements. On the other hand, cam 12 of the transplanting arm drives fork 10 to swing around fork shaft 11 to achieve reciprocating motion of push rod 9, which controls the opening and closing of the clamping jaw to complete the seedling clamping and releasing actions.

3.2 Kinematics model of the transplanting mechanism

The motion diagram of the sweet potato seedling transplanting mechanism is shown in Figure 4. With the fixed center O of the sun gear and the planetary carrier as the coordinate origin, the rectangular coordinate system O-xy was established, and the counterclockwise angular displacement was specified as positive[16]. A, B, and C are the rotary centers of the intermediate gear and the planetary gear, and the end point of the transplanting arm, respectively. P and Q are the meshing points between the sun gear and intermediate gear, and the intermediate gear and planetary gear, respectively. In the Initial installation position of the mechanism, the long semi-axis of the sun gear coincides with the OA segment of the planetary carrier. φ_0, δ_0, and α_0 are the initial installation angle of the transplanting mechanism, inflection angle of the planetary carrier, and initial installation angle of the transplanting arm, respectively. S is the distance from the rotary center B of the planetary gear to the end point C of the transplanting arm, and φ is the angular displacement of the planetary carrier at a certain moment.



a. Initial installation position of the mechanism

b. Position of the mechanism when the angular displacement of the planetary carrier is φ

1. Planetary gear 2. Intermediate gear 3. Planetary carrier 4. Sun gear 5. Transplanting arm

Figure 4 Motion diagram of the transplanting mechanism

According to the pitch curve equation of deformed elliptical gear and its meshing theory[17-19], the distance from the meshing point P to rotary center O of the sun gear is obtained as:

$$r_{12}=\begin{cases}\dfrac{a(1-k^2)}{1-k\cos(m_{11}\varphi)}, & 0^\circ\le\varphi\le 180^\circ/m_{11}\\ \dfrac{a(1-k^2)}{1-k\cos\left[m_{12}(360^\circ-\varphi)\right]}, & 180^\circ/m_{11}\le\varphi\le 360^\circ\end{cases} \tag{1}$$

where, a is the long semi-axis of the deformed ellipse; k is the eccentricity of the deformed ellipse; m_{11} and m_{12} are the deformed coefficients of the deformed ellipse. To ensure the pitch curve is continuous and closed, the deformed coefficients should satisfy equation $m_{12}=m_{11}/(2m_{11}-1)$.

The distances from the meshing point P to the rotary center A of the intermediate gear, meshing point Q to the rotary center A of the intermediate gear, meshing point Q to the rotary center B of the planetary gear are

$$r_{21}=\begin{cases}\dfrac{a(1-k^2)}{1+k\cos(m_{11}\varphi_2)}, & 0^\circ\le\varphi_2\le180^\circ/m_{11}\\ \dfrac{a(1-k^2)}{1+k\cos\left[m_{12}(360^\circ-\varphi_2)\right]}, & 180^\circ/m_{11}\le\varphi_2\le360^\circ\end{cases}\tag{2}$$

$$r_{22}(\varphi_2)=r_{21}(\varphi_2-180^\circ-\delta_0)\tag{3}$$

$$r_{31}=2a-r_{22}\tag{4}$$

where, the angular displacement of the intermediate gear relative to the planetary carrier is

$$\varphi_2=\begin{cases}\dfrac{2\arctan\left(\dfrac{1+k}{1-k}\tan\dfrac{m_{11}\varphi}{2}\right)}{m_{11}}, & 0^\circ\le\varphi\le180^\circ/m_{11}\\ 2\pi-\dfrac{2\arctan\left[\dfrac{1+k}{1-k}\tan\dfrac{m_{12}(360^\circ-\varphi)}{2}\right]}{m_{12}}, & 180^\circ/m_{11}\le\varphi\le360^\circ\end{cases}\tag{5}$$

The angular displacement of the planetary gear relative to the planetary carrier is calculated by applying the method of numerical integration.

$$\varphi_3=-\int_0^{2\pi}\frac{r_{22}}{r_{31}}\mathrm{d}\varphi_2\tag{6}$$

The relative displacement equations for the rotary center A of the intermediate gear, rotary center B of the planetary gear, and end point C of the transplanting arm are

$$\begin{cases}x_A=2a\cos(\varphi+\varphi_0)\\ y_A=2a\sin(\varphi+\varphi_0)\end{cases}\tag{7}$$

$$\begin{cases}x_B=x_A+2a\cos(\varphi+\varphi_0+\delta_0)\\ y_B=y_A+2a\sin(\varphi+\varphi_0+\delta_0)\end{cases}\tag{8}$$

$$\begin{cases}x_C=x_B+S\cos(\varphi+\varphi_0+\varphi_3+\delta_0+\alpha_0)\\ y_C=y_B+S\sin(\varphi+\varphi_0+\varphi_3+\delta_0+\alpha_0)\end{cases}\tag{9}$$

As the transplanting mechanism rotates one cycle, the transplanter moves forward one plant distance H. Therefore, the absolute displacement equation for the end point C of the transplanting arm is

$$\begin{cases}x_{C'}=x_C-\varphi H/360^\circ\\ y_{C'}=y_C\end{cases}\tag{10}$$

4 Parameter-guided optimization design of the transplanting mechanism

In this study, the general idea of the parameter-guided optimization design of the sweet potato seedling transplanting mechanism is: According to the design requirements for the sweet potato seedling transplanting mechanism, the numerical objective functions of the transplanting mechanism were established from the aspects of motion interference, motion trajectory, transplanting arm posture and mulching film-broken requirement. Due to the fuzzy characteristics of the transplanting mechanism optimization problem, the membership function of fuzzy mathematical theory was applied to describe each objective function. Then, the optimization design model of the transplanting mechanism was established with the maximized sum of the membership degree of each objective function as the optimization objective, and a computer-aided analysis and optimization software of the transplanting mechanism was developed to obtain the better parameters of the mechanism which meet the requirements for the horizontal insertion transplanting of sweet potato seedling[20-23].

4.1 Optimization design model of the transplanting mechanism

4.1.1 Numerical objectives of the mechanism

1) Requirements for the motion trajectory

The motion trajectory of the sweet potato seedling transplanting mechanism should ensure the sweet potato seedlings have certain depth and horizontal length in the soil. As shown in Figure 5, F' is the starting point of the transplanting arm into the soil in the absolute motion trajectory with coordinate (xF', yF'), G' is the seedling planting point in the absolute motion trajectory with coordinate (xG', yG'). Therefore, the first and second objective functions are

$$M_1=|y_{F'}-y_{G'}|\tag{11}$$

$$M_2=|x_{F'}-x_{G'}|\tag{12}$$

According to the agronomic requirements for the horizontal insertion method of sweet potato seedling, the depth and horizontal length of the absolute motion trajectory in the soil are about 50 mm and 120 mm, so the ideal range for M_1 and M_2 are determined to be 47 mm≤M_1≤53 mm with an expected value of 50 mm, and 118 mm≤M_2≤122 mm with an expected value of 120 mm, respectively.

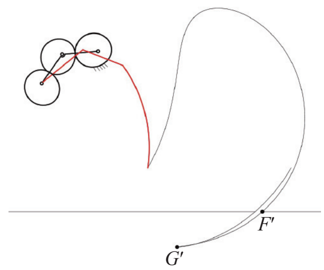


Figure 5 Diagram of the motion trajectory requirements for horizontal insertion transplanting

2) Requirement for non-interference between transplanting arm and seedling delivery device

During the transplanting operation of sweet potato seedlings, there should be no interference between the transplanting arm and seedling delivery device, which will affect the success ratio of seedling transplanting, so the minimum distance DE between the transplanting arm and seedling delivery device should be ensured, as shown in Figure 6. Therefore, the third objective function is

$$M_3=\sqrt{(x_D-x_E)^2+(y_D-y_E)^2}\tag{13}$$

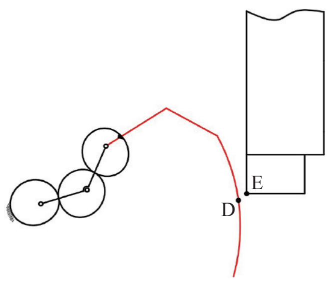


Figure 6 Diagram of non-interference between transplanting arm and seedling delivery device

To ensure there is no interference between the transplanting arm and the seedling delivery device, the ideal range for M_3 is determined to be 3 mm≤M_3≤6 mm with an expected value of 4.5 mm, on the comprehensive consideration of the manufacturing and installation errors, and the compactness of the mechanism.

3) Requirements for the angles of seedling pick-up and seedling planting

The unreasonable angles of seedling pick-up and seedling planting of the transplanting mechanism will injure sweet potato seedling and affect their subsequent growth, so they should meet certain requirements. As shown in Figure 7, α_1 and α_2 are the seedling pick-up angle and seedling planting angle. J is the seedling pick-up point of the transplanting mechanism with coordinate (x_J, y_J). F is the starting point of the transplanting arm into the soil with coordinate (x_F, y_F). J_{D1} and F_{D2} are the tangents of the seedling clamping jaw of the transplanting arm in the moments of seedling pick-up and planting, respectively. Therefore, the fourth and fifth objective functions are

$$M_4 = \arctan \frac{y_{D_1} - y_J}{x_J - x_{D_1}} \tag{14}$$

$$M_5 = \arctan \frac{y_{D_2} - y_F}{x_{D_2} - x_F} \tag{15}$$

Based on the previous research, the ideal ranges for the fourth objective function and the fifth objective function are determined to be 85°≤$M4$≤90° with an expected value of 87.5° and 30°≤$M5$≤35° with an expected value of 32.5°, respectively.

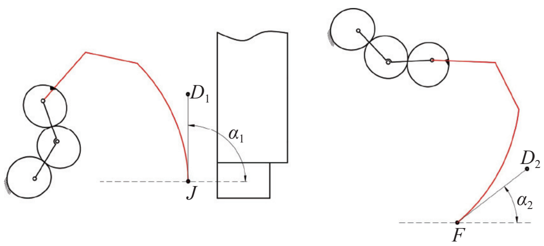


Figure 7 Diagram of seedling pick-up angle α_1 and planting angle α_2

4) Requirement for the size of mulching film hole

Sweet potato seedlings are generally transplanted in a mulching film with the advantages of moisture retention, pest prevention and promoting yield and efficiency. To ensure the effectiveness of sweet potato seedling transplanting with mulching film, it is necessary to control the size of the mulching film hole. As shown in Figure 8, points M and N are the leftmost and rightmost positions of the clamping jaw in contact with the mulching film during seedling transplanting, with coordinate (x_M, y_M) and (x_N, y_N), respectively. Therefore, the sixth objective function is

$$M_6 = |x_M - x_N| \tag{16}$$

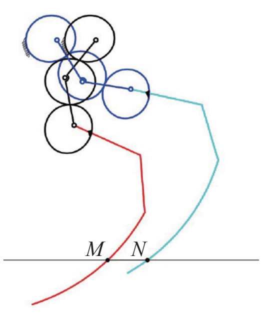


Figure 8 Diagram of the size of mulching film hole

According to the agronomic requirements for sweet potato seedling transplanting, the size of the mulching film hole should not exceed 50 mm, therefore, the ideal range for the sixth objective function is determined to be 30 mm≤$M6$≤50 mm with an expected value of 40 mm.

4.1.2 Optimization objectives and design variables for the transplanting mechanism

In this study, due to the fuzzy characteristics of the mechanism optimization problem, the fuzzy boundaries for the objectives of the membership functions are determined by the amplification coefficient method[24]. To improve the reliability of the fuzzy boundary, the upper and lower limits of the amplification coefficient are chosen as 1.05 and 0.95, respectively[25], and the objective functions M_1 to M_6 are all described by the following symmetric trapezoidal distribution membership function.

$$\mu_i = \begin{cases} 0, & \left(M_1 < \underline{m_i^l}\right) \\ \dfrac{M_i - \underline{m_i^l}}{E_i - \underline{m_i^l}}, & \left(\underline{m_i^l} \le M_1 \le M_i\right) \\ \dfrac{\overline{m_i^l} - M_i}{\overline{m_i^l} - E_i}, & \left(M_i < M_1 \le \overline{m_i^l}\right) \\ 0, & \left(M_1 > \overline{m_i^l}\right) \end{cases} \quad i = 1, 2, \dots 6 \tag{17}$$

where, μ_i, M_i, and E_i are the membership degree, objective function and expected value of the i-th objective, respectively. $\underline{m_i^l}$ and $\overline{m_i^l}$ are the lower and upper limits of the ith objective, respectively, determined using the amplification coefficient method.

In this study, the sum T of the membership degree of each objective is determined as the parameter optimization objective of the mechanism.

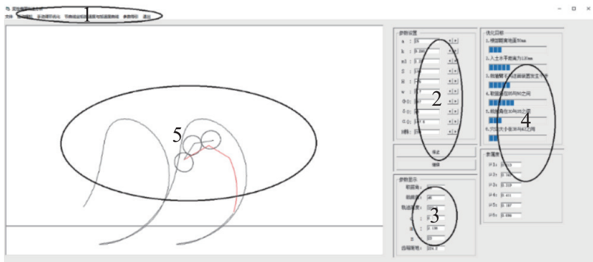
$$T = \sum_{i=1}^{n} \mu_i \, (0 \le \mu_i \le 1) \tag{18}$$

According to the kinematics analysis and numerical objectives of the transplanting mechanism, the seven main parameters affecting the transplanting trajectory and posture, such as the long semi-axis a of the deformed ellipse, eccentricity k of the deformed ellipse, deformed coefficient m_{11} of the deformed ellipse, inflection angle δ_0 of the planetary carrier, initial installation angle φ_0 of the mechanism, initial installation angle α_0 of the transplanting arm, and distance S from the rotary center B of the planetary gear to end point C of the transplanting arm, are identified as the optimization design variables.

4.2 Optimization results analysis of the transplanting mechanism

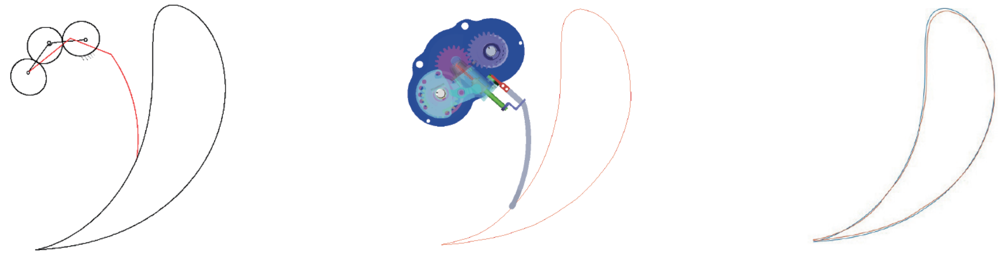
Based on the kinematics model and optimization design model of the transplanting mechanism, a Visual Basic program-based aided analysis and optimization software for the transplanting mechanism was developed[26,27], shown in Figure 9. While the initial parameters are input in region 2, the software could display the objective values in region 3 and the mechanism and trajectory in region 5 in real-time, and also calculate and display the membership degree of each objective and display them in real-time in the form of value and progress bars shown in region 4. When the actual values of the objectives are closer to the ideal values, the more blue cells in the progress bar will be. By adjusting the input values of the mechanism parameters automatically by the software, the sum of membership degrees can reach the greatest and the number of blue cells in progress bar the most, then the parameter-guided optimization of the sweet potato seedling transplanting mechanism is completed and the optimal parameters of the mechanism will be obtained.

A set of optimal parameters for the mechanism was obtained by applying the parameter-guided optimization method: a=25 mm, k=0.268, m_{11}=1.29, φ_0=185º, δ_0=50º, α_0=87º, S=190 mm. After the transplanting mechanism is optimized, the end point of the transplanting arm forms the theoretical relative and absolute motion trajectories shown in Figures 10a and 10d, which meets the requirements of the transplanting trajectory of the horizontal insertion method of sweet potato seedling. The depth and horizontal length in the soil of the sweet potato seedling are 49 mm and 119.6 mm, respectively. The seedling pick-up and planting angles are 85.6° and 32.0°, respectively. The minimum distance between the transplanting arm and seedling delivery device is 3.9 mm, and they also do not interfere with each other during the transplanting process. The size of the mulching film hole formed during transplanting is 40.4 mm, which also meets the requirements for transplanting sweet potato seedlings with mulching film.



1. Menu area 2. Parameter input area 3. Data output area 4. Display area of membership degree 5. Trajectories display area

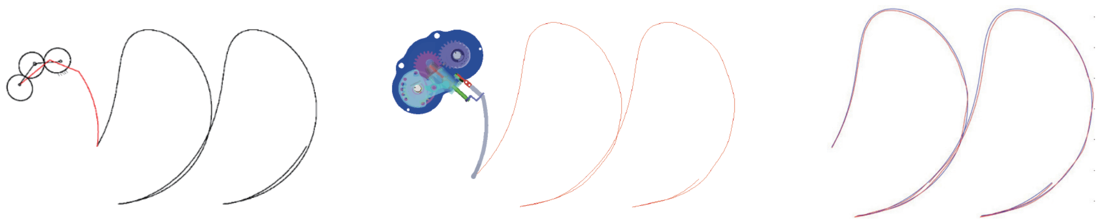
Figure 9 Interface of the parameter-guided optimization software for sweet potato seedling transplanting mechanism



a. Relative motion trajectory of theoretical analysis

b. Relative motion trajectory of virtual simulation

c. Comparison of relative motion trajectory



d. Absolute motion trajectory of theoretical analysis

e. Absolute motion trajectory of virtual simulation

f. Comparison of absolute motion trajectory

Figure 10 Comparison for the Trajectory of the end point of the transplanting arm

4.3 Virtual motion simulation of the transplanting mechanism

According to the optimized parameters of the sweet potato seedling transplanting mechanism of planetary gear train with deformed elliptical gear transmission, the structural design of the mechanism was completed, and its three-dimensional model was established by applying SolidWorks and imported into ADAMS software to build a virtual prototype, then ADAMS software was used to conduct the virtual motion simulation for the mechanism. The motor rotary speed was set to 30 r/min, simulation time to 2 s, and step length to 360 steps. The relative and absolute motion trajectories of virtual simulation for the end point of transplanting arm of the mechanism are shown in Figures 10b and 10e.

AS shown in Figure 10, comparing the theoretical analysis trajectories with the virtual simulation trajectories of the mechanism, it can be seen that both trajectories have the same shape. In addition, from the virtual simulation of the mechanism, the following results can be obtained: the depth and the horizontal length in the soil of the moving trajectory are 51.5 mm and 122.7 mm, respectively, the minimum distance between the transplanting arm and the seedling delivery device is 3.5 mm, and the size of the mulching film hole formed by the transplanting arm during the transplanting process is 41.0 mm, which are basically consistent with those of theoretical analysis. The study show that the theoretical model and optimization design of the transplanting mechanism is correct.

5 Prototype tests of the transplanting mechanism

The prototype of transplanting mechanism for sweet potato seedling was developed and assembled on a test bench designed for the sweet potato seedling transplanting, shown in Figure 11. The kinematics test of the mechanism prototype and sweet potato seedling transplanting tests were conducted to study kinematic characteristics and check the transplanting performance and application feasibility of the transplanting mechanism.

Figure 11 Test bench for sweet potato seedling

5.1 Kinematics test of the transplanting mechanism

The kinematic characteristics of the transplanting mechanism were tested by using a high-speed camera to record the video of the idling of the transplanting mechanism for being imported into Photoshop software, which was used to draw the relative motion trajectory of the end point of the transplanting arm, shown in Figure 12. The relative motion trajectory of the prototype test is basically consistent with those of theoretical analysis (Figure 10a) and virtual simulation (Figure 10b), indicating that the transplanting mechanism can meet the agronomic requirements of the horizontal insertion method of sweet potato seedling, and its theoretical model and design results are correct.

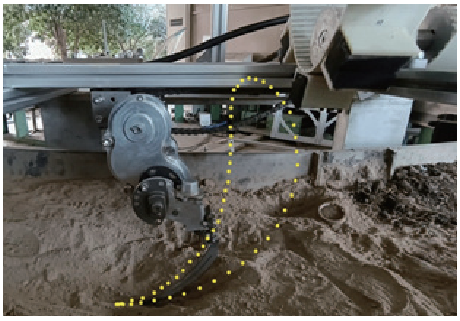


Figure 12 Test trajectory of the transplanting mechanism transplanting mechanism

As the angle meter will interfere with the seedling delivery device and soil when it is used to directly measure the seedling pick-up and planting angles of the transplanting mechanism, this study used an indirect method to determine the angles. Firstly, the angles between the straight-line section of the clamping jaw and the horizontal surface at the seedling pick-up and planting moments were measured with an angle meter as 7.4° and 62.6°, as shown in Figures 13a and 13b, respectively. Then, according to the intersection angle between the straight-line section of the clamping jaw and tangent-line of the clamping jaw arc is 95.3°, the seedling pick-up and planting angles were calculated as 87.9° and 32.7°, respectively. In addition, the minimum distance between the transplanting arm and the seedling delivery device was measured as 3.7 mm with a vernier scale, as shown in Figure 14. The measurement results indicate that the mechanism prototype meets the design objectives of seedling pick-up angle, seedling planting angle, and non-interference.

5.2 Transplanting performance tests of sweet potato seedling

Seedling transplanting performance tests for the mechanism were conducted with sweet potato seedlings of an average length of 285 mm and average stem diameter of 4 mm, as shown in Figure 15a. Two groups of seedling transplanting tests of 50 plants were carried out at the mechanism speed of 20 r/min and 30 r/min, respectively. During the transplanting operation, a video camera was used to record the transplanting operation of the mechanism and count the seedlings successfully pick-up and planting, respectively. Then the success ratios of seedling pick-up, planting and transplanting were calculated out, respectively.

The operations of seedling pick-up and planting of the transplanting mechanism are shown in Figures 15b and 15c, respectively, and the test results of sweet potato seedling transplanting are listed in Table 1.

Table 1 lists the success ratios of sweet potato transplanting are 90% and 82% respectively when the rotary speeds of the transplanting mechanism are 20 r/min and 30 r/min, indicating that the transplanting mechanism has the application feasibility to practical machines. As the rotary speed of the mechanism increases, the success ratios of seedling pick-up and transplanting will decrease significantly, except for the success ratio of seedling planting which keeps basically constant. The main reasons for the failure of sweet potato seedling transplanting are analyzed as the following.

The actual seedling pick-up positions of some sweet potato seedlings are shifted due to the twisted stems of seedlings, resulting in the failure of the transplanting arm to accurately clamp the roots of sweet potato seedlings.

Due to a small amount of sweet potato seedlings have too slender stem with small diameter, it is difficult for the seedlings to be clamped by the clamping jaw of the transplanting arm. These sweet potato seedlings detached from the claw under centrifugal force or soil resistance, resulting in the failure of seedling planting.

a. Seedling pick-up angle

b. Seedling planting angle

Figure 13 Indirect measurement of seedling pick-up and planting angles

Figure 14 Measurement of the minimum distance between the transplanting arm and seedling delivery device

a. Sweet potato seedlings b. Seedling pick-up operation c. Seedling planting operation

Figure 15 Transplanting tests for sweet potato seedling

Table 1 Test results of sweet potato seedling transplanting

Rotary speed/r·min⁻¹	Total No. of test seedlings	No. of seedlings successfully pick-up	No. of seedlings successfully planting	Success ratio of seedling pick-up/%	Success ratio of seedling planting/%	Success ratio of seedling transplanting/%
20	50	46	45	92	98	90
30	50	43	41	86	95	82

6 Conclusions

In this study, according to the agronomic requirements for the horizontal insertion method of sweet potato seedling, a new transplanting mechanism of planetary gear train based on deformed elliptical gear transmission for sweet potato seedling was designed. The motion simulation of the transplanting mechanism, kinematics test and transplanting performance tests for the mechanism prototype were conducted. The main conclusions are drawn as followings:

A sweet potato seedling transplanting mechanism of planetary gear train with deformed elliptical gears was proposed and its kinematics model was established. A set of parameters satisfying the requirements for sweet potato seedling transplanting were obtained by applying the parameter-guided optimization method: a=25 mm, k=0.268, m_{11}=1.29, φ_0=185°, δ_0=50°, α_0=87°, S=190 mm. The theoretical model and design of the transplanting mechanism are verified correct and reliable through the virtual simulation of the sweet potato transplanting mechanism.

The simulation and test results of the kinematic characteristics of the mechanism prototype show that the motion trajectory, seedling pick-up angle, and seedling planting angle can meet the requirements for sweet potato seedling transplanting. The seedling transplanting tests show that the success ratios of seedling pick-up and planting are 90% and 82% respectively while the rotary speeds of the mechanism prototype are 20 r/min and 30 r/min, indicating the transplanting mechanism designed has better performance of sweet potato seedling transplanting and application feasibility in the practical machines.

For the sweet potato seedling transplanting mechanism developed in this study, the transplanting success ratio is not high for the sweet potato seedling with thin and curved stems. In later stage, the opening size and the holding force of the clamping jaw will be optimized, and the dynamic analysis and optimization of the mechanism will be carried out to reduce the vibration of the frame, ensure the working accuracy and improve the transplanting success ratio.

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