Design and experiment of the side insertion horizontal transplanting device for sweet potato (*Ipomoea batatas* Lam.) seedlings on mulch film

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Abstract: Side insertion horizontal transplanting sweet potato seedlings on mulch film is one kind of new planter pattern, which keeps the soil warm and moist restraining the infestation of pests and weeds, realizing dense transplanting and ensuring uniformity of sweet potato sizes. Therefore, a side insertion horizontal transplanting device for sweet potato seedlings on mulch film was designed, including the details and parameters of the reciprocating mechanism and the seedling clamping mechanism. Both the two mechanisms and the whole device were simulated and the test bench was built for field experiments to detect if this device can meet the agronomic requirements. The simulation results show that the designed device is in accordance with the agronomic requirements of horizontal transplanting, transplanting depth and transplanting length, and is potential for achieving rational close planting. The lateral length of the designed transplanting device is extended at about 90 mm compared with previous machine, which will promote the number of soil nodules of sweet potato seedlings and the growth of production enormously. The horizontal velocity of the transplanting claw is −17 mm/s when picking the seedling, the horizontal velocity of the transplanting claw 645 mm/s and the vertical velocity 83 mm/s when releasing the seedling. These data could ensure the accuracy requirements of horizontal transplanting trajectory. The field experiment results show the expulsion rate of sweet potato seedlings at 1.38%, the qualified rate of transplanting length and depth at 94.17% and 95.11% respectively, the average length and width of the mulch film breaking hole at 44.67 mm and 43.00 mm in several. The postures of the actual transplanted seedlings are consistent with the simulation results, meeting the requirements of horizontal transplanting with less damage to the mulch film. The designed transplanting device lays a foundation for the development of sweet potato seedlings side transplanting machine.

Keywords: sweet potato seedlings, Transplanting device, mechanism design, motion simulation, field experiments
DOI: 10.25165/j.ijabe.20231606.8360

Citation: Zhang W Z, Zhu Q, Ge D M, Zheng D H, Zhang T T. Design and experiment of the side insertion horizontal transplanting device for sweet potato (*Ipomoea batatas* Lam.) seedlings on mulch film. Int J Agric & Biol Eng, 2023; 16(6): 148–157.

1 Introduction

Sweet potato is an important food crop in China with high nutritional, medicinal and economic values[1-6], which can be used in food processing, chemical industry, medical treatment and so on. According to the planting mode of sweet potato, sweet potato grow seedlings should firstly be carried out with seed potatoes according to the requirements of agronomy, and then transplanted into the soil. Hence, sweet potato transplanting is one of the most important links during the whole process of sweet potato production[7]. Compared with transplanting without mulch film, transplanting with mulch film not only keeps the soil warm and moist restraining the infestation of pests and weeds, but also promotes the growth of sweet potato seedlings, which further increases the fruiting number of tubers and boosts the yield[8-12]. However, due to the numerous restrictive conditions of mechanical transplanting on mulch film, higher requirements are put forward for the transplanting device working on the coated ridges. The suitable transplanting machines considering mulch film mainly include duckbill transplanting machines and clip transplanting machines. For example, Markumningsih et al.[13] proposed a 4-bar link type vegetable semi-automatic transplanting device, which can move in a certain trajectory making the entry point and the exit point roughly at the same position, which can minimize the damage to mulch film. Nevertheless, the sweet potato seedling can only be transplanted vertically by this device. The clip-type transplanting machine produced by Iseki & Co. clamps the sweet potato seedling from the seedling belt with a connecting rod seedling claw, and transplants sweet potato seedling obliquely[14,15]. At present, the sweet potato transplanting machines are mostly transformed from general agricultural transplanting machinery, and their transplanting methods are mainly vertical or oblique transplanting. Besides, these machines either cannot be used on mulch film or lead to huge damage to mulch film. Compared with vertical and oblique planting, horizontal planting could harvest higher commodity rate (uniformity of sweet potato sizes) and more tubers per plant[16]. Most of the existing horizontal transplanting machines transplant after soil breaking leading to destroys to the shape of ridge. Yan et al.[17]

Received date: 2023-05-30 **Accepted date:** 2024-01-10

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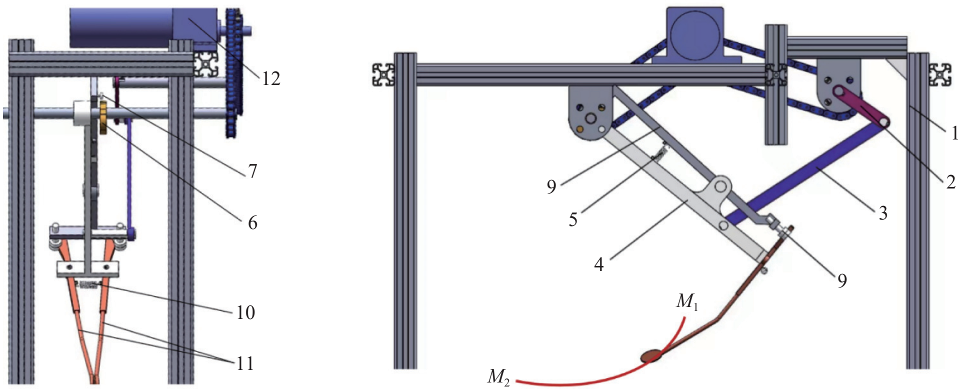
designed a horizontal transplanter for sweet potato seedlings. Due to the inertia force, sweet potato seedlings fall freely from the groove of the seedling conveyor belt to the open seedling ditch. And then the sweet potato seedlings are transplanted horizontally along the ridge under the actions of soil covering device and pressure wheel. However, this machine transplants without covering mulch film and cannot achieve dense planting for the transplanting direction is along the ridge[18]. Dense planting improves the yield of sweet potato and other crops[19-21]. Hence, it's very important to achieve dense planting. The dense transplanting of sweet potato seedlings can be further accomplished by adjusting the transplanting direction of sweet potato seedlings, that is, side transplanting (transplanting perpendicular to the direction of ridge).

The side insertion horizontal transplanting sweet potato seedlings on mulch film could not only keep the soil warm and moist restraining the infestation of pests and weeds, but also achieve dense planting of sweet potato seedlings which boosts the yield and ensures the uniformity of sweet potato sizes. These best meets the agronomic needs of sweet potato transplanting. However, there is currently no relevant machine available. Therefore, a horizontal transplanting device, consisting of a reciprocating mechanism and a seedling clamping mechanism, was designed for sweet potato seedlings transplanting with side insertion on mulch film. Based on the design of the overall structure and the analysis of working principle, the parameters of the reciprocating mechanism, the external contour of the transplanting claw and the cam were determined. And then, the reciprocating mechanism, seedling clamping mechanism and the whole transplanting device were simulated by SolidWorks and Recudyn-EDEM software. Meanwhile, the test bench was built for field experiments. The research of this device solved the problem of the shortage of sweet potato transplanting machine on mulch film, and provided a reference for the development of horizontal transplanting device.

2 Overall structure and working principle

2.1 Overall structure

The side insertion horizontal transplanting device for sweet potato seedlings on mulch film mainly includes reciprocating mechanism and seedling clamping mechanism as shown in Figure 1. Of which, the reciprocating mechanism is mainly composed of frame, crank, connecting rod and follower rod. The seedling clamping mechanism is mainly composed of cam swing rod, bearing, cam, transplanting claw, spring I and spring Ⅱ. The cam swing rod in the seedling clamping mechanism is rotatably connected to the follower rod, the bearing is installed on the lower end of the cam rocker, the cam is coaxial with the upper end of the follower rod, and fixed to the rotating shaft by a flat key. The transplanting claw is rotatably connected to the lower end of the driven rod. Two springs are respectively installed between the cam fork and the follower rod and between the two transplanting claws.



1. Frame 2. Crank 3. Connecting rod 4. Follower rod 5. Spring I 6. Cam 7. Bearing I 8. Cam swing rod 9. Bearing Ⅱ 10. Spring Ⅱ 11. Transplanting claw 12. Driving motor

Figure 1 Side insertion horizontal transplanting device for sweet potato seedlings on mulch film

2.2 Working principle

The crank rotates clockwise under the drive of the DC motor, driving the connecting rod and the follower rod to move, making transplanting claws move back and forth between the seedling picking point and the seedling releasing point as shown in the Figure 1, the curve M_1M_2. The cam rotates clockwise under the drive of the same motor. And with the effect of spring Ⅰ, the bearing on one side of the cam swing rod is always in direct contact with the cam surface, making cam swing rod rotate following the cam around the fixing pin. With the effect of spring Ⅱ, the bearing on the other side of the cam swing rod is pressed tightly onto the outside of the upper end of the transplanting claw, and moves along the outside of the transplanting claw as the cam swing rod rotates. With the shape design of the cam and the outer contour of the transplanting claw, the effect of spring Ⅱ and the principle of leverage, the clamping and loosening actions of the transplanting claw are realized. The spring Ⅱ always acts on the transplanting claws making the transplanting claws tighten. The bearing of the cam swing rod acts on the upper end of the transplanting claw in periods, making the transplanting claw open with the effect of the leverage.

3 Design and simulation of device structure

3.1 Design of reciprocating mechanism

3.1.1 Determination of the parameters of the mechanism

The reciprocating mechanism is a key component that determines the transplanting trajectory of sweet potato seedlings. As shown in Figure 2, a reciprocating mechanism that can realize the horizontal transplanting trajectory is designed. According to the movement characteristics of the crank rocker, this paper designs the transplanting claw to be fixedly connected to the driven rod to realize the horizontal transplanting of sweet potato seedlings. In which, the reciprocating mechanism is simplified as a hinged four-bar linkage by analyzing the transplanting trajectory. Among them, *AB* is the frame, *AD* the crank, *CD* the connecting rod, *BC* the follower rod, *FE* the transplanting claw. The follower rod *BC* and the connecting rod CD are hinged at point C, and $ABCDA$ constitutes a closed graph.

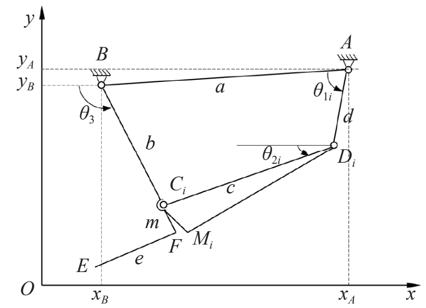


Figure 2 Simplified diagram of reciprocating mechanism

In Figure 2, the trajectory of point E_i is the repetitive transplanting trajectory of sweet potato seedling, and the point M_i is a certain point on the connecting rod. According to the predetermined position of the connecting rod, the four-bar linkage is analyzed and calculated. The relationship between the coordinates of E_i point and M_i point is as follows:

$$\begin{cases} (x_{Mi}-x_B)^2+(y_{Mi}-y_B)^2=\left(\sqrt{(x_{Ei}-x_B)^2+(y_{Ei}-y_B)^2-e^2}-m\right)^2 \\ (x_{Ei}-x_{Mi})^2+(y_{Mi}-y_{Ei})^2=m^2+e^2 \end{cases} \tag{1}$$

where, e is the vertical length from the end of the transplanting claw to BC, here e = 270 mm; m is the distance from C_i to F, here m = 48 mm.

In order to determine the length of each rod system, the simplified structure in Figure 2 can be further divided into two rod groups on left and right, as shown in Figure 3.

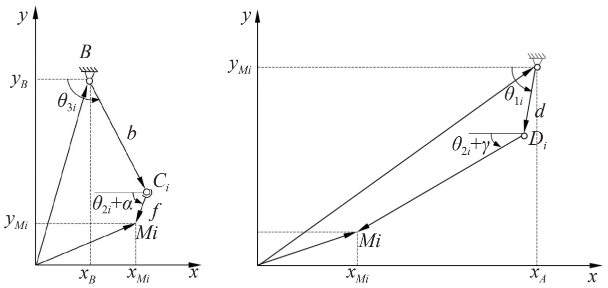


Figure 3 Left and right rod group

The vector closed equations of the left and right double rod groups are respectively established as,

$$\begin{cases} \overrightarrow{OA}+\overrightarrow{AD_L}+\overrightarrow{D_LM_L}-\overrightarrow{OM_L}=0 \\ \overrightarrow{OB}+\overrightarrow{BC_l}+\overrightarrow{C_lM_l}-\overrightarrow{OM_l}=0 \end{cases} \tag{2}$$

Its relationships of projections on x and y axes are

$$\begin{cases} x_A+d\cos\theta_{1i}+g\cos(\theta_{2i}+\gamma)-x_M=0 \\ y_A+d\sin\theta_{1i}+g\sin(\theta_{2i}+\gamma)-y_{Mi}=0 \end{cases} \tag{3}$$

$$\begin{cases} x_B-b\cos\theta_{3i}+f\cos(\theta_{2i}+\alpha)-x_{Mi}=0 \\ y_B+b\sin\theta_{3i}+f\sin(\theta_{2i}+\alpha)-y_{Mi}=0 \end{cases} \tag{4}$$

where, b is the length of the follower rod BC, mm; d is the length of crank AD, mm; f is the length from point M_i to connecting rod C_i, mm; g is the length from point M_i to connecting rod D_i, mm; α is the angle between the extension line of D_iC_i and C_iM_i, (°); β is the angle between the extension line of D_iC_i and D_iM_i, (°); θ_i is the angle at which the crank rotates when point E_i moves to point M_i, (°); θ_{2i} is the angle at which the connecting rod rotates when point E_i moves to point M_i (°); θ_{3i} is the angle at which the follower rod rotates when point E_i moves to point M_i (°).

After integrated calculation, it can be obtained

$$\begin{aligned} &(x_{Mi}-x_A)^2+(y_{Mi}-y_A)^2+g^2-d^2- \\ &\quad 2[(x_{Mi}-x_A)g\cos\gamma+(y_{Mi}-y_A)g\sin\gamma]\cos\theta_{2i}+ \\ &\quad 2[(x_{Mi}-x_A)g\sin\gamma-(y_{Mi}-y_A)g\cos\gamma]_{2i}=0 \end{aligned} \tag{5}$$

$$\begin{aligned} &(y_{Mi}-y_B)^2+(x_{Mi}-x_B)^2+f^2-b^2- \\ &\quad 2[(x_{Mi}-x_B)f\cos\alpha+(y_{Mi}-y_B)f\sin\alpha]\cos\theta_{2i}+ \\ &\quad 2[(x_{Mi}-x_B)f\sin\alpha-(y_{Mi}-y_B)f\cos\alpha]\sin\theta_{2i}=0 \end{aligned} \tag{6}$$

Equations (5) and (6) are both nonlinear equations, which contain five undetermined parameters respectively: (x_A, y_A, g, d, γ) and (x_B, y_B, f, b, α). Therefore, x_A, y_A and x_B, y_B are pre-selected to convert Equations (5) and (6) into linear equations.

$$X_0+A_1X_1+A_{2i}X_2+A_{3i}=0 \tag{7}$$

$$Y_0+B_{1i}Y_1+B_{2i}Y_2+B_{3i}=0 \tag{8}$$

Where,

$X_0=g^2-d^2, X_1=g\cos\gamma, X_2=g\sin\gamma_0=f^2-b^2, Y_1=f\cos\alpha,$

$Y_2=f\sin\alpha, A_{1i}=2[(x_A-x_{Mi})\cos\theta_{2i}+(y_A-y_{Mi})\sin\theta_{2i}2i],$

$A_{2i}=2[(y_A-y_{Mi})\cos\theta_{2i}-(x_A-x_{Mi})\sin\theta_{2i}],$

$A_{3i}=(x_{Mi}-x_A)^2+(y_{Mi}-y_A)^2,$

$B_{1i}=2[(x_B-x_{Mi})\cos\theta_{2i}+(y_B-y_{Mi})\sin\theta_{2i}],$

$B_{2i}=2[(y_B-y_{Mi})\cos\theta_{2i}-(x_B-x_{Mi})\sin\theta_{2i},\ B_{3i}=(x_{Mi}-x_B)^2+(y_{Mi}-y_3)^2$

According to Equations (7) and (8), it can be obtained

$$\begin{cases} g=\sqrt{X_1^2+X_2^2} \\ d=\sqrt{g^2-X_0} \\ \tan\gamma=X_2/X_1 \end{cases} \tag{9}$$

$$\begin{cases} f=\sqrt{Y_1^2+Y_2^2} \\ b=\sqrt{f^2-Y_0} \\ \tan\alpha=Y_2/Y_1 \end{cases} \tag{10}$$

According to the relative position relationships of points C_i, D_i and M_i in Figure 3, the coordinates of point C and point D can be written as

$$\begin{cases} x_{ci}=x_{Mi}-f\cos(\theta_{2i}+\alpha) \\ y_{ci}=y_{Mi}+f\sin(\theta_{2i}+\alpha) \end{cases} \tag{11}$$

$$\begin{cases} x_{Di}=x_{Mi}+g\cos(\gamma+\theta_{2i}) \\ y_{Di}=y_{Mi}+g\sin(\gamma+\theta_{2i}) \end{cases} \tag{12}$$

According to the relative position relationships of points A, B, C_i and D_i in Figure 2, the length of each rod can be yielded as

$$\begin{cases} a=\sqrt{(x_A-x_B)^2+(y_A-y_B)^2} \\ b=\sqrt{(x_B-x_{Ci})^2+(y_B-y_{Ci})^2} \\ c=\sqrt{(x_{ci}-x_{Di})^2+(y_{ci}-y_{Di})^2} \\ d=\sqrt{(x_{Di}-x_A)^2+(y_{Di}-y_A)^2} \end{cases} \tag{13}$$

where, a is the length of frame AB, mm; c is the length of connecting rod CD, mm.

Therefore, combine Equations (1) and (7)-(13), apart from points A and B, three arbitrary positions of E_i should be pre-selected to get values of a, b, c, and d during the working process. In order to ensure that the transplanting of sweet potato seedlings meets the agronomic requirements, the vertical depth of the transplanting claw into the ridge is set to 40-60 mm, and the transverse length 180-220 mm when the four-bar linkage reciprocates[22]. Within this range, it is satisfied that the seedlings can be picked and released at a certain position, and the movement trajectory of the transplanting claws agrees to horizontal transplanting. Thus, set the coordinates of points A, B, E_1, E_2 and E_3 as (528, 543), (63, 493), (288, 97), (223, 66) and (25, 31), respectively. Among them, point E_1 is the seedlings picking point, point E_2 an arbitrary position during seedlings transplanting, and point E_3 seedlings releasing point. According to the calculation, the frame length a is 460 mm, the crank length d is 140 mm, the connecting rod length c is 350 mm, and the follower rod length b is 300 mm.

3.1.2 Motion simulation of mechanisms

In order to confirm whether the reciprocating mechanism meets the requirements of the horizontal transplanting trajectory, and whether the transplanting depth and transplanting length meet the agronomic requirements of sweet potato transplanting, the calculated data are modeled and assembled by SolidWorks software. The reciprocating mechanism is simulated by means of the motion module, and the motion trajectory is exported and shown in Figure 4. It can be seen that the transplanting trajectory meets the requirements of horizontal transplanting, and the maximum horizontal distance is 295 mm and the maximum vertical distance is 60 mm. The distances meet the requirements of the transplanting depth and transplanting length of sweet potato seedlings. The transplanting device designed in this paper selects a transplanting depth of 50 mm, which is in accordance with the existing sweet potato transplanting machinery[7,23,24].

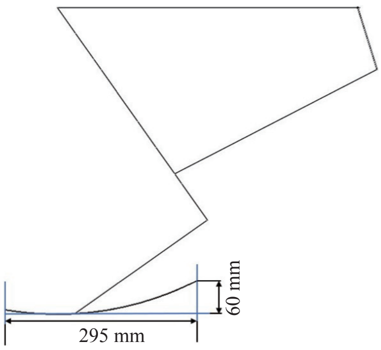
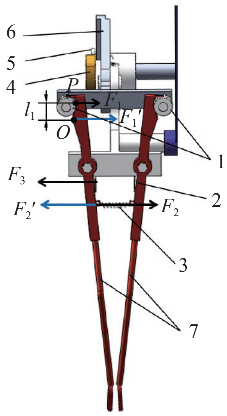


Figure 4 Transplanting trajectory of reciprocating mechanism

3.2 Design of seedling clamping mechanism

3.2.1 Determination of external contour parameters of transplanting claw

The structure of seedling clamping mechanism is shown in Figure 5. This mechanism needs to pick out the sweet potato seedlings from the specified position, release the seedlings when the reciprocating mechanism moves to the designated point, and then return to the seedlings picking point to pick the seedlings again. Among them, the transplanting claw needs to meet the following two requirements. One is to hold the sweet potato seedlings without damaging the roots of the seedlings, the other is to minimize the damage to mulch film without bringing out the seedlings when returning from the seedlings releasing point. According to previous statistics, the diameter of the end of sweet potato seedlings is 4-5 mm, and the diameter of sweet potato seedlings leaves is 45-65 mm. In order to meet the above conditions, the distance between the ends of the two transplanting claws is 40 mm, and the distance between the two transplanting claws is 60 at the hinge connection with the follower rod. In order to avoid collisions between machines, the relative positions of the parts are comprehensively considered as shown in Figure 5. The vertical distance l_1 from point O to point P of the guide platform protrusion is set to 13.5 mm. Thus, point P corresponds to the seedlings picking point, and when the bearing Ⅱ moves here, F_1 decreases and transplanting claws close. Point O corresponds to the seedlings releasing point, and when the bearing Ⅱ moves here, F_1' increases and the transplanting claws open.



1. Bearing Ⅱ 2. Positioning plate 3. Spring Ⅱ 4. Cam 5. Bearing I 6. Cam swing rod 7. transplanting claw

Figure 5 Seedling clamping mechanism

3.2.2 Determination of cam parameters

The cam is a key part to determines the transplanting point of sweet potato seedlings, and its shape needs to be combined with the preset positions for picking and releasing seedlings. In order to simplify the seedling clamping mechanism, the cam and the rotor on the cam swing bar are designed as center-to-center structure, as shown in Figure 6. That is, the total length of the cam swing rod equals to the length of the reciprocating four-bar linkage BF, and the distance from the H point of the cam swing rod to the radius of the cam base circle equals to the distance between the cam swing rod and the driven rod when it is parallel to the follower rod. When only considering the rotation of the cam swing rod, that is the bearing at the lower end of the cam swing rod moves from point P to point O, the maximum distance that the cam swing rod HN rises can be obtained, which is the actuating travel during the camming.

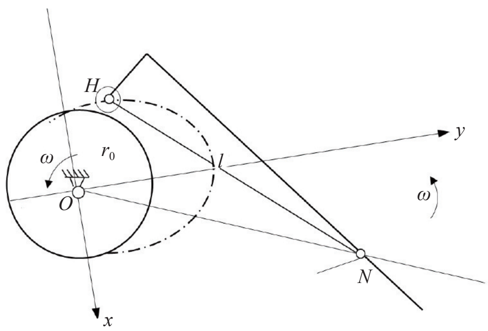


Figure 6 Oscillating follower cam mechanism

The whole mechanism adopts one power source, and the rotational velocity ratio of the crank and the cam is set to be 1:1. On the basis of the above, the basic parameters of cam structure are designed. Through the analysis of the movement velocity of the four-bar, the relationship between the angle and the velocity of the M_i point as AD rotates from parallel to the frame is obtained as shown in Figure 7. In order to ensure the smooth progress of transplanting, the velocity of transplanting seedlings should be set slow enough to achieve stable seedlings picking and reduce the rate of seedlings leakage. Combined with the seedling picking point, the AD rotation angle of 104° to 166° is selected as the motion angle for actuating travel.

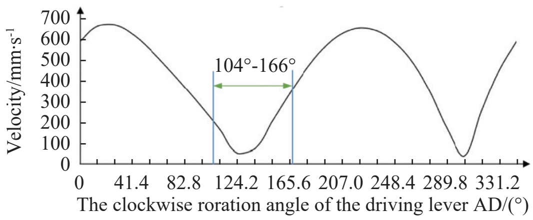


Figure 7 Curve diagram of velocity relationship

According to the known conditions, the instantaneous center position of the reciprocating mechanism, and the state diagram when the crank and connecting rod are collinear are shown in Figure 8. Among them, 1, 2, 3, 4 are the frame, crank, connecting rod and driven rod, respectively. P_{12}, P_{23}, P_{34}, P_{14}, P_{24} are the instantaneous center positions. P_{24} is on the connecting line of P_{12} P_{24} and P_{23} P_{34}. D_1 and D_2 are the extreme positions when the crank and connecting rod are collinear respectively[25,26].

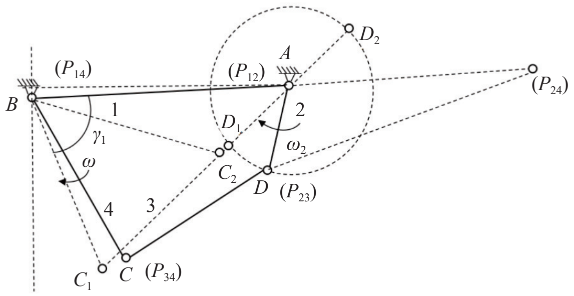


Figure 8 Instantaneous center positions of reciprocating mechanism

By analyzing the relative position of the crank and the follower rod, the transmission ratio of the mechanism is yielded as

$$i = \omega_2/\omega_4 = P_{14}P_{24}/P_{12}P_{24} \tag{14}$$

where, ω_2 is instantaneous angular velocity of crank, rad/min; ω_4 is instantaneous angular velocity of the connecting rod, rad/min.

From the seedlings entering field ridge point E_2 to the seedlings releasing point E_3, the rotation angle of the follower $\Delta\sigma_1$ is

$$\Delta\sigma_1 = \arctan|x_{E1} - x_B/y_{E1} - y_B| - \arctan|x_{E3} - x_B/y_{E3} - y_B| \tag{15}$$

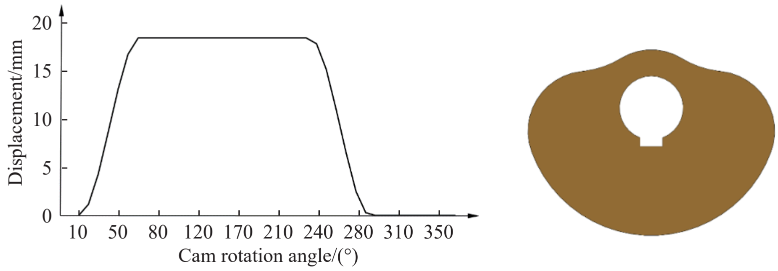
It can be concluded that the rotation angle of the cam at the corresponding position is

$$\Delta\delta = \Delta\sigma_1/\omega_2 \tag{16}$$

From this, it can be calculated that the nearest dwell angle of the cam is 75°. According to the specific operation requirements of the transplanting claws that can realize side insertion horizontal transplanting of sweet potato seedlings and the relevant oscillating follower cam design criteria[27], the main design parameters of the cam are obtained, as listed in Table 1. In order to ensure the stability of the push rod movement and the accuracy of the work, the cosine acceleration motion regularity is selected as the push rod motion regularity. The relevant parameters are input into the cam design module of the Mindy tool set, and the cam contour curve is calculated and exported. According to the exported data, the cam virtual entity is established by SolidWorks, as shown in Figure 9.

Table 1 Design parameters of the cam

Design parameters of cam	Specific values
The base circle radius of cam r_0	15.5 mm
Roller radius of clamping arm r_r	2 mm
Motion angle for actuating travel δ_0	62°
Farthest dwell angle δ_{01}	161°
Motion angle for return travel δ_0'	62°
Nearest dwell angle δ_{02}	75°
Length of swing rod l	265 mm
Push	18.5 mm
The number of seedlings inserted per rotation of the cam	1 time



a. Contour curve of cam b. Cam entity

Figure 9 Determination of cam shape

3.2.3 Motion simulation of seedling clamping mechanism

To verify the feasibility of the seedling clamping mechanism, the virtual model of seedling clamping mechanism is established by SolidWorks software matching with the virtual reciprocating mechanism. The simulation of the whole transplanting device is carried out by using the motion module, and the relative displacement of the two transplanting claws is obtained as shown in Figure 10. It can be seen that the closed distance of the transplanting claws is less than 5 mm, and the open distance of the transplanting claws is 40 mm. It shows that the clamping mechanism can clamp or hold sweet potato seedling with the damage to the mulch film mulching on the ridge reduced. Thus, the transplanting machine device is suitable for transplanting on the mulch film.

The velocity and acceleration curves at the end of the transplanting claws are derived from Motion as shown in Figure 11. It can be seen that when the transplanting claws move to the seedlings releasing point, the horizontal velocity is –17 mm/s and the vertical velocity –15 mm/s, which can ensure the smooth process of picking sweet potato seedling and improve the success rate of transplanting. During the transplanting process, the velocity of the transplanting claws gradually increases, which can improve the transplanting efficiency. The horizontal velocity of the transplanting claw is 645 mm/s and the vertical velocity is 83 mm/s when the seedling is released. The horizontal and vertical velocity are relatively small, which could ensure the accuracy of sweet potato seedling side transplanting.

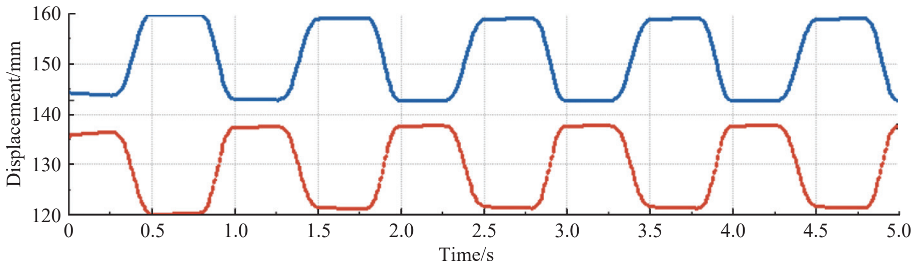
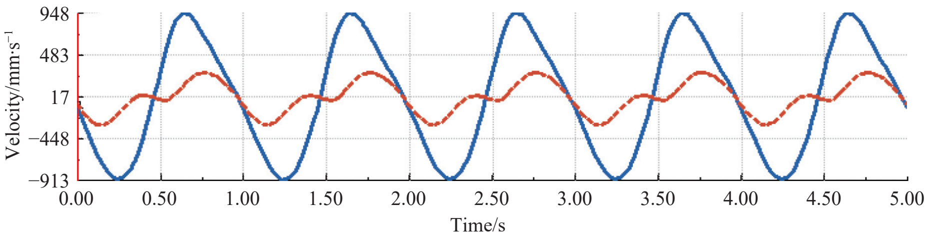


Figure 10 Relative motion displacement of transplanting claw. Solid line, the relative motion displacement of the right transplanting claw. Dotted line, the relative motion displacement of the left transplanting claw

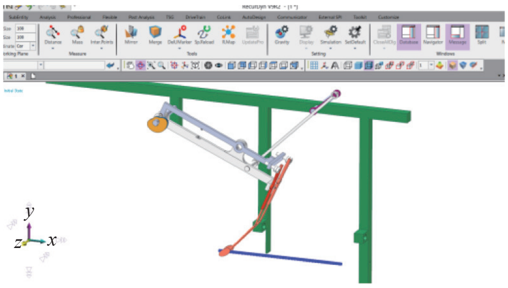


Note: Solid line is the horizontal velocity; Dotted line is the vertical velocity.

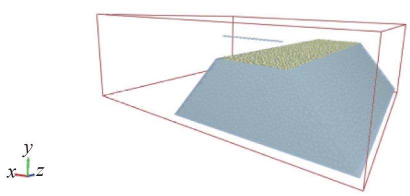
Figure 11 Horizontal and vertical velocity of transplanting claw centroid

3.3 Simulation test of transplanting device

In order to verify the feasibility of the designed side insertion horizontal transplanting device for sweet potato seedlings on mulch film, the sweet potato seedlings transplanting process was tested by mechanical-discrete element joint simulation with RecurDyn and EDEM software. The simplified model of the three-dimensional device is imported into the RecurDyn software. Then the crank of the reciprocating mechanism is added with a revolute pair at the rotational velocity of 6 rad/s. The device simulation model is shown in Figure 12a. Since the young leaves of the sweet potato seedling will not affect the transplanting trajectory, the flexible body model of the sweet potato seedling is simplified without affecting the simulation effect. In the RecurDyn/External SPI module, a simplified leafless sweet potato seedling flexible body model is established, and the sweet potato seedling flexible body model is set as wall, through which EDEM software is connected. In the Geometry option of EDEM, the particle factory is set up to simulate the soil particles. The upper bottom surface of the trapezoidal particles is 300 mm, the lower bottom surface 650 mm, and the height is 300 mm, as shown in Figure 12b.



a. Simulation model of the device

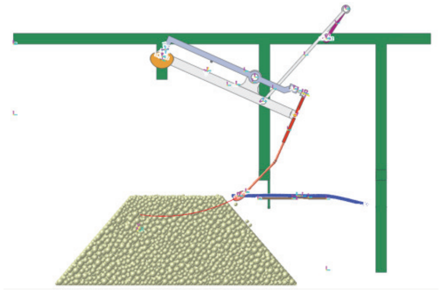


b. Soil particle

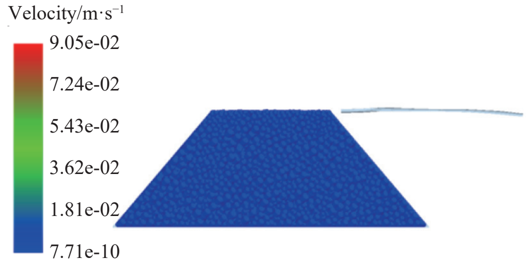
Figure 12 Simulation modeling

The trajectory of the transplanting claw is obtained by simulation test as shown in Figure 13a. It can be seen that the transplanting trajectory of sweet potato seedling is approximately horizontal meeting the expected requirement. Compared with 2CGFS-2 compound sweet potato transplanter[28], the transplanting device designed in this paper realizing the complete overlap of the point transplanting claw entering the field ridge and the point transplanting claw leaving the field ridge, which further effectively reduces the damage to mulch film during the transplanting process. At present, there are transplanters that can realize the overlap between the points entering and leaving the field ridge. For example, Shao et al.[23] developed the a transplanting mechanism for sweet potato seedlings with 'boat-bottom' transplanting trajectory. In which, the two points entering and leaving the field ridge are overlapped at the cost of the increase of transplanting distance of sweet potato seedlings to about 350 mm. Li et al.[24] developed the sweet potato up-film transplanting device with a boat-bottom posture with a complex structure. Hence, apart from the agronomic requirements of horizontal transplanting, transplanting depth and transplanting length, the designed device is potential for achieving rational close planting with simple structure.

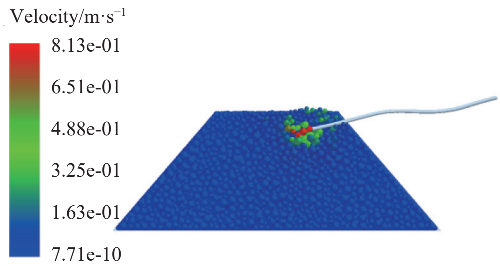
The soil fluctuation changes under different conditions during the transplanting process are shown in Figures 13b-13d. From which, during the process of the transplanting claws picking the



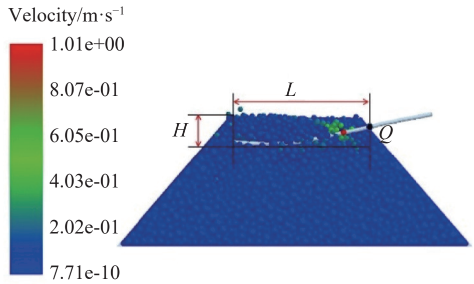
a. Moving track of transplanting claws



b. Velocity of particle disturbance when the transplanting claws are closed



c. Velocity of particle disturbance when transplanting claws enter soil



d. Velocity of particles disturbed when the transplanting claws are open

Figure 13 Results of simulation test

sweet potato seedling and moving to the seedlings releasing point, when the sweet potato seedling start to enter the soil, the ridge does not have any fluctuations. When the seedling moves into the soil, the ridge body begins to fluctuate, and when the transplanting claws are opened to release the seedling, the ridge collapses slightly. After the transplanting claws left the soil, the trapezoidal ridge basically kept its shape. The lateral length L of the sweet potato seedling entering the soil is 190 mm, and the vertical depth H is 51 mm, which meet the agronomic requirements of sweet potato horizontal planting. Point Q shown in Figure13d is the entering point of transplanting claw into field ridge and also the leaving point of transplanting claw from field ridge. Compared with the sweet potato seedling transplanting machine developed by Wu et al.[29], the lateral length of the designed transplanting device in this paper is 90 mm longer. And accordingly, the number of soil nodules of sweet potato seedlings will increase, which will promote the growth of production enormously.

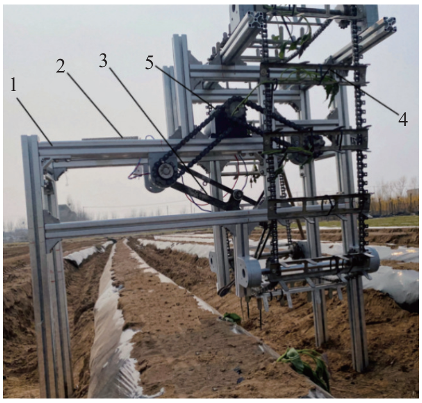
4 Field experiment

4.1 Conditions of the test

In order to further verify the feasibility of the side insertion horizontal transplanting device for sweet potato on mulch film, a field test is carried out at the sweet potato transplanting base in Taian, Shandong Province, as shown in Figure 14. The test bench mainly includes an aluminum profile frame, a side inserted horizontal transplanting device, a 6D300-24 DC motor, a switching power supply and a camera. Ridging and mulch film covering operations have been completed before the test, with a ridge height of 300 mm, an upper ridge surface width of 300 mm, and a ridge bottom width of 650 mm. The variety of sweet potato seedlings is Yanshu 25, with growth time at about 30 days, the average root diameter of seedlings at 4 mm, and the average length of potato seedlings at 260 mm. The reciprocating mechanism and seedling clamping mechanism are driven by 6D300-24 DC motors.

4.2 Evaluation indicators of the test

The test indicators are the expulsion rate of sweet potato seedlings, the qualified rate of transplanting depth, the qualified rate



1. Rack 2. Switch power supply 3. Side insertion horizontal transplanting device 4. Seedling delivery device 5. 6D300-24 DC motor

Figure 14 Field experiment

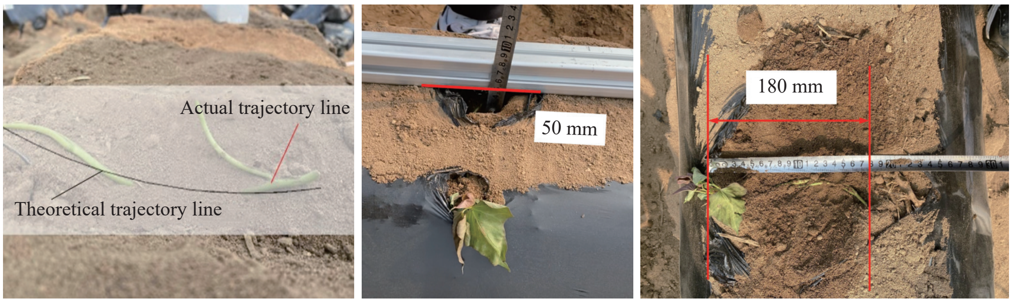
of transplanting length, the average length of the mulch film rupture hole and the width of the mulch film rupture hole during the transplanting process of the side insertion horizontal transplanting device. The expulsion rate refers to the probability of sweet potato seedlings falling off from the picking point to the releasing point during transplantation. The qualified rate of transplanting length refers to the percentage of the number of sweet potato seedlings with qualified transplanting length and the total number of sweet potato seedlings in the measured interval. The qualified rate of transplanting depth refers to the percentage of the number of sweet potato seedlings with qualified transplanting depth and the total number of sweet potato seedlings in the measured interval.

4.3 Discussion of test results

After the test is completed, the working process of the side insertion horizontal transplanting device is analyzed. As shown in Figure 15, the transplanting device successfully completes the picking seedling and transplanting operation. After the transplanting, the sweet potato seedling stayed in the ridge. In the process of transplanting claws leaving the soil, the sweet potato seedlings will not move with the movement of the transplanting claws.

Figure 15 Working process of the side insertion horizontal transplanting device

The soil was removed at appropriate position to observe the posture, depth and length of transplanted sweet potato seedlings in ridge as shown in Figure 16. It can be seen that the posture of the seedlings meets the theoretical trajectory line calculated before. The length and the depth of potato seedlings entering the ridge agree to the designed values. To further verify the results, three planting areas were randomly selected for measurement, and the results are shown in Table 2. It can be obtained by calculation that the average depth of sweet potato seedlings into the ridge is 45 mm, and the average length of the sweet potato seedlings is 185 mm, which is consistent with the simulation results and the agronomic requirements. The expulsion rate of sweet potato seedlings is 1.38%, the qualified rate of transplanting length 94.17%, and the qualified rate of transplanting depth 95.11%. The test data meets the performance requirements of the sweet potato transplanter and the agronomic requirements of sweet potato planting.



a. Comparison diagram of posture of bare sweet potato seedlings b. Depth of transplanted sweet potato seedlings in ridge c. Length of transplanted sweet potato seedlings in ridge

Figure 16 Analysis of actual transplanting results of sweet potato seedlings

Table 2 Results of the field test.

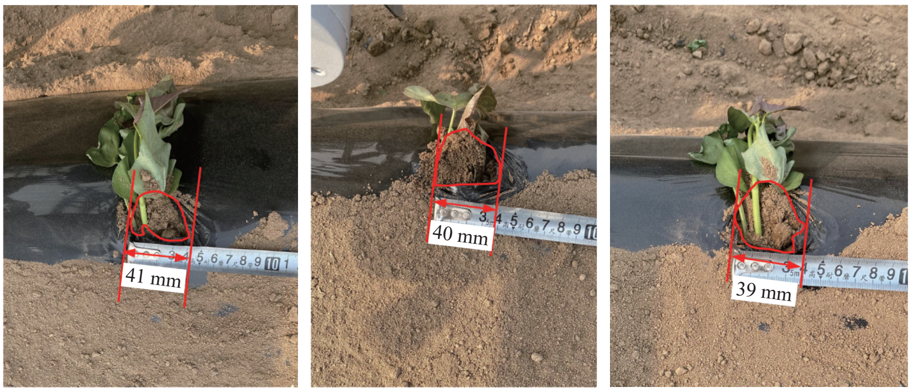
Test No.	Expulsion rate of sweet potato seedlings/%	Qualification rate of transplanting depth/%	Qualification rate of transplanting length/%	Average length of the mulch film rupture hole/mm	Average width of the mulch film rupture hole/mm
1	0	92.00	94.00	49.00	43.00
2	0	95.83	93.75	44.00	43.00
3	2.80	96.67	95.00	42.00	45.00
4	3.20	96.08	94.12	46.00	44.00
5	0	94.23	92.30	47.00	41.00
6	2.30	95.83	95.83	40.00	42.00
Average value	1.38	95.11	94.17	44.67	43.00

In addition, since the point where the seedling clamping mechanism enters the field ridge and the point where it leaves are at the same position, the damage to the mulch film during the transplanting process is mainly determined by the opening degree of the transplanting claws and the movement of the claw arm. As shown in Table 2 and Figure 17, the average length of the mulch film breaking hole is 44.67 mm, and the width of the broken mulch film hole is 43.00 mm. The length of the mulch film rupture hole is lower than that of the up-film transplanter for sweet potato[30] designed for hilly and mountainous. During the test, few sweet potato seedlings shed during the transplanting process due to the small contact area between the root of the sweet potato seedlings and the end of the transplanting claw. The expulsion rate can be reduced by increasing the end area of the transplanting claw. Under the condition of consistent growth of sweet potato seedlings and good rhizomes, the side insertion horizontal transplanting device has higher reliability.

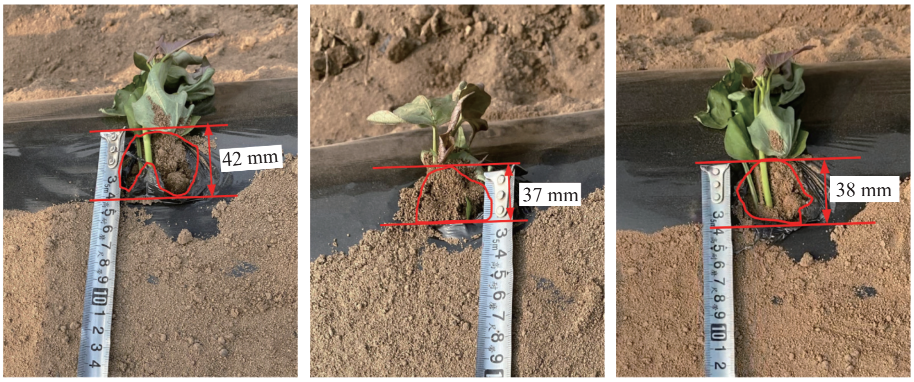
5 Conclusions

A side insertion horizontal transplanting device for sweet potato seedlings on mulch film was designed including a reciprocating mechanism and a seedling clamping mechanism. Based on the design of the overall structure and the analysis of the working principle, the parameters of the reciprocating mechanism, the external contour of the transplanting claw and the cam were determined.

1) The motion simulation of mechanisms shows that the design of reciprocating mechanism makes sure the maximum horizontal distance at 295 mm and the maximum vertical distance at 60 mm. According to the agronomic requirements, a transplanting depth of 50 mm is selected. The motion simulation of the designed seedling clamping mechanism gives the horizontal velocity of the transplanting claw at −17 mm/s when the seedling is picked from



a. Length of the mulch film breaking hole



b. Width of the broken mulch film hole

Figure 17 Analysis of the damage degree to mulch film

the belt, the horizontal velocity of the transplanting claw at 645 mm/s and the vertical velocity at 83 mm/s when the seedling is released.

2) The simulation of the whole transplanting device shows that the designed device is in accordance with the agronomic requirements of horizontal transplanting, transplanting depth and transplanting length, and is potential for achieving rational close planting with simple structure. Besides, the lateral length of the designed transplanting device is extended at about 90 mm compared with previous machine, which will promote the number of soil nodules of sweet potato seedlings and the growth of production enormously. The above data can ensure the accuracy requirements of the horizontal transplanting trajectory.

3) The test bench was built for field experiments. The field experiment results show that the expulsion rate of sweet potato seedlings is at 1.38%, the qualified rate of transplanting length at 94.17%, the qualified rate of transplanting depth at 95.11%, the average length of the mulch film breaking hole at 44.67 mm and the width of the mulch film breaking hole at 43.00 mm. The posture of the actual transplanted seedlings agrees with the simulation results, which met the requirements of horizontal transplanting causing less damage to the mulch film. The design of the side insertion horizontal transplanting device for sweet potato seedlings on mulch film provides technical support for the development of sweet potato side transplanting machine.

Acknowledgements

The authors acknowledge that this work was financially supported by the Shandong Province Potato Industry Technology System Agricultural Machinery Project (SDAIT-16-10), Key R&D Program of Shandong Province, China (Grant No. 2022CXGC 010611) and Jiangsu Planned Projects for Postdoctoral Research Funds (2020Z101).

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