Kinematic analysis and experiment of planetary five-bar planting mechanism for zero-speed transplanting on mulch film

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Abstract: A novel seedling transplanting mechanism with planetary five-bar was developed in order to solve some problems when transplanting seedlings on mulch film, such as a large cave diameter, a low proportion of upright seedlings, and inconsistent planting depths, which seriously restrict the development of transplanting equipment used in dryland agriculture. The planetary five-bar structure of transplanting mechanism was designed based on analysis of the seedling transplanter on mulch film. The kinematics model of the transplanting mechanism was established and the optimal parameters of the transplanting mechanism were obtained by satisfying the motion trajectory conditions. Subsequently, the virtual prototype of transplanting mechanism was developed, and the simulation of motion trajectory was illustrated. Finally, the physical prototype of the transplanting mechanism was assembled and tested with the high-speed photography. The simulation results indicated that the desired "spindle" trajectory for the duckbill can be obtained, of which the height was 350 mm, and the diameter of the planting cave was 32 mm. The experimental results showed that the diameter of the planting cave was less than 70 mm, the seedling perpendicularity qualification rate reached 96%, the film injury rate was less than 0.5%, and the hanging membrane phenomenon was avoided. Therefore, the proposed transplanting mechanism can meet the requirements for a mulch-film transplanting machine.

Keywords: seedling transplanting, mulch-film, planetary five-bar mechanism, zero-speed transplanting, parameter optimization
DOI: 10.3965/j.ijabe.20160904.2073

Citation: Liu J D, Cao W B, Tian D Y, Tang H Y, Zhao H Z. Kinematic analysis and experiment of planetary five-bar planting mechanism for zero-speed transplanting on mulch film. Int J Agric & Biol Eng, 2016; 9(4): 84－91.

1 Introduction

Seedlings are widely transplanted in cold areas and drought regions. A transplanting machine used on mulch film can protect the seedlings from the extremes of temperature and weather, thus increasing their survival rate. Moreover, the moisture retention and weed suppression are beneficial to crops[1]. Since the 1980s, a mass of researches focused on the development of seedling transplanters and their components[2,3]. There are many kinds of semi-automatic commercial transplanters, such as tobacco transplanters (Iseki Company, Japan), finger-clip-type double transplanters (Nick Ma Chi Company, America), and semi-automatic scallion transplanters (Kubota Company, Japan)[4]. All of these requires the seedlings to be fed manually into the planting mouth, which results in high workload and low efficiency.

Automatic transplanting machines have also been further developed and applied in seedling transplanting

Received date: 2016-04-28 **Accepted date:** 2016-05-13
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fields in recent years[5-7]. Ferrari (Italy) and Pearson (France) developed a series of automatic dry-field transplanters[8], which are only suitable for transplanting into bare areas and unsuited on mulch film in cold and drought areas. The processes of punching through the film, planting the seedling, covering it with soil, and pressing the soil around the planted seedling are required in seedlings transplant on mulch film. Furthermore, a high rate of upright seedlings is closely related to a narrow cave diameter, which is a key factor affecting their growth. Kenco (USA) designed a semi-automatic punching transplanter that can transplant single and multiple rows on mulch. Subsequently, the company also produced a transplanting machine with a firing mechanism, which uses a flame to singe a cave on mulch film before punching the cave. Thus, the film tear can be avoided during the cave punching process[9]. Kubota Corp (Japan) exploited an automatic duckbill transplanting machine. In China, Liu et al.[10] and Jin et al.[11] developed a kind of transplanter on mulch film that included a planting duckbill or a hanging-basket planting mechanism[12,13]. Unfortunately, it led to a large cave diameters and a low rate of upright seedlings. Therefore, it cannot achieve the agronomic standard for transplanting on mulch film.

Two processes are needed in most of transplanting mechanisms, i.e., punching the cave and planting the seedling. Both of which should be completed simultaneously in one operation[14,15] if the mechanism contains a duckbill or a hanging-basket. If the trajectory of the hanging-basket planting mechanism is trochoidal, an ideal planting (i.e., a high rate of upright seedlings) can be obtained. However, the structure of the mechanism is relatively complex. In addition, the leakage rate of seedlings will increase with the acceleration of transplanting seedlings. As a result, the speed of feeding seedlings is restricted seriously.

The main objectives and contributions of this work are as follows.

(1) An automatic transplanter with a planetary five-bar planting mechanism is developed to meet the demands of seedling transplanting on mulch film.

(2) A series of optimized parameters is derived to ensure that the seedlings are planted with zero-speed operation, and narrow cave diameters for obtaining a high perpendicularity qualification rate.

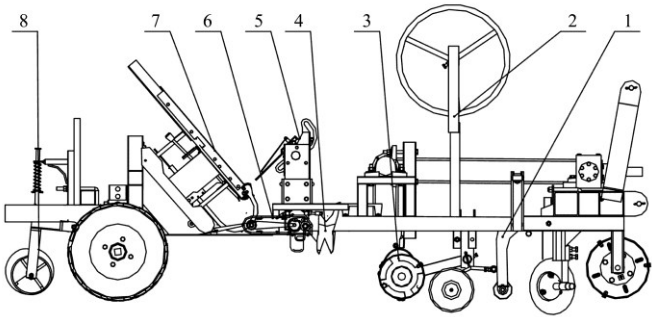
(3) The rational transplanting trajectory and structure are designed and demonstrated in terms of kinematics simulation.

(4) Field experiments with two-row transplanting machine are conducted to verify the reasonability of the optimal parameters.

2 Materials and methods

2.1 Configuration and working principle

The conditions on laying both the drip tape and mulch film are required when seedlings are transplanted in cold and drought regions. The seedling transplanter with planetary spur gears is depicted in Figure 1. Note that the transplanter is coupled to a tractor's three-point suspension, which is composed of filming device, laying drip device, covering and press unit, pick-up mechanism, seedling planting mechanism and transporting device. In a process, two operations should be completed simultaneously to achieve the transplanting, i.e., laying both the drip tape and the mulch film. As a result, the labor efficiency is improved. Meanwhile, the utilization of the mechanism and the transplanting efficiency are optimized[16].



1. Filming device 2. Laying drip tape device 3. Overburden device 4. Planting duckbill 5. Pick-up mechanism 6. Transplanting mechanism 7. Transporting device 8. Covering and press unit

Figure 1 Seedling transplanter on mulch film

First, the potted tray transporting device and the seedling pick-up mechanism run concertedly such that the operations of feeding seedlings and extracting seedlings are coordinated. After that the planting duckbill is driven by the planting mechanism to complete all processes of catching, carrying, and planting seedlings in soil overlaid with mulch film. Finally, the press drill covers soil and presses them.

2.2 Experiment design

To confirm the influence factors of the plug seedling transplanting mechanism, the parameters of the seedling transplanting experiments in field were set as Table 1.

Table 1 Parameters of seedling transplanting experiments in field

Parameters	Values
The variety of tomato seedlings	Shihong No. 303
Seedling age/d	50
Seedling average height/mm	150
The moisture content of pot seedling soil/%	60-72
Transplanting spacing/mm	200-280
The number of transplanted seedlings	512
The rotation speed of the carrier/r·min^{-1}	150
The transplanter driving speed/m·s^{-1}	0.5

The above field experiment was conducted in the Agricultural Center of Shihezi University. The field soil was sandy clay soil and leveled the ground for the experiment.

2.3 Kinematic model of the transplanting mechanism

2.3.1 The motion principle of the transplanting mechanism

By considering the prescribed trajectory of the planting duckbill, the planting mechanism is designed as a planetary geared five-bar linkage. It is assumed that each part of the mechanism is made of steel without elastic deformation, and the gaps between rotations can be neglected[17,18]. Therefore, the original planting mechanism can be simplified as shown in Figure 2. Specially, the coordinate origin O is set on the rotated center of the sun gear axis. In addition, the horizontal direction is set as the x axis, and the y axis represents the vertical direction.

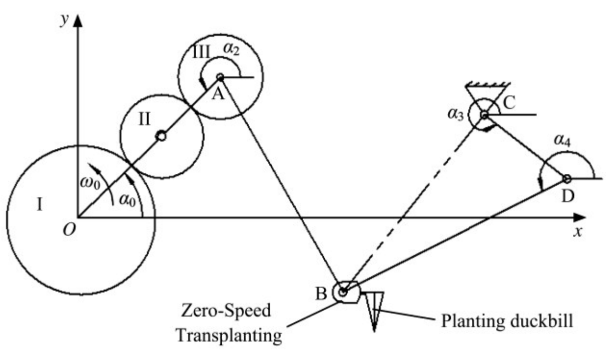


Figure 2 Transplanting mechanism with planetary five-bar

The transplanting mechanism with planetary five-bar consists of a planetary gear train system, a link rod AB, rod BD, rod CD and a frame. Since the sun gear I, idle gear II and planet gear III are included in the planetary gear box, thus it can be simplified to a crank OA. The whole planetary gears are driven by the transmission mechanism. Furthermore, the idle gear and the planet gear rotate around the sun gear that is consolidated with a planetary gear box, and the planetary gear box can drive other bars. Finally, the transplanting duckbill can move up and down in a plane with the rods AB, BD, and CD.

The related parameters are presented in Table 2.

Table 2 Definition of related parameters of the transplanting mechanism

Parameters	Explanation of related parameters
l_1	The length of crank OA, mm
l_2	The length of connecting rod AB, mm
l_3	The length of connecting rod BC, mm
l_4	The length of rocker CD, mm
L_{BD}	The length of rocker BD, mm
α_0	The angle of crank OA and x axis, deg
α_1	The initial angle of crank OA and x axis, deg
α_2	The angle of connecting rod AB and x axis, deg
α_3	The angle of connecting rod BC and x axis, deg
α_4	The angle of rocker CD and x axis, deg
Z_1	The number of sun gear tooth
Z_2	The number of idle gear tooth
Z_3	The number of planetary gear tooth
W_0	The initial angular velocity of planetary box, r/min
W_1	The angular velocity of planetary box, r/min
W_2	The angular velocity of idle gear, r/min
W_3	The angular velocity of planetary gear, r/min
i_{12}	The transmission ratio of idle gear and sun gear
i_{23}	The transmission ratio of idle gear and planet gear

The planting duckbill driven by the planetary five-bar transplanting mechanism moves in a particular trajectory to ensure zero-speed planting and perpendicularity qualification rate of the seedlings. When the transplanting duckbill rises to the top, a seedling is put into it by the seedling picker. The duckbill and seedling then move downward together, and the duckbill punches through the mulch film on the ground. Once the planting depth is reached, a planar cam rotates and pushes a pin shaft to open the duckbill. After that, the seedling is planted in the soil cave. Note that the duckbill remains open till it moves over the top of the planted seedling.

2.3.2 Displacement analysis

To satisfy the special demand of the transplanting track, the angular displacements of the link rod AB and the crank rod OA should be equal, and their directions must be opposite. The equation $\alpha_2=\alpha_0+2\alpha_1$ can always hold by the following conditions, i.e., the teeth of the sun gear are twice as those of the idle gear and the planet gear. Moreover, the transmission ratio of the sun gear and the idle gear is $i_{12}=\frac{w_1}{w_2}=\frac{z_2}{z_1}=1:2$, and the transmission ratio of the idle gear and the planet gear is $i_{23}=\frac{w_3}{w_2}=\frac{z_3}{z_2}=1$. Thus, Equation (1) can be derived.

$$\alpha_2=\alpha_0+w_3t=\alpha_0+2w_1t=\alpha_0+2\alpha_1 \tag{1}$$

According to Figure 2 and Table 1, l_1, l_2, l_3, l_4, x_D, y_D, α_0, ω_1 are given, and α_1 is variable parameter. The kinematic model of the planting mechanism indicates that the following closed-loop Equation (2) is suitable for the kinematic chain established in *O-xy*:

$$\overrightarrow{OB}=\overrightarrow{OA}+\overrightarrow{AB},\quad \overrightarrow{DB}=\overrightarrow{DC}+\overrightarrow{CB} \tag{2}$$

From the above results, Equations (3)-(6) are deduced as below.

Equation (3) describes the A-point displacement.

$$\begin{cases} x_A=l_1\cos\alpha_1 \\ y_A=l_1\sin\alpha_1 \end{cases} \tag{3}$$

Equation (4) gives the B-point displacement.

$$\begin{cases} x_B=l_1\cos\alpha_1+l_2\cos\alpha_2 \\ y_B=l_1\sin\alpha_1+l_2\sin\alpha_2 \end{cases} \tag{4}$$

From $\alpha_2=\alpha_0+2\alpha_1$, Equation (5) can be obtained.

$$\begin{cases} x_B=l_1\cos\alpha_1+l_2\cos(\alpha_0+2\alpha_1) \\ y_B=l_1\sin\alpha_1+l_2\sin(\alpha_0+2\alpha_1) \end{cases} \tag{5}$$

The C-point displacement is expressed as Equation (6).

$$\begin{cases} x_C=x_D+l_4\cos\alpha_3 \\ y_C=y_D+l_4\sin\alpha_3 \end{cases} \tag{6}$$

where,

$\alpha_3=\arcsin\frac{a-b}{\sqrt{c^2+d^2}}-\arctan\frac{c}{d}$,

$a=l_3^2-l_1^2-l_2^2-x_D{}^2-y_D{}^2-l_4{}^2$,

$b=2l_1l_2\cos(\alpha_1-\alpha_2)-2l_1x_D\cos\alpha_1-2l_1y_D\sin\alpha_1-2l_2\cos\alpha_2x_D-2l_2y_D\sin\alpha_2$,

$c=2x_Dl_4-2l_1l_4\cos\alpha_2-2l_1l_4\cos\alpha_2$, and

$d=2y_Dl_4-2l_2l_4\sin\alpha_2+2l_1l_4\sin\alpha_1$

2.3.3 Modeling velocity and acceleration of the planting mechanism

By computing the first and second derivative of above displacement equations, the corresponding speed and acceleration equations at each point can be derived. Similarly, the rod's angular velocity and angular acceleration are also found. For brevity, the velocity and acceleration equations only for planting point B are listed in the paper.

The velocities of point B in *x*-direction and y-direction are shown as below.

$$\begin{cases} \dot{x}_B = \text{[illegible]}\ \alpha_1) \\ \dot{y}_B = \text{[illegible]}\ \alpha_1) \end{cases} \tag{7}$$

The accelerations of point B in *x*-direction and *y*-direction are depicted as follows.

$$\begin{cases} \ddot{x}_B = \text{[illegible]}\ +4l_2\cos(\alpha_0+2\alpha_1)] \\ \ddot{y}_B = \text{[illegible]}\ +4l_2\sin(\alpha_0+2\alpha_1)] \end{cases} \tag{8}$$

2.4 Preconditions of optimal trajectory

2.4.1 Constraint conditions

In order to achieve the transplanting, the transplanting mechanism in Figure 2 should satisfy the conditions that the two bars BC and CD cannot be aligned linearly, i.e., ∠BCD=360° and ∠BCD=180°), Otherwise, there exists dead-points that will prevent the mechanism from further moving. Generally, the angle between the CD and BC bars is always between 0° and 180°. That is to say, B, C, and D should constitute a triangle, and the length of BD meets the following conditions:

$$|l_3-l_4|<l_{BD}<l_3+l_4 \tag{9}$$

2.4.2 Motion trajectory planning

Zero speed is an important condition for the transplanting pot seedlings on mulch-film[19-21]. To achieve it, the following multiple complicated objectives should be satisfied.

1) To avoid the planting duckbill damaging or knocking over the planted seedlings, the height of the planting duckbill trajectory must be greater than that of the planted seedling.

2) The absolute velocity of the planting duckbill is zero when it releasing the seedling for planting.

3) To avoid the planting duckbill from interfering with the upright seedling (e.g., changing its position or orientation), the motion of the duckbill should be kept in a straight line during its return trip, and its state should be opened before passing through the planted seedling.

4) The distance from the gearbox to the ground is greater than 15 mm.

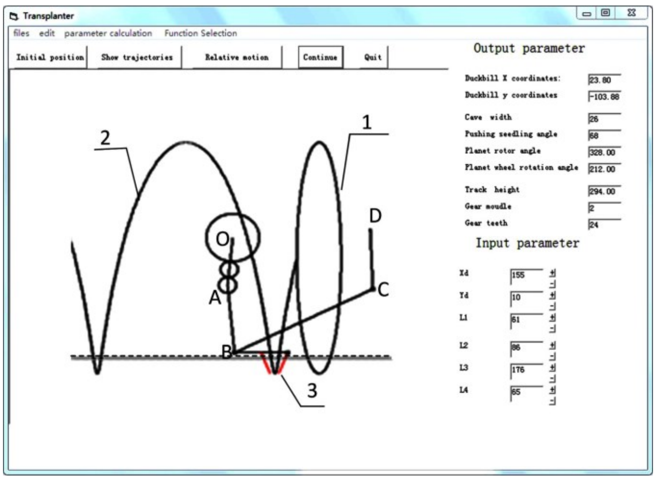
5) The distance between the top point and rock bottom of the trajectory must be greater than 260 mm.

6) The diameter of the planting cave should be less than 70 mm.

3 Results and analysis

3.1 Optimal parameter for transplanting mechanism

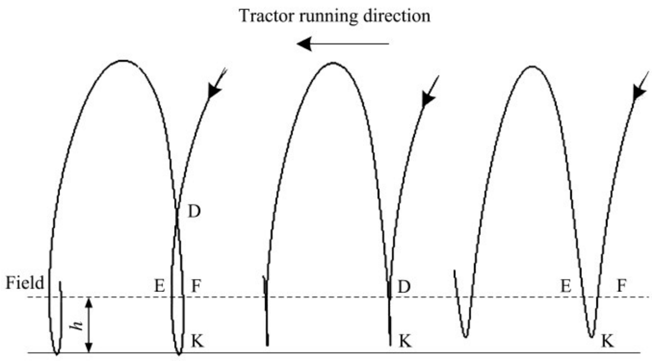
To design a simple transplanting mechanism that satisfies aforementioned objectives, a number of parameters of the transplanting mechanism should be optimized[18,22]. Optimizing the transplanting mechanism with planetary five-bar is a fuzzy, nonlinear, and complicated problem with multiple objectives and multiple parameters. It is difficult to solve this problem by using the traditional optimization methods. By comparison, the software is designed in this paper based on the Visual Basic programming platform, as shown in Figure 3, which can analyze and optimize the transplanting mechanism with a visual interface.



1. Static trajectory 2. Movement trajectory 3. Planting duckbill

Figure 3 Analysis and optimization software for the seedling transplanting mechanism with planetary five-bar

By adjusting the parameters of the mechanism, their effects on the trajectory of the planting duckbill[20] can be further analyzed. It can be verified that the lengths of OA, BD and CD have little impact on the planting trajectory, and it can be neglected. However, the lengths AB and BC have obvious impact on the trajectory. For an instance, three planting trajectories are compared with different lengths of the AB and BC as shown in Figure 4.



a. l_{AB}= 97 mm, l_{BC} = 184 mm b. l_{AB} = 77 mm, l_{BC} = 166 mm c. l_{AB} = 87mm, l_{BC} = 176 mm

Figure 4 Effects of lengths AB and BC on working track of the plant duckbill

K is the lowest point of the working track of the plant duckbill. D marks the intersection of the trajectory on the planting and its return trip. E and F are the intersections of the track on the ground of the planting and its return route, respectively. Tracks (a) and (b) in Figure 4 have loop points[15,23] that can reduce the size of the planting cave, and both of them include zero horizontal speed points. Consequently, tracks (a) and (b) can realize zero-speed planting. Particularly, E and F almost overlap in track (b). Thus, the trajectory is always vertical line from the planting operation to its return. It can be concluded that the cave size of track (b) is smallest. On the contrary, the cave of track (c) is the biggest of those tracks.

Through analyzing the parameters of the mechanism by the software, the optimal parameters are obtained: l_1 = 68 mm, l_2 = 77 mm, l_3 = 166 mm, l_4 = 65 mm, x_D = 155.5 mm, and y_D = 10 mm. The initial phase of the crank OA angle is 90°. The static track of the planting duckbill tip is defined as a "spindle" in Figure 3, and its height is 350 mm. The cave diameter is 32 mm, which satisfies the condition of ideal trajectory.

3.2 Virtual prototype test

According to the optimal parameters, a three-dimensional model of the transplanting mechanism was designed, and a virtual prototype model was then established and simulated by using ADAMS software.

Consequently, the stationary trajectory of the transplanting duckbill tip was obtained as shown in Figure 5.

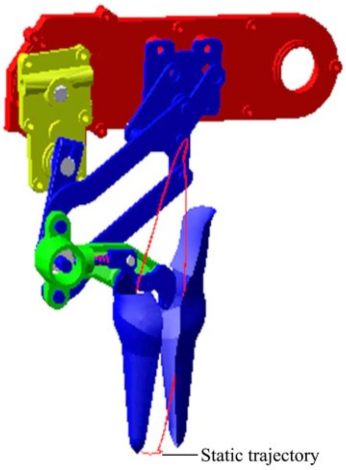


Figure 5 Virtual prototype test of the transplanting mechanism

Since the spring force and contact constraints are added to the virtual prototype, it leads to local shocks in the transplanting mechanism, which is an undesirable phenomenon in the "spindle" trajectory. Fortunately, the results of the virtual prototype test are basically consistent with the theoretical analysis, which verify the reliability of the trajectory[24].

The velocity and acceleration curves of the planting duckbill tip in the *x*-direction and *y*-direction are obtained by using the ADAMS/Post-processor, respectively, as shown in Figures 6 and 7.

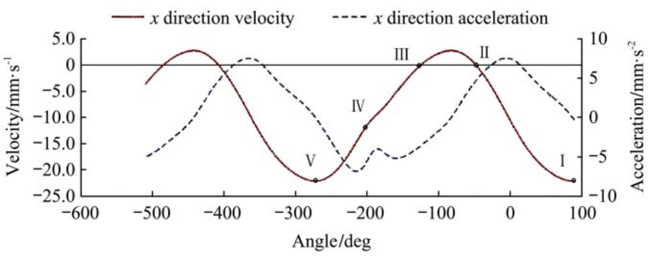


Figure 6 Velocity and acceleration in *x*-direction of the planting duckbill tip

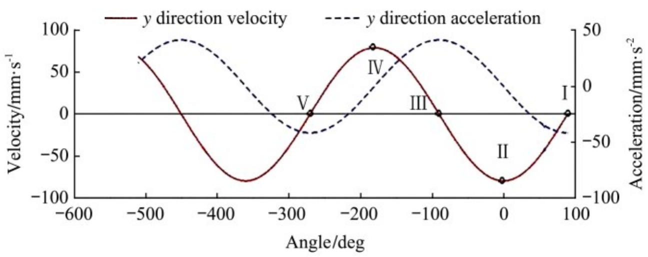


Figure 7 Velocity and acceleration in *y*-direction of the planting duckbill tip

In the process of carrying seedlings (I and II in Figures 6 and 7), when the crank OA moves from 90° to 0°, the acceleration of the planting duckbill tip in the *x*-direction gradually increases to a maximum value with the velocity decrease. However, the acceleration in the *y*-direction decreases with the velocity increase. As a whole, the planting duckbill accelerates, which leads to a high efficiency of the transplanting.

In the process of planting seedlings (II and III in Figures 6 and 7), the speeds of *x*-direction and *y*-direction decrease when the crank OA rolls from 0° to −55°. It indicates that the laws of motion can lower the seedling's landing inertia, which contributes to achieve the zero-speed planting and a perpendicular orientation. If the crank rotates from −55° to −100°, the duckbill tip velocity in the *y*-direction is very small. There are two zero-speed points in the horizontal direction. Obviously, the zero-speed transplanting of the seedling in the horizontal direction is accessible.

In the process of unearthing and returning the planting duckbill (III and IV in Figures 6 and 7), the crank rolls from −100° to −150°. The vertical motion of the duckbill is much quickly in return, which provides the small cave size and avoids the entrainment of planted seedlings. As the crank angle progresses from −150° to −180°, the velocities in the *x*-direction and *y*-direction increase simultaneously, which indicates that the return time can be shorten greatly.

As the planting duckbill returns (IV and V in Figures 6 and 7), the crank angle rotates from −180° to −270°, and the duckbill rises slowly. When it reaches the highest point, its speed comes to zero in both the *x*-direction and *y*-direction. It ensures that the duckbill is zero-speed when the seedlings enter into it, which means that the seedling matrix cannot be damaged.

3.3 Experiment bench verification

A physical prototype of the seedling transplanting mechanism with planetary five-bar was manufactured and mounted on the transplanting test rig. First, the rotation speed of the gearbox was set as 150 r/min. After that the high-speed photography of the transplanting mechanism was shot by using a CPL-MS70K digital camera, the perturbation frequency was then set as 800 fps, and the captured images were analyzed using

Blasters MAS software. Finally, the trajectory of the planting duckbill was obtained with the high-speed photography test, as shown in Figure 8.

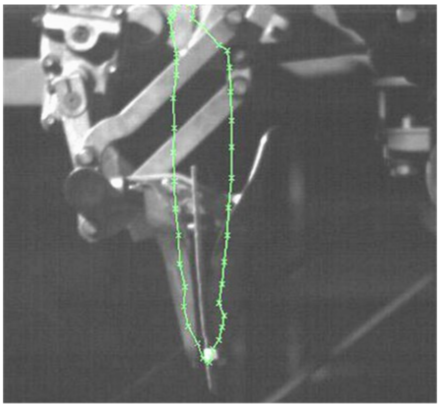


Figure 8 High-speed photography of the planting duckbill tip

By analyzing the high-speed photography images, it can be concluded that the planetary five-bar planting mechanism has a "spindle" trajectory of the duckbill tip, and its height is 350 mm, and the planting cave diameter is 32 mm. It is worth noting that the corresponding trajectories of the transplanting mechanism from the theoretical analysis, virtual prototype simulation, and physical prototype are consistent.

3.4 Field test

A seedling transplanting experiment using the pot seedling transplanting mechanism with planetary five-bar was conducted in field, as shown in Figure 9. According to the national transplanting standard (JB/T10291-2013)[25], the statistical results of field transplanting test are shown in the Table 3.

a. Field test of the seedling transplanter b. Test of seedling perpendicularity

Figure 9 Field test with transplanting mechanism

Table 3 The results of field test

Testing index	Planting depth/mm	Planting cave diameter/mm	Perpendicularity rate/%	Film injury rate/%
index value	50-80	30-40	96	0.5

The experimental results indicate that the testing parameters in Table 3 meet the agronomic requirements. Since the duckbill planter keeps the vertical moving trajectory, the planting depth is consistent, and the cave diameter is small. In details, the seedling perpendicularity rate is 96%, and the film injury rate is less than 0.5%. There are six caves only exceed the standard in the whole experimental seeding caves, and the hanging membrane phenomenon is almost unfound.

4 Conclusions

To solve the problems of transplanting seedlings on mulch film in dryland agriculture, a new seedling transplanting mechanism with planetary five-bar was proposed, which can realize "spindle" trajectory with a high rate of upright seedlings, a small planting cave, and zero-speed transplanting.

A kinematic model of the seedling transplanting mechanism with planetary five-bar was established, and its related optimized software was developed based on the Visual Basic platform. Moreover, the optimal parameters of the transplanting mechanism were derived to meet the transplanting requirements. The proposed method can shorten the design cycle of the transplanting mechanism.

By comparing the results of virtual prototype simulation with the theoretical analysis, it can be verified that the results are essentially identical. Meanwhile, the effectiveness of the theoretical model, virtual prototype, and physical prototype are verified. In sequel, the field test showed that the seedling transplanting mechanism with planetary five-bar proposed in the paper is more feasible for planting on mulch film.

Acknowledgments

We acknowledge that this work was supported by the Open Fund of the State Key Laboratory of Mechanical Transmissions (Grant No. SKLMT-KFKT-201516), the National Natural Science Foundation of China (Grant No. 51565048), and the Chinese Technology Aid Project in Xinjiang (Grant No. 2013AB013). The authors thank the anonymous reviewers for their constructive suggestions on the article.

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