Reverse design and tests of vegetable plug seedling pick-up mechanism of planetary gear train with non-circular gears

Zhifang Zhu[1,2], Guohuan Wu[3], Bingliang Ye[1*], Yongchang Zhang[1]

(1. *Faculty of Mechanical Engineering, Zhejiang Province Key Laboratory of Transplanting Equipment and Technology, Zhejiang Sci-Tech University, Hangzhou 310018, China*;
2. *School of Mechanical Engineering, Nanchang Institute of Technology, Nanchang 330099, China*;
3. *School of Intelligent Manufacturing, Wenzhou Polytechnic, Wenzhou 325035, Zhejiang, China*)

Abstract: In the previous research, the seedling pick-up mechanism of the planetary gear train with incomplete eccentric circular gear and non-circular gears for vegetable plug seedlings still has two shortcomings. One is that not enough seedling pick-up depth leads to a low success ratio of seedling pick-up at high rotation speeds, the other is that the smaller seedling pushing angle results in poor seedling pushing effect. Therefore, the reverse design of the seedling pick-up mechanism based on its motion trajectory was carried out. The local trajectory of seedling pick-up and seedling pushing sections was adjusted to obtain the theoretical motion trajectory of the seedling pick-up mechanism. The cubic non-uniform B-spline curve was used to fit the adjusted trajectory. A novel seedling pick-up mechanism of the planetary gear train with non-circular gears was proposed, including three combined non-circular gears, four non-circular gears, one planetary carrier, and two seedling pick-up arms. The reverse design model of the mechanism was established. The analysis and design software of the mechanism was developed to obtain the mechanism parameters meeting design requirements. The virtual prototype of the mechanism was established and its physical prototype was manufactured. Through the virtual motion simulation and high-speed photographic kinematics bench tests of the mechanism, the kinematic model and results of reverse design of the mechanism were verified, with the kinematic performances of the mechanism prototype studied. The seedling pick-up tests of the mechanism were conducted in the laboratory. The success ratios of seedling pick-up were 94.2%, 95.6% and 90.2% while the seedling pick-up efficiencies of the mechanism were 60, 80 and 100 plants per minute per row, respectively. Besides, the seedling pushing effect was improved mush because of the greater seedling pushing angle. The seedling pick-up mechanism through revise design is of high value to be applied in the practical vegetable plug seedling transplanters.

Keywords: vegetable plug seedling, seedling pick-up mechanism, non-circular gear, reverse design, virtual simulation, seedling pick-up tests
DOI: 10.25165/j.ijabe.20231602.7423

Citation: Zhu Z F, Wu G H, Ye B L, Zhang Y C. Reverse design and tests of vegetable plug seedling pick-up mechanism of planetary gear train with non-circular gears. Int J Agric & Biol Eng, 2023; 16(2): 96–102.

1 Introduction

China is the largest vegetable producing and consuming country, and its total vegetable production accounts for more than half of the global production[1]. About 60% of vegetable varieties are planted by the model of seedling cultivation and transplanting. Seedling transplanting has comprehensive benefits of increasing yield, climate compensation, and efficient utilization of lands. It has become the urgent and inevitable trend of vegetable production development to realize the mechanized transplanting of vegetable plug seedlings[2-4]. The mechanized transplanting of vegetable plug seedlings includes two modes of semi-automatic transplanting and full-automatic transplanting. For the semi-automatic transplanting, the plug seedlings are manually fed into the planting devices, such as flexible disc, chain clamp, seedling-guiding tube, and dibble types, with low efficiency, higher labor intensity, and cost. Full-automatic transplanting adopts multiple sets of mechanisms to complete seedling pick-up, transporting, and planting. Therefore, as the key component affecting the working performance of automatic vegetable transplanter, the automatic seedling pick-up mechanism has become a research hotspot at home and abroad[5,6].

Automatic transplanting technologies have been studied early in foreign countries, and some mature transplanters have been applied in actual production. In European and American countries, automatic transplanters have high efficiency in seedling pick-up (more than 120 plants per minute per row), and three sets of devices are generally used to complete seedling pick-up, transporting, and planting. However, these automatic transplanters cannot be widely applied in China because of their high cost and complicate structure[7]. In Japan and Korea, the automatic seedling pick-up mechanisms with multiple rods have lower efficiency (generally about 50 plants per minute per row) and large vibration[8-10]. Recently, China has been exploring automatic seedling pick-up mechanisms suitable for mechanized transplanting of vegetable seedlings, but the mechanisms have not been promoted[11-14]. The Agricultural Machinery Institute of Zhejiang Sci-Tech University in China has comprehensively studied automatic seedling transplanting mechanisms of planetary gear trains generally designed by using

Received date: 2022-02-12 **Accepted date:** 2022-08-21
Biographies: Zhifang Zhu, PhD candidate, Associate Professor, research interest: agricultural machinery design, Email: zhuzhifang1984@163.com; **Guohuan Wu**, PhD candidate, research interest: agricultural machinery design, Email: 422361992@qq.com; **Yongchang Zhang**, Master, research interest: agricultural machinery design, Email: 2232643046@qq.com.
***Corresponding author: Bingliang Ye**, PhD, Professor, research interest: agricultural machinery design. Faculty of Mechanical Engineering, Zhejiang Sci-Tech University, Hangzhou 310018, China. Tel: +86-13336060776, Email: zist_ybl@zstu.edu.cn.

two methods of forward design and revise design. The forward design method was applied to design vegetable and rice seedling transplanting mechanisms of planetary gear train, and kinematic analysis and parameters optimization of the mechanism were carried out by human-computer interaction design software. During the design process, it usually takes many times to modify the parameters to get the relatively ideal motion trajectory which still has the possibility of further optimization[15-20]. In the forward design method, the pitch curve equations of non-circular gears are predetermined, the motion trajectory of the mechanism are constrained to a certain degree. In addition, the method of reverse design based on the trajectory has also been applied to design tomato and rice seedling transplanting mechanisms of planetary gear train[21-25]. During the reverse design process, the ideal motion trajectory curve fitting was used to establish the mechanism kinematics model to calculate out the total transmission ratio of the planetary gear train, and the total transmission ratio was allocated to the two-stage non-circular gear pairs, thus quickly determining the pitch curves of non-circular gears of the planetary gear train. In generally speaking, for the reverse design based on the motion trajectory of the seedling transplanting mechanism, it is difficult to determine the ideal trajectory and it can be usually obtained by experts' experience, experiment analysis or modifying the trajectory achieved by the forward design of the mechanism.

In the previous study, Yu et al.[18] proposed a seedling pick-up mechanism of the planetary gear train with combined incomplete-eccentric-circular and non-circular gears only including one combined middle gear, and the forward design of the mechanism was carried out through the human-computer interaction optimization. The seedling pick-up tests of the mechanism show that it has a high success ratio of seedling pick-up (93.8%) while the efficiency of seedling pick-up is 60 plants per minute per row. But because of not enough seedling pick-up depth, when the efficiencies increase to 80 and 100 plants per minute per row, the success ratios of seedling pick-up decrease to 87.5% and 83.6%, respectively. In addition, the smaller seedling-pushing angle causes the problems of seedling hanging and poor seedling pushing effect. Therefore, in this study for solving the two problems, the local trajectory of seedling pick-up and pushing sections in the motion trajectory of the original mechanism was firstly adjusted to obtain an ideal motion trajectory. Then a new seedling pick-up mechanism of the planetary gear train with non-circular gears was proposed based the comprehensive consideration of the adjusted trajectory as well as the design and manufacturing feasibility of gears. Moreover, the work performed the reverse design modeling and solution and virtual motion simulation of the mechanism, and the high-speed photography test and seedling pick-up tests of the mechanism physical prototype.

2 Materials and methods

2.1 Adjustment of the motion trajectory

Figure 1 shows the motion trajectory before and after adjustment, generated by the previous seedling pick-up mechanism of the planetary gear train with combined incomplete-eccentric-circular and non-circular gears[18].

The motion trajectory is divided into four parts. In the seedling pick-up section *ABC*, the seedling pick-up claws insert into the seeding plug and clamp the plug seedling at the deepest Point *B* to extract the seedling. *CDE* is the seedling transportation section where the claws transport the plug seedling to the initial position of seedling pushing. *EF* is the seedling pushing section. At Point *E*, the seedling pick-up claws were driven to open, and then the seedling falls into the planting mechanism. *FA* is the return section where the seedling pick-up claws return to the initial position of seedling pick-up, and the mechanism resumes the working cycle. The motion trajectory basically meets the working requirements, with a seedling pick-up depth in the plug tray of 30.4 mm, a ring width of 1.9 mm, and a seedling pushing angle of 52°[18].

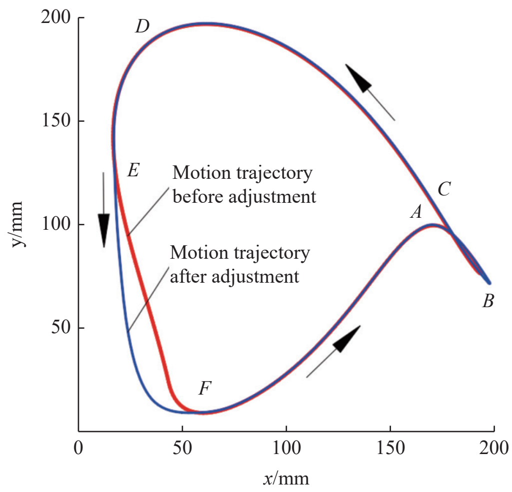


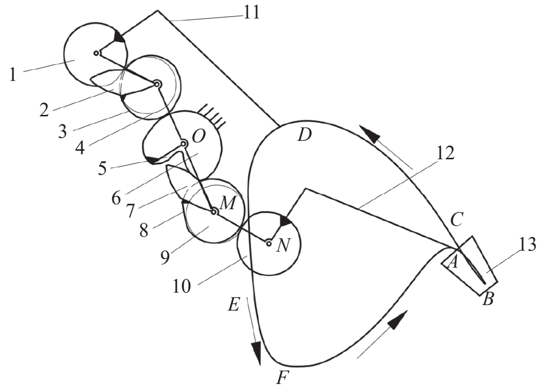
Figure 1 Motion trajectory before and after adjustment

The seedling pick-up depth should deepen and the seedling pushing angle should increase to solve the problems of the original seedling pick-up mechanism by adjusting motion trajectory, so the red motion trajectory was adjusted to the blue one shown in Figure 1 by changing the shape of the *EF* curve and lengthening the length of seedling pick-up section *ABC*, and the trajectories of *CDE* and *FA* were kept unchanged to obtain the relatively ideal motion trajectory for the reverse design of the seedling pick-up mechanism.

2.2 Structure and working principle of the seedling pick-up mechanism

A novel seedling pick-up mechanism of the planetary gear train with non-circular gears was proposed to meet the blue motion trajectory in Figure 1. It consists of three combined non-circular gears (combined sun gears composed of the first and second central incomplete non-circular gears 5 and 6; two combined middle gears composed of the first and second middle non-circular gears 2 and 3, and 7 and 8, respectively), four non-circular gears (the third middle non-circular gears 4 and 9; the planetary non-circular gears 1 and 10), one planetary carrier 12 and two seedling pick-up arms 11 and 13, as shown in Figure 2. By adding two middle non-circular gears, the seedling pick-up mechanism solves the problem that the gears cannot be designed and manufactured because of the overlarge transmission ratio of first-stage gear transmission.

The seedling pick-up mechanism is symmetrically designed on both sides. The combined sun gear is fixed to the frame; the planetary carrier is fixed to the central axis. The servo motor drives the central shaft and planetary carrier to rotate counterclockwise around rotation center *O*. Then, the combined middle gear and third middle non-circular gear rotate around rotation center *O* and rotation center *M* counterclockwise. Moreover, the planetary non-circular gear rotates around rotation center *O* with the planetary carrier and its rotation center *N* clockwise. Finally, the cusp of the seedling pick-up arms form motion trajectory *ABCDEF*, and the mechanism realizes seedling pick-up and pushing operations twice in one working cycle.



1, 10. Planetary non-circular gears 2, 7. First middle incomplete non-circular gears 3, 8. Second middle non-circular gears 4, 9. Third middle non-circular gears 5. First central incomplete non-circular gear 6. Second central incomplete non-circular gear 11, 13. Seedling pick-up arms 12. Planetary carrier 14. Plug seedling tray

Figure 2 Motion diagram of the seedling pick-up mechanism

2.3 Reverse design of the seedling pick-up mechanism

2.3.1 Curve fitting of the motion trajectory

The cubic non-uniform B-spline curve was used to fit the adjusted motion trajectory shown in Figure 3. A cubic non-uniform B-spline curve was constructed by selecting 35 data points on this trajectory, where Point 0 is the initial point of trajectory; Point 3 the farthest point relative to the rotation center of the mechanism (the deepest point where the seedling claws insert to the plug tray); Point 9 the highest point of the trajectory; Point 14 the closest point relative to the rotation center of the mechanism; Point 24 the lowest point of the trajectory; Point 34 the final point of trajectory coincided with Point 0. The equation of the cubic B-spline curve is as the following.

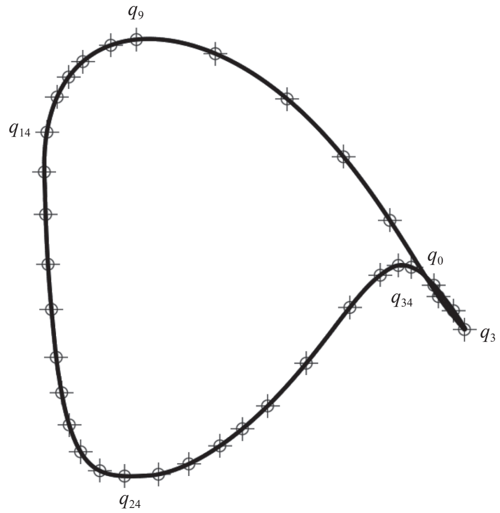


Figure 3 Data points of the adjusted motion trajectory

$$p(u)=\sum_{j=0}^{n} d_j N_{j,3}(u)=\sum_{j=i-3}^{i} d_j N_{j,3}(u); u\in[u_3, u_{n+1}]=[0, 1] \tag{1}$$

where, d_j is the control point; $N_{j,3}(u)$ is the primary function.

The parameter value sequence was obtained from the data points by using the method of standard accumulated chord length parameter. The parameter values were substituted into Equation (1) to derive the coordinates of all control points. At last, the coordinates of data points of the adjusted motion trajectory as q_0-q_{34} were solved according to Debuer's recursive formula.

2.3.2 Reverse design model

Table 1 lists the relative parameters during designing the seedling pick-up mechanism of the planetary gear train with non-circular gears.

Table 1 Kinematic parameters and their meanings

Parameter	Meaning	Parameter	Meaning
l_1/m	Distance between the rotation lefts of the planetary carrier and planetary gear	φ_1/(°)	The angle between the line from the rotation left of the planetary gear to the cusp of the seedling pick-up claw, and the *x*-axis
l_2/m	Distance between the rotation left of the planetary gear and the cusp of the seedling pick-up claw	φ_2/(°)	The angle between the line from the rotation left of the planetary carrier to that of the planetary gear, and the *x*-axis
l_3/m	Distance between the rotation left of the planetary carrier and the cusp of the seedling pick-up claw	φ_3/(°)	The angle between the two lines from the rotation left of the planetary carrier to the cusp of the seedling pick-up claw and the rotation left of the planetary gear
φ_4/(°)	The angle between the two lines from the rotation left of the planetary gear to that of the planetary carrier and the cusp of the seedling pick-up claw	φ_6/(°)	The rotation angle of the combined middle gear relative to the planetary carrier
φ_5/(°)	The rotation angle of the planetary carrier	φ_7/(°)	The rotation angle of the planetary gear relative to the planetary carrier
R_1	Radius vector of the pitch curve of the combined sun gear	R_3	Radius vector of the pitch curve of third middle gear
R_2	Radius vector of the pitch curve of the combined middle gear	R_4	Radius vector of the pitch curve of the planetary gear
α/(°)	The angle of the toothed part of the second middle gear	γ/(°)	The angle between the two lines from the rotation left of the middle gear to those of the planetary carrier and the planetary gear
β/(°)	The angle of the toothed part of the second central gear	δ/(°)	The angle between the two lines from the rotation left of the planetary carrier to those of the middle gear and the planetary gear

In Figure 4, the seedling pick-up mechanism of the planetary gear train with non-circular gears is converted into a three-bar mechanism model. The line between Points *O* and *N* serve as crank *ON*, rotating counterclockwise around Point *O*. The line between Points *N* and *A* served as rocker *NA*, swinging around Point *N* relative to the crank. Angular displacements of the crank and rocker are ϕ_2 and ϕ_4, respectively. The following equations are obtained[26].

$$l_2=\frac{\max(l_3)+\min(l_3)}{2} \tag{2}$$

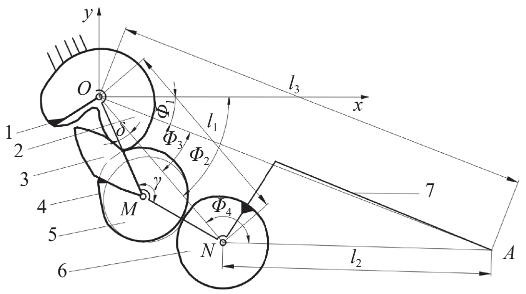
$$l_1=\frac{\max(l_3)-\min(l_3)}{2} \tag{3}$$

$$l_2=\frac{\max(l_3)+\min(l_3)}{2} \tag{4}$$

where, (x_A, y_A) is the coordinates of Point *A*.

The coordinate (x_A, y_A) of the data points of the seedling pick-up trajectory are used to calculate the lengths of the crank and rocker, angular displacement ϕ_1 of rod *OA*, respectively. According to the cosine theorem in the triangle ΔONA, ϕ_3 and ϕ_4 can be derived, and then the angular displacement ϕ_2 of the crank *ON*. The total transmission ratio of the mechanism is calculated as the following.

$$i=\frac{d\varphi_2}{d\varphi_4} \tag{5}$$



1. First central incomplete non-circular gear 2. Second center incomplete non-circular gear 3. Middle incomplete non-circular gear 4. Middle non-circular gear 5. Third middle non-circular gear 6. Planetary non-circular gear 7. Seedling pick-up arm

Figure 4 One side of the seedling pick-up mechanism

The third middle and planetary non-circular gears are complete gears. According to the gear meshing conditions, the transmission ratio of second stage gear is initially determined as $\sqrt[8]{i}$, and the following equation is obtained.

$$\sum \mathrm{d}\varphi_6 = \sum \sqrt[8]{i}\mathrm{d}\varphi_7 \tag{6}$$

The second stage of the transmission center distance a_2 is determined as 48.2 mm[18]. Then, the radius vectors of pitch curves of the planetary and third middle non-circular gears are calculated as follows:

$$R_4 = \frac{a_2 i_{23}}{1+i_{23}} \tag{7}$$

$$R_3 = a_2 - R_4 \tag{8}$$

where,

$$i_{23} = k\sqrt[8]{i} \tag{9}$$

$$k = \frac{2\pi}{\sum \mathrm{d}\varphi_6} \tag{10}$$

The transmission ratio of the first stage non-circular gear transmission is calculated as the follows:

$$i_{12} = \frac{i}{i_{23}} \tag{11}$$

The initial center distance between the middle and central gears a_{10} is firstly assumed as 52 mm. According to the closed condition of the pitch curve and the meshing condition of the gears, the iterative search is applied to obtain the parameters of the mechanism, such as the center distance a_1, radius vectors R_1 and R_2, and angles β and α. The specific calculations are as follows:

$$R_2 = a_1 i_{12}/(1+i_{12}) \tag{12}$$

$$R_1 = a_1 - R_2 \tag{13}$$

According to the meshing principle of the gears, the arc length of the second middle gear should be equal to that of the second center gear. The following equations are obtained.

$$R_1 \mathrm{d}\varphi_5 = R_2 \mathrm{d}\varphi_6 \tag{14}$$

$$\mathrm{d}\varphi_5 = \frac{R_2}{a_1 - R_2}\mathrm{d}\varphi_6 \tag{15}$$

The second center gear should rotate by angle β, while the second middle gear rotates by angle α; therefore, the following equations can be obtained.

$$\sum \mathrm{d}\varphi_5 = \sum \frac{R_2}{a_1 - R_2}\mathrm{d}\varphi_6 = \beta \tag{16}$$

$$\sum \mathrm{d}\varphi_6 = \alpha \tag{17}$$

The initial value of the radius vector of second middle gear R_{20} equal to $a_{10}i_{12}/(1+i_{12})$ is substituted into Equation (16) for iterative search. Until the difference between φ_5 and β meets the accuracy requirements (0.01), center distances a_1 of the first non-circular gear pair and radius vectors R_2 of the second middle gear are calculated. Then, radius vector R_1 of the sun gear was obtained according to Equation (13). Therefore, α and β can be determined according to Equations (16) and (17), respectively.

After the rotation angles of the crank and rocker, and the radius vectors of the pitch curves of the gears corresponding to the coordinates of data points are determined, with the coordinates of the pitch curves of the combined sun gear, combined middle gear, third middle non-circular gear and planetary non-circular gear obtained as follows.

$$\begin{cases} x_1 = R_1\cos(\varphi_2) \\ y_1 = R_1\sin(\varphi_2) \end{cases} \tag{18}$$

$$\begin{cases} x_2 = -R_2\cos(\varphi_6 - \varphi_6(0) - \varphi_2(0)) \\ y_2 = R_2\sin(\varphi_6 - \varphi_6(0) - \varphi_2(0)) \end{cases} \tag{19}$$

$$\begin{cases} x_3 = -R_3\cos(\varphi_6 - \varphi_6(0) - \varphi_2(0) + \gamma + \delta) \\ y_3 = R_3\sin(\varphi_6 - \varphi_6(0) - \varphi_2(0) + \gamma + \delta) \end{cases} \tag{20}$$

$$\begin{cases} x_4 = R_4\cos(\varphi_4 + \pi - \gamma - \delta + \varphi_7(0)) \\ y_4 = R_4\sin(\varphi_4 + \pi - \gamma - \delta + \varphi_7(0)) \end{cases} \tag{21}$$

$$\gamma = \arccos\frac{{a_1}^2 + {a_2}^2 - {l_1}^2}{2a_1 a_2} \tag{22}$$

$$\delta = \arccos\frac{{l_1}^2 + {a_1}^2 - {a_2}^2}{2l_1 a_1} \tag{23}$$

where, $\varphi_2(0)$ is the initial installation angle of the planetary carrier; $\varphi_6(0)$ the initial rotation angle of the combined middle gear relative to the planetary carrier; $\varphi_7(0)$ is the initial installation angle of the planetary gear.

2.3.3 Software and results of the reverse design

Based on the Matlab platform, the software shown in Figure 5 was developed for the reverse design of the seedling pick-up mechanism of the planetary gear train with non-circular gears. After the .xls or .txt files of data points of the adjusted trajectory curve were input to the software, the main parameters were obtained and displayed in the data area using the software, such as the initial installation angles of the planetary carrier and the seedling pick-up arm of mechanism, the central angle of toothed part of the combined sun gears, and the curve of the transmission ratio and the pitch curves of the gears. Simultaneously, the mechanism diagram was displayed in the graphic area. The main parameters of the seedling pick-up mechanism and the trajectory listed in Table 2 were obtained through the reverse-design software of the mechanism.

3 Experiments and results

3.1 Virtual motion simulation of the seedling pick-up mechanism

The structural design of the mechanism was completed according to the mechanism parameters obtained from the reverse design. UG software was used to conduct the three-dimensional modeling and virtual assembly of the seedling pick-up mechanism.

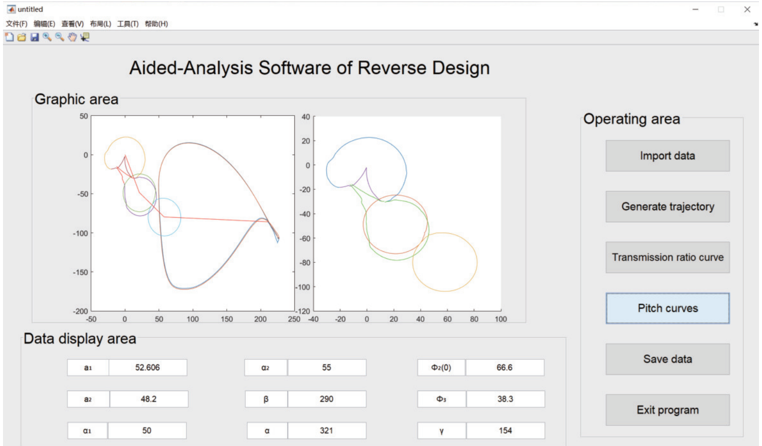
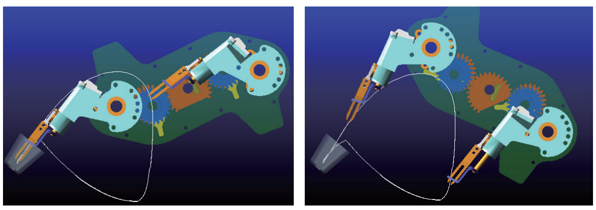


Figure 5 Interface of the software for the reverse design

Table 2 Parameters results of the reverse design

Name	Value
The angle of the toothed part of the second left gear (β)/(°)	290.00
The angle of the toothed part of the second middle gear (α)/(°)	321.00
Initial installation angle of the planetary carrier$\boldsymbol{\varphi}_2(0)$/(°)	66.60
Seedling pushing angle (α_2)/(°)	55.00
Seedling pick-up angle (α_1)/(°)	50.27
left distance of the first stage transmission (a_1)/mm	52.60
Distance between the rotation lefts of the planetary carrier and planetary gear (l_1)/mm	98.22
Distance between the rotation left of the planetary gear and the cusp of the seedling pick-up claw (l_2)/mm	153.18
Initial installation angle of the seedling pick-up arm (φ_3)/(°)	38.30
Seedling pick-up depth (l)/mm	35.00
Trajectory height of seedling pick-up (h)/mm	187.28
left distance of the second stage transmission (a_2)/mm	48.20

The virtual assembly was saved as a Parasolid file and then imported to ADAMS to add constraints, loads, and drives. The motion simulation of the virtual prototype was performed to verify the correctness of the reverse design model and results. Figure 6 shows the motion trajectory, moments of the seedling pick-up and seedling pushing of the virtual simulation of the seedling pick-up mechanism. From the simulation, the depth of seedling pick-up is about 35.09 mm, and the angles of seedling pick-up and pushing are about 50° and 55°, respectively.



a. Seedling pick-up moment b. Seedling pushing moment

Figure 6 Virtual simulation of the seedling pick-up mechanism

3.2 Bench tests of the seedling pick-up mechanism

3.2.1 Kinematics test

In the laboratory, the high-speed photographic kinematics test was used to study the kinematic characteristics of the mechanism prototype and further verify the correctness of the reverse design. The components, such as the non-circular gears and shafts, were machined and assembled into the prototype of the seedling pick-up mechanism, installed on the test bench for high-speed photographic kinematics tests. The cusp of the seedling pick-up arm was marked, and its positions were captured with a high-speed camera (Canon EOS 80D) during the rotation of the mechanism prototype. A series of images were obtained by the image processing software. After that, the cusp trajectory of the seedling pick-up arm was obtained by depicting the marked points in different images. Figure 7 shows the test trajectory of the seedling pick-up mechanism.

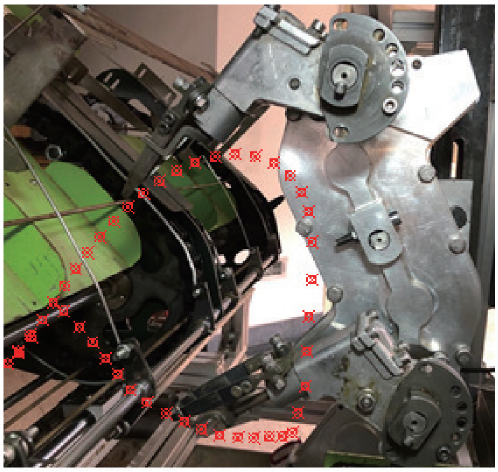


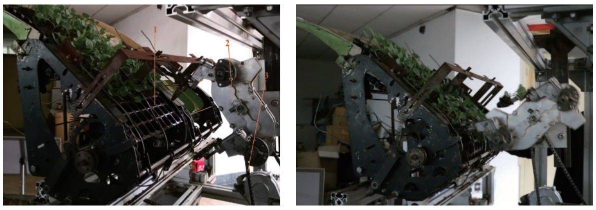
Figure 7 Test trajectory of the seedling pick-up mechanism

3.2.2 Seedling pick-up tests

As shown in Figure 8, broccoli plug seedlings and 16×8 seedling trays are used for seedling pick-up tests in the laboratory. The top and bottom sizes of the tray cells are 31 mm×31 mm and 17 mm×17 mm; the depth of each cell is 44 mm; the height of the individual plant is about 10 cm. The broccoli plug seedlings are placed on the seedling-feeding device of the seedling pick-up test bench in Figure 9. The servo motor speeds are set to 30, 40, and 50 r/min, respectively, which means the seedling pick-up efficiencies are 60, 80, and 100 plants per minute per row, respectively. Record the total number of seedlings, the numbers of seedlings successfully extracted and pushed. Then calculate the success ratio of seedling

a. Broccoli plug seedlings b. Individual plug seedling

Figure 8 Broccoli plug seedlings for tests pick-up and pushing of the mechanism, respectively. From the seedling pick-up tests, the phenomenon of seedling hanging reduces obviously compared with the original seedling pick-up mechanism. The results of seedling pick-up tests are listed in Table 3.



a. Test bench of seeding pick-up b. The process of seedling pick-up

1. Seedling-feeding device 2. Seedling pick-up mechanism 3. Transmission device

Figure 9 Seedling pick-up tests of the seedling pick-up mechanism

Table 3 Results of seedling pick-up and pushing tests

Mechanism rotation speed/(r·min^{-1})	Total number of seedlings	Number of seedlings successfully extracted	Success ratio of seedling pick-up/%	Number of seedlings successfully pushed	Success ratio of seedling pushing/%
30	104	98	94.2	87	83.7
40	90	86	95.6	76	84.4
50	82	74	90.2	63	76.8

4 Discussion

1) The main parameters of the seedling pick-up mechanism and the trajectory listed in Table 2 show that the seedling pick-up depth increases from 30.4 mm to 35 mm, which is conducive to improve the success ratio of seedling pick-up and prevent the plug seedlings from falling down during the seedling transportation compared with the original mechanism[24]. At the same time, the seedling pushing angle of the mechanism increases from 52° to 55°, which is also conducive to improve the seedling pushing effect. Besides, the seedling pick-up angle of the mechanism is 50.27° with a height of the trajectory of 187.28 mm and a width of the ring of 2.4 mm, almost remained unchanged.

2) The results of the virtual simulation of the mechanism, the motion trajectory shown in Figure 6, the depth of seedling pick-up (35.09 mm) and the seedling pick-up and pushing angles (about 50° and 55°, respectively), are basically consistent with those of theoretical analysis, which verifies correctness of the reverse design model and results of the mechanism.

3) The test trajectory of the seedling pick-up mechanism shown in Figure 7, and the results of seedling pick-up tests which are the success ratios of seedling pick-up (94.2%, 95.6%, and 90.2%, respectively) and the success ratios of seedling pushing (83.7%, 84.4%, and 76.8%, respectively) under the seedling pick-up efficiencies 60, 80, and 100 plants per minute per row, respectively, listed in Table 3, show that the seedling pick-up mechanism proposed in the study and designed by the reverse design method meets the working requirements of seedling pick-up.

5 Conclusions

A new type of seedling pick-up mechanism of planetary gear train with non-circular gears, consisting of three combined non-circular gears, four non-circular gears, one planetary carrier and two seedling pick-up arms, was proposed and designed by using the reverse design method, improving the problems of the original seedling pick-up mechanism. The virtual motion simulation, kinematic test and seedling pick-up tests were conducted in laboratory, verifying the design results and working performance of the mechanism.

1) The local trajectory of seedling pick-up and pushing sections were adjusted to obtain the theoretical motion trajectory with larger seedling pick-up depth and seedling pushing angle, and the adjusted motion trajectory was fitted by using the cubic non-uniform B-spline curve. The reverse design model of the proposed seedling pick-up mechanism of planetary gear train was established and the mechanism parameters were obtained through the design software developed based on Matlab platform. The theoretical results show the mechanism after reverse design realized the adjusted trajectory.

2) The virtual prototype of the seedling pick-up mechanism was established based on UG and ADAMS for carrying out the virtual motion simulation. The trajectory, the depth of seedling pick-up and the seedling pick-up and pushing angles of virtual simulation are basically consistent with those of theoretical analysis, verifying the correctness of reverse design of the mechanism.

3) The physical prototype of the seedling pick-up mechanism was manufactured and test bench was constructed. The motion characteristics and seedling pick-up performance of the mechanism prototype were studied through the high-speed photographic kinematics test and seedling pick-up tests. The test results show the seedling pick-up mechanism after revise design has high application feasibility in the automatic vegetable plug seedling transplanter.

Acknowledgements

The authors acknowledge the editors and the anonymous reviewers whose constructive comments have notably contributed to the improved quality and clarity of this work. This study was financially supported by the National Natural Science Foundation of China (Grant No. 32171899), and the Basic Research Projects of the Wenzhou Science & Technology Bureau (Grant No. N20220001).

[References]

[1] Zhang Z H. The prominent problems and countermeasures in the development of modern vegetable industry in China. Chinese Vegetable, 2014; 8: 1–6. (in Chinese)

[2] Parish R L. Current developments in seeders and transplanters for vegetable crops. Hort Technology, 2005; 15(2): 346–351.

[3] Li B, Gu S, Chu Q, Yang Y L, Xie Z J, Fan K J, et al. Development of transplanting manipulator for hydroponic leafy vegetables. Int J Agric & Biol Eng, 2019; 12(6): 38–44.

[4] Jin X, Cheng Q, Zhao B, Ji J T, Li M Y. Design and test of 2ZYM-2 potted vegetable seedlings transplanting machine. Int J Agric & Biol Eng, 2020; 13(1): 101–110.

[5] Liu N C, Yang C W, Liu B L, Jiang H, Wu S H, Huang H. Development of automatic single pendulum vegetable pot seedling picking and feeding system. Transactions of the CSAE, 2020; 36(22): 87–95. (in Chinese)

[6] Jin X, Ji J T, Liu W X, He Y K, Du X W. Structural optimization of duckbilled transplanter based on dynamic model of pot seedling movement. Transactions of the CSAE, 2018; 34(9): 58–67. (in Chinese)

[7] Shaw L. N. Removing and handling modular vegetable seedlings from nursery trays. Proceedings of Florida State Horticultural Society, 1999; 112: 153–155.

[8] Konosuke Tsuga. Development of fully automatic vegetable transplanter. Japan Agricultural Research Quarterly, 2000; 34(1): 21–28.

[9] Kang T G, Kim S W, Kim Y K, Lee S H, Jun H J, Choi II S, et al. Analysis of pick-up mechanism for automatic transplanter (I). Journal of Agriculture & Life Science, 2017; 51(1): 187–192.

[10] Choi W C, Kim D C, Ryu I H, Kim K U. Development of seedling pick-up device for vegetable transplants. Transaction of ASAE, 2001; 45(1): 13–19.

[11] Zhao Y, Liu X, Xue X L, Zhang W X, Shan Y Y, Zhou M L. Optimal design and experiment of fully-automated potted eggplant seedling

transplanting mechanism. Transactions of the CSAM, 2018; 49(5): 152–160. (in Chinese)

[12] Yin D Q, Wang J Z, Zhou M L, Yang Y C, Wang J W. Optimal design and experiment of vegetable potted seedlings pick-up mechanism for exploring and picking-pushing plugs. Transactions of the CSAM, 2019; 50(10): 64–71. (in Chinese)

[13] Yuan T, Wang D, Wen Y S, Zhu S S, Chen Y, Tan Y Z. Design and experiment of seedlings unloading mechanism based on methods of air-blowing and vibration for vegetable transplanter. Transactions of the CSAM, 2019; 50(10): 80–87. (in Chinese)

[14] Zhao X, Zhang X S, Wu Q P, D L, Chen J. Research and experiment of a novel flower transplanting device using hybrid-driven mechanism. Int J Agric & Biol Eng, 2020; 13(2): 92–100.

[15] Sun L, Shen J H, Zhou Y Z, Ye Z Z, Yu G H, Wu C Y. Design of non-circular gear linkage combination driving type vegetable pot seedling transplanting mechanism. Transactions of the CSAE, 2019; 35(10): 26–33. (in Chinese)

[16] Ye B L, Zeng G J, Deng B, Yang C L, Liu J K, Yu G H. Design and tests of a rotary plug seedling pick-up mechanism for vegetable automatic transplanter. Int J Agric & Biol Eng, 2020; 13(3): 70–78.

[17] Ye B L, Yi W M, Yu G H, Gao Y, Zhao X. Optimization design and test of rice plug seedling transplanting mechanism of planetary gear train with incomplete eccentric circular gear and non-circular gears. Int J Agric & Biol Eng, 2017; 10(6): 43–55.

[18] Yu Y X, Liu J K, Ye B L, Yu G H, Jin X J, Sun L, et al. Design and experimental research on seedling pick-up mechanism of planetary gear train with combined non-circular gear transmission. Chinese Journal of Mechanical Engineering, 2019; 32(3): 42–54. (in Chinese)

[19] Ye B L, Zeng G J, Deng B, Yang C L, Liu J K, Yu G H. Design and tests of a rotary plug seedling pick-up mechanism for vegetable automatic transplanter. Int J Agric & Biol Eng, 2020; 13(3): 70–78.

[20] Wu G H. Optimization design and test on rice pot-seedling transplanting mechanism with non-circular planetary gears. Hangzhou: Thesis of Zhejiang Sci-Tech University, 2016; 15p.

[21] Wang L, Sun L, Huang H M, Yu Y X, Yu G H. Design of clamping-pot-type planetary gear train transplanting mechanism for rice wide–narrow-row planting. Int J Agric & Biol Eng, 2021; 14(2): 62–71.

[22] Wang L, Sun L, Xu Y D, Yu G H, Zhang W, Zheng J. Design method of transplanting mechanism of planetary gear train based on spatial trajectory. Transactions of the CSAM, 2021; 52(7): 51–59.

[23] Li G, Ying K Y, Zhang J Z, Li J F, Yu G H, Ye Y S, et al. Computation method of non-circular gear based on seedling needle tip point's static trajectory in transplanting mechanism. Chinese Journal of Mechanical Engineering, 2016; 52(1): 64–71. (in Chinese)

[24] Li H, Chen B B, Cao W B, Ma X X, Zhao H Z. Reverse design and analysis of automatic pick-up mechanism for tomato plug seedlings. International Agricultural Engineering Journal, 2017; 26(1): 126–134.

[25] Wu G H, Yu G H, Zhou H L, Ge Y J, Ye A K, Wang L. Reverse design and tests of three-arms rotary rice seedling transplanting mechanism. Transactions of the CSAE, 2022; 53(7): 84–91,149. (in Chinese)

[26] Wu G H, Yu G H, Ye B L, et al. Forward-reverse design method for rice potted-seedling transplanting mechanism with compound planetary gear train. Transactions of the CSAE, 2020; 51(2): 85–93,102. (in Chinese)