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DESIGN AND EXPERIMENTS FOR SHOVEL-FINGER AND CYLINDER PEANUT-PICKING DEVICE

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KEYWORDS

peanut plant, shovel finger, picking mechanism, optimization design.

ABSTRACT

Two-stage harvesting is the main method for performing the mechanized harvesting of peanuts, and the picking device is a core part of the combined harvester in China. In order to solve the problem of pod loss caused by the "stacking", "impact" and "throwing up" of peanut plants by a traditional cam-slide spring-finger cylinder picking device, the shovel-finger and cylinder peanut-picking device was developed and used in a picking-up performance test based on the study of peanut-plant strip-picking characteristics. The mathematical model of the mechanism was established by analyzing the structure of the mechanism and the peanut-plant strip-picking characteristics, and the parameters of the mechanism were optimized using the objective function method. The prototype was developed and tested. The experiments in which the prototype was used to collect peanut plants indicated that the phenomenon of peanut plants being stacked and thrown disappeared. Through a response surface analysis and prototype test, the optimal working parameters of the picking device were obtained: the forward speed *V* was 48.0 m/minute, the rotational speed *N* was 45.3 r/minute and the ground height *H* was -18 mm. The peanut-plant picking rate was 98.9% and the fruit loss rate was 2.8% under two different harvesting conditions for which the peanut-plant moisture content was 15~17%.

INTRODUCTION

China's perennial peanut planting area is about 4.7 million ha, with a total output of more than 17 million tons, accounting for about 38% of the world's peanut production; the peanut is also one of the most internationally competitive agricultural products (National Agricultural Statistics Service, 2016; Gao et al., 2017). However, the mechanization rate of peanut harvesting in China is not high, and the pod loss and damage caused by the machine harvesting of peanuts are quite serious, which reduces the profitability, food safety and international competitiveness of peanuts; it has become a bottleneck problem that urgently needs to be solved (Afshin et al., 2014a; Chen et al., 2017). A comprehensive analysis found that the most widely used peanut-picking machine in China mainly uses a toothed-belt pickup device and a cam-slide spring-finger cylinder pickup device ("spring-finger cylinder pickup" device for short). Fingered toothed-belt pick-up devices are generally used in small peanut-picking machines with two ridges. because of their structure and speed limitations (Afshin et al., 2014b; Guan et al., 2014; Lu et al., 2019 a). The spring-finger cylinder pickup device has the advantages of a small size, a high speed, a wide picking operation, a good pick-up performance, strong adaptability and other advantages for cereal plants. However, the device has poor adaptability to the vertical peanut plant; in the process of picking up the peanuts, some problems can occur, including plant accumulation and throwing, plant leakage, pod loss, pod damage due to cracking and flying dust created by the spring finger, and the wear on the cam slide and movement impacts are serious (Johnson et al., 2015).

The American peanut plant is a creeping plant, and the side branches of this plant can form good-quality plant

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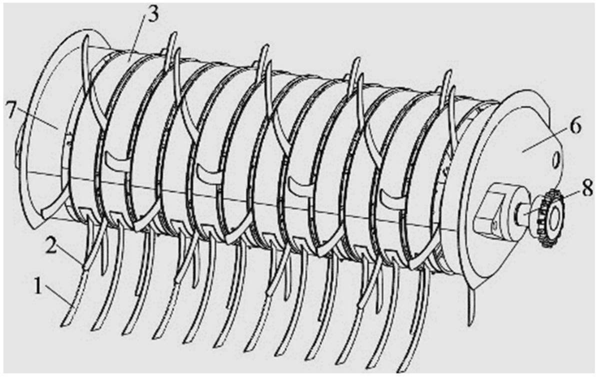
windrow; large harvesters generally use the spring-finger picking device to harvest this plant. In contrast, the vertical peanut plant in China is not of high quality, and the adaptability of the picking device of currently used peanut-harvesting machines is poor.

In China, research on spring-finger cylinder picking devices for rice and wheat has been ongoing for some time, and fruitful research results have been obtained. For example, Sheng & Zeng (1991) established a mathematical model of the spring-finger cylinder pick-up mechanism. Wang et al. (2014) used the B-spline curve in the ADAMS software to optimize and fit the curve of the cam slide. Yuan et al. (2011) designed the center line of the cam slide with an analytical method. Wang & Wang (2012) and Yu et al. (2017) optimized the center line of the cam slide using the law of sinusoidal acceleration motion and conducted an experimental study on the picking performance, combined with a picking test bench. On this basis, Xu et al. (2016) used the non-dominated sorting genetic algorithm II (NSGA-Ⅱ) to optimize the parameters of the spring-finger cylinder peanut pick-up mechanism. Yao et al. (2017) and Wang et al. (2020) used the Box-Behnken center combination test method to carry out experimental research on the spring-finger peanut pick-up device. Xu et al. (2021) established the mathematical model of the missing area of the picking device and optimized the movement parameters of the whole machine. Wang et al. (2019 a) designed a non-slide spring-finger peanut pick-up device with a "convex" guard plate. Chen et al. (2020) developed a non-slide spring-finger peanut-picking device suitable for harvesting after peanut cutting. However, the above studies mainly focus on the cam-slide spring-finger picking device, and this device has some shortcomings, such as a relatively large drum diameter, a limited collection width and the cylinder impact on the slide. The non-slide cylinder pick-up device is still in the experimental stage, and its ability to pick up sparse strips is poor. According to analysis, the spring finger cannot exert an effective upward force on the peanut plants during the picking operation, which is the main reason for the formation of a "stack."

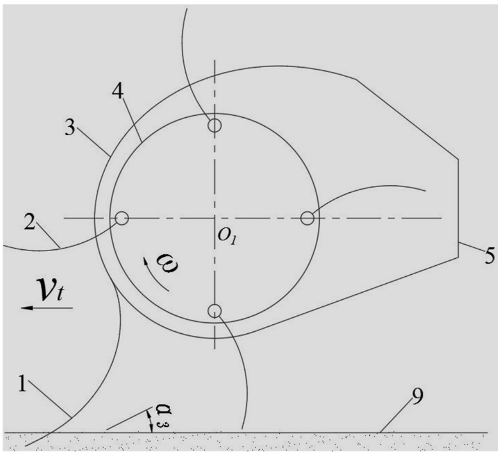
Considering the agronomic characteristics of peanut paving and airing, a new type of shovel-finger and cylinder peanut-picking device that uses dynamic and static fingers to perform peanut-picking is designed; the static finger will scoop up the peanut plant to a certain vertical height, and subsequently the dynamic finger will complete the picking action. NSGA-II is used to optimize the parameters of the multi-mechanism device. It does not use a slide design, and compared to currently used peanut-picking devices, the diameter of the guard plate is smaller and the device's applicability to the vertical peanut plant is stronger; this design can be used as a reference for the design of the medium and large two-stage pick-up harvesters.

Overall structure and working principle

As shown in Figure 1, the shovel-finger cylinder pick-up device is composed of the shovel finger, guard plate, pick-up finger, pick-up-finger seat, rear-side plate, left-side plate, right-side plate and spindle. The pick-up finger is elastically hinged on the pick-up-finger seat, the pick-up-finger seat is fixed on the spindle, the spindle is installed through the bearing on the left- and right-side plates, the left- and right-side plates are fixed between the adjacent pick-up finger and the rear plate, and the shovel finger is installed in front of the guard plate. During the picking operation, the picking device moves forward with the unit, and the shovel finger shovels the peanut plants up to 20~50 mm; then, the pick-up finger completes the picking, lifting and pushing actions in turn. The pick-up finger and spindle rotate together while the unit moves forward; therefore, the pick-up finger performs the pick-up movement using the spindle rotation speed ω and unit forward speed v_t.



a. Schematic diagram of the structure of the picking device



b. Schematic diagram of the pick-up device

1. Shovel finger. 2. Pick-up finger. 3. Guard plate. 4. Pick-up-finger seat. 5. Rear-side plate. 6. Left-side plate. 7. Right-side plate. 8. Spindle. 9. The Earth's surface.

FIGURE 1. Diagram of the structure of the picking device.

Unlike the traditional slide-type spring-finger cylinder pick-up mechanism, the combined shovel toothed cylinder peanut-pick-up device has no slide design; the spring finger was connected to the cylinder, and the relatively movable components such as the crank, roller and slide were removed; the pick-up device was simplified in terms of the working principle and structure.

During the picking process, the spring-finger shaft rotates with the cylinder without relative swing, thus reducing the stiffness requirement of the spring-finger shaft, avoiding an increase in the relative torsion angle of the spring-finger shaft due to the increase in the axial length of the pick-up device, and thus the problem that the spring-finger irregularly swing is solved. Therefore, this device can be used in medium and large two-stage peanut-pick-up harvesters.

Unlike the cam-slide spring-finger cylinder picking mechanism, in the no-slide design, the pick-up finger and pick-up-finger seat are able to swing in a small range. The front end of the guard plate is equipped with shovel fingers to complete the picking-up action, together with the pick-up fingers. By changing the installation angle of the picker and the curvature of the working surface of the curved guard plate, the problems of the clamping of the picker at the end of the pushing stage and the guard plate impacting the peanut plants were solved. The main features of the device are the following:

(1) The shovel finger moves forward with the unit, end of which into the soil 10~20 mm; peanut plants are moved by inertial forces and plant interforce due to the upward movement of the shovel-finger work surface, and this is taken into account so that the picking is performed more smoothly.

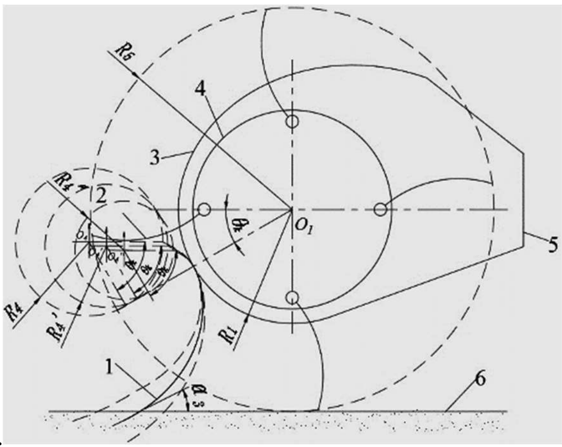
(2) The pick-up finger is not in the soil during the operation to avoid deformation in the deep soil, which can affect the pick-up finger's instantaneous pendulum, causing pod loss.

(3) The pick-up finger does not hit soil; this can reduce the pick-up load, avoid permanent deformation and damage caused when the pick-up finger encounters hard objects and effectively reduce air pollution caused by dust.

Design of key components of pickup device

Shovel finger design

As shown in Figure 2, in order to ensure that peanut plants move more fluidly on the shovel finger, the curvature of the working surface of the shovel finger should gradually decrease from large to small, and the working surface of the shovel finger should be designed as an involute curve. The shovel finger is fixed on the guard plate. At the tangent point between the shovel finger and the guard plate, the occurrence line at the involute spread angle θ_k of the shovel finger is collinear with the radius R_1 of the guard plate, that is, the angle between the radius at the tangent point of the guard plate and the horizontal line is θ_k, which gives the arch structure of the guard plate better compressive resistance. According to the analysis, the base circle radius R_4 of the working arc surface of the shovel finger is affected by the position of the cutter between the shovel finger and the guard plate, the rotation track R_5 of the pick-up finger end, the insertion angle α_3 of the shovel finger, etc. Therefore, the parameters of the shovel-finger mechanism can be determined based on the parameters of the key components of the picking device.



1. Shovel finger. 2. Pick-up finger. 3. Cylinder guard plate. 4. Pick-up-finger seat. 5. Rear-side plate. 6. The Earth's surface.

FIGURE 2. Shovel-finger structure diagram.

In order to make the peanut plant slide up smoothly along the shovel finger, a stress analysis of the plant during the sliding process was carried out. As shown in Figure 3, the left-direction velocity of the shovel finger is v_t, and the peanut plant is considered to be a particle m. The initial velocity of the peanut plant is $v_0 = 0$, and its velocity is $v_1 = v_t$ when it moves with the shovel finger. The force exerted by the shovel finger on the peanut plant is F, and F is decomposed into a horizontal component F_x and a vertical component F_y. According to the law of conservation of kinetic energy, the work done by the horizontal component F_x is equal to the increase in the kinetic energy of the plant:

$$F_x s' = \frac{1}{2} m v_1^2 - \frac{1}{2} m v_0^2, \tag{1}$$

$$F_x = \frac{1}{2} m v_1^2 / s'. \tag{2}$$

When the vertical component is equal to the weight of the plant, the plant stops moving up the shovel finger. The trigonometric relationship between the horizontal component F_x and the vertical component F_y can be written as follows:

$$F_y = F_x \tan\alpha_3 = mg, \tag{3}$$

$$\alpha_3 = \arctan(v_1^2 / 2gs'), \tag{4}$$

Where:

F = the force of the shovel finger on the peanut plant (N);

F_x = the horizontal component of the force on the plant (N);

F_y = the vertical component of the force on the plant (N);

v_1 = the horizontal velocity of the plant under the stress balance (m/s);

v_0 = the initial horizontal velocity of the plant (m/s);

α_3 = the shovel finger insertion angle (rad);

s' = the horizontal distance that the plant moves when the force is balanced (m);

s = the horizontal distance between two adjacent plants (m);

m = the weight per plant (kg), and

g = the acceleration due to gravity (m/s^2).

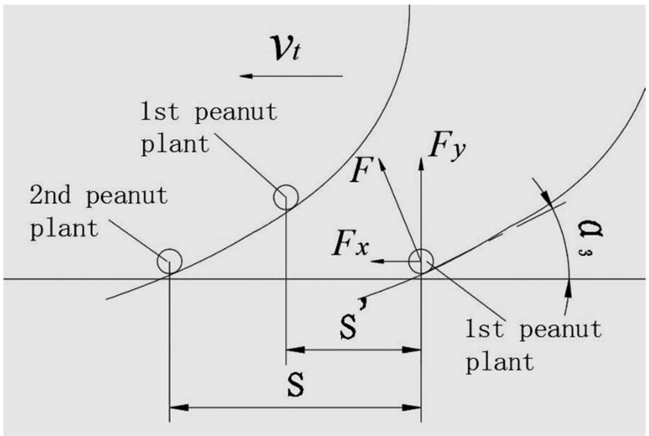
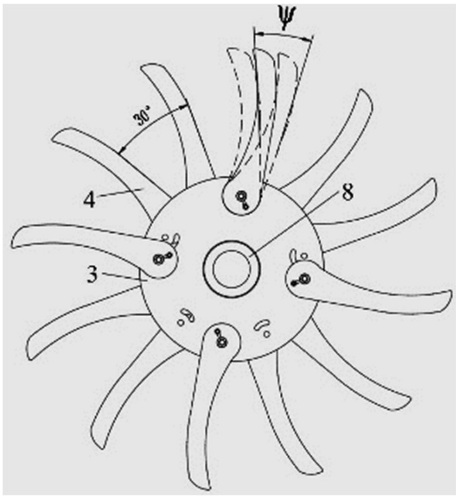


FIGURE 3. Stress analysis of a peanut plant

Based on the operation speed of the existing two-stage peanut combined harvester, v_t = 1.07m/s, and the average mass of a vine pod *m* is 0.8–1.2 kg. The variable *s* represents the horizontal distance between adjacent peanut plants; *s* is equal to 0.01–0.15 m. In order to avoid affecting the upward movement of subsequent peanut plants along the shovel finger, *s′* should be equal to 0.05–0.08 m. According to Equation (4), the limit value of the shovel finger's angle α_3 is 0.628–0.872 rad, so if the shovel finger's angle $\alpha_3 < 0.628$ rad, peanut plants can move upward along the shovel finger. Considering the structural characteristics and resistance of the shovel finger, the angle α_3 of the shovel finger was determined to be 0.349~0.610 rad, and the depth h_2 was determined to be 10~20 mm.

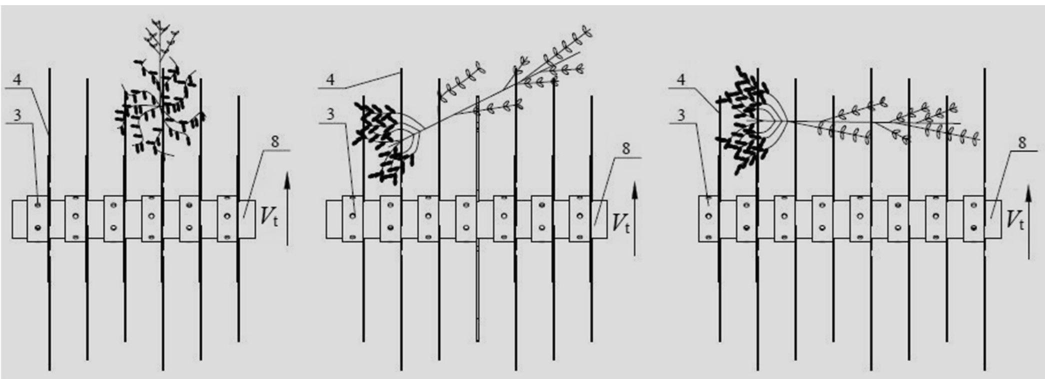
Finger cylinder design

As shown in Figure 4, the working face of the pick-up finger is an arc structure with a thickness of 3 mm; this structure can increase the friction force and centripetal force of the pick-up finger on peanut plants. The pick-up finger is elastically hinged on the finger seat, relative to the hinged rotation angle ψ, to keep the pick-up finger from encountering hard objects and being damaged. At the same time, because the height of upright peanut plants in China is 350~450 mm, the axial spacing of adjacent pick-up fingers is 50 mm; adjacent pick-up fingers are separated by 30° and are fixed in the spindle, and there is a circumferential formation of 12 rows of pick-up fingers to reduce the rotational speed of the cylinder, improve the efficiency of plant pick-up and reduce the size of the plant area that is missed. Through experimental observation, during the picking operation, the plant can generally experience three kinds of operation states: horizontal pick up, oblique pick up and vertical pick up (Figure 5). When the thickness of the peanut strip is larger, mostly horizontal pick up is observed, and the same row of 2~3 pick-up fingers make contact with the peanut plants. When the thickness of the peanut strip is relatively large, in order to pick up a peanut strip that is slanted and vertical, 2~3 pick-up fingers from the next row make contact with the plant, and the pick-up finger is inserted into the collateral plant to complete the pick-up operation.



3. Pick-up-finger seat. 4. Pick-up finger. 8. Spindle.

FIGURE 4. Diagram of the structure of the pick-up-finger seat.



a. Vertical pick up. b. Inclined pick up. c. Horizontal pick up.

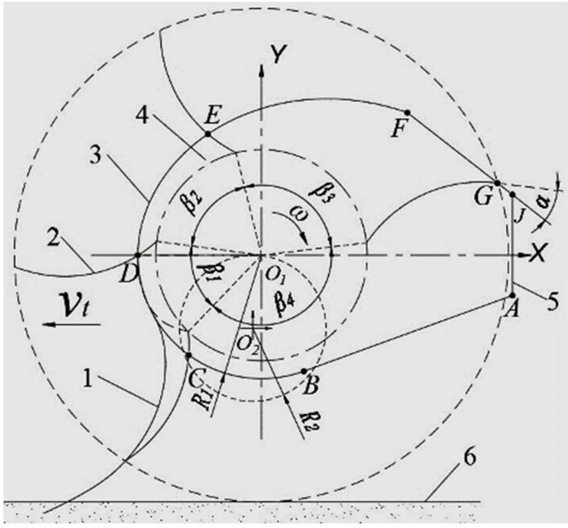
3. Pick-up-finger seat. 4. Pick-up finger. 8. Spindle.

FIGURE 5. Schematics of the three operation states of the picking mechanism.

Cylinder guard plate design

Based on the functions of the pick-up finger, that is, pick-up, lifting, pushing and emptying, the cylinder guard plate's working surface is designed as an irregular surface. Based on the working section and the rotation of the pick-up spring finger, the translation of the machine cooperates with the pick-up fingers to complete the picking operation, and it is divided into four parts of an eccentric irregular curve that correspond to pick-up (β_1), lifting (β_2), pushing (β_3) and emptying (β_4) stations (Figure 6); in Figure 6, *C*, *D*, *E* and *G* indicate the pick-up finger's location at various points in each position, and this figure shows a projection of its intersection with the guard:

(1) Collecting station (pick-up-finger phase angle β_1): In this stage, the pick-up finger, due to the spindle rotation, gradually becomes level; the pick-up finger comes out of the guard board with a maximum length L_1, $\overset{\frown}{CD}$ is the guard arc segment, O_1 is the center of the circle and R_1 is the radius of the circular arc. The clockwise rotation of the pick-up finger causes it to become level, pick-up finger with sheeting section intersection for D.



1. Shovel finger. 2. Pick-up finger. 3. Cylinder guard plate. 4. Pick-up-finger seat. 5. Rear-side plate. 6. The Earth's surface.

FIGURE 6. Finger phase diagram of the picking mechanism.

(2) Lifting station (pick-up-finger phase angle β_2) and pushing station (pick-up-finger phase angle β_3): To avoid the clamping of the pick-up finger and guard plate on the peanut plant at the end of the pushing station, the length of the pick-up finger out of the guard board should be reduced gradually. The lifting and pushing plate has an involute curve design, and at the same time, it is ensured that the pick-up finger in the emptying station has enough space for rotation; the end of the guard plate has a straight-line-segment design. In Figure 6, O_2 and R_2 represent the center of the circle and the radius of the base circle, respectively, $\overset{\frown}{DE}$ is the involute arc segment, *D* is the point of tangency with the circular arc $\overset{\frown}{CD}$. When the front surface of the pick-up finger is vertical, point *E* represents the intersection of the pick-up finger and the guard plate; the corresponding rotary phase angle is β_2. The pick-up finger moves completely into the guard board, and the pick-up finger and guard board intersect at point G, corresponding to the rotation phase angle β_3.

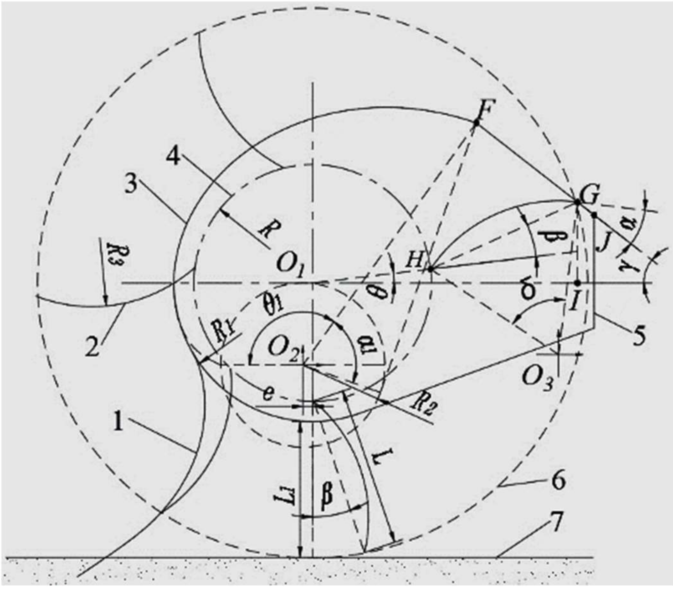
(3) Emptying station (pick-up-finger phase angle β_4): In Figure 6, the corresponding guard plate is denoted by the straight-line segments *GJ*, *AB* and *JA* and the arc segment $\overset{\frown}{BC}$. O_1 is the center of the circle and R_1 is the radius of the circular arc. The design ensures that the pick-up finger in the emptying station has enough rotation space to prepare for the pick-up location.

Optimization of parameters of picking device

According to the analysis, the parameters of the mechanism are coupled, so the overall optimization of the mechanism cannot be achieved by changing a single parameter. Here, the objective function method is used to establish the mathematical model of the mechanism and solve for the parameters of the mechanism to achieve the purpose of mechanism optimization and realize the parametric design.

Determination of optimization variables

As shown in Figure 7, through the index analysis of the design of the picking device and the relationships between component parameters, the pick-up finger installation angle β, pick-up-finger arc radius R_3, pressure angle α_1 at point *F* of the involute section of the guard plate, pick-up-finger radius *R*, guard line segment *FG*, horizontal angle γ and the base circle deviation *e* of the involute section of the guard plate are selected as optimization variables: $x = (\beta, R_3, \alpha_1, R, \gamma, e)$.



1. Shovel finger. 2. Pick-up finger. 3. Cylinder guard plate. 4. Pick-up-finger seat. 5. Rear-side plate. 6. The Earth's surface.

FIGURE 7. Parameter analysis diagram of the picking mechanism.

Determination of objective function

(1) The maximum length of the pick-up finger out of the guard plate (L_1) is taken as a constant value. The greater the corresponding central angle δ, the smaller the radius of gyration; the greater the curve, the greater the centripetal force on the peanut plant, which is beneficial for picking up the plant, allowing the mechanism to effectively avoid the problem of the peanut plant moving "up" at the lifting station. As a result, determining the pick-up-finger arc's central angle δ is the optimization goal, and objective function $f_1(x)$ is established for this purpose.

There should be a gap of 20 mm between the pick-up-finger seat and the cylinder guard plate. According to the geometric relationships between the component parameters shown in Figure 7,

$$L = (L_1 + 20) / \cos\beta , \tag{5}$$

$$L = 2R_3 \sin\left(\frac{\delta}{2}\right), \tag{6}$$

$$\delta = 2\arcsin\left(\frac{L_1 + 20 / \cos\beta}{2R_3}\right), \tag{7}$$

$$\min f_1(x) = \frac{1}{\delta} . \tag{8}$$

(2) When it is picking up peanuts, the speed of the end line of the pick-up finger has a direct influence on the peanut plants and the centrifugal force of inertia. Therefore, the cylinder rotation speed is unchanged; the smaller the end rotation radius of the pick-up finger, the smaller the speed of the finger end line, the smaller the area of the peanut plant that is hit and the smaller the generated centrifugal inertia force. In addition, when the radius defined by the pick-up finger end is smaller, the radius of the guard plate can also be reduced, which can reduce the pick-up height of peanut plants. Therefore, the pick-up finger pick-up length of L_1 is unchanged; the smaller the radius of the guard plate R_1, the smaller the radius defined by the finger end. Therefore, the radius of the guard plate R_1 is taken as the optimization objective to establish the following objective function:

$$\min f_2(x) = R + 20 . \tag{9}$$

Constraints

(1) According to a previous field investigation, the thickness of the peanut-plant strip was set to 100~130 mm, and the shovel fingers were made to reach a depth of 10~20 mm in the ground. Considering the range of the rotation path between the shovel finger and the pick-up finger, the maximum radial distance L_1 of the pick-up finger past the guard plate was used to create the following constraint:

$$100 \le L_1 . \tag{10}$$

(2) To avoid the clamping of the pick-up finger and cylinder guard plate on the peanut plants at the pushing station, another inequality constraint was introduced:

$$\alpha_{min} < \alpha , \tag{11}$$

Where:

α = the angle between the pick-up finger and the upper guard plate at the end of the pushing station, and

α_{min} = the clamping angle of the pick-up finger on the peanut plants (0.87 rad).

For the pick-up finger at the end of the pick-up station, the acute angle between the tangential direction of the finger end and the straight section of the guard plate (α) can be determined based on the geometric relationship between the pick-up finger and cylinder guard plate:

$$\angle FGH = \pi - (\frac{\pi}{2} - \theta - \beta) - (\frac{\pi}{2} - \gamma) = \theta + \beta + \gamma, \quad (12)$$

$$\angle O_3GH = \frac{\pi}{2} - \frac{\delta}{2}, \quad (13)$$

$$\angle O_3GJ = \pi - \angle FGH - \angle O_3GH, \quad (14)$$

$$\alpha = \frac{\pi}{2} - \angle O_3GJ = \theta + \beta + \gamma - \frac{\delta}{2}, \quad (15)$$

Where:

β = the pick-up-finger installation angle (0~0.70 rad);

R_3 = the pick-up-finger working-surface arc radius (100~175 mm);

α_1 = the pressure angle at point F of the involute segment of the guard plate (1.31–1.40 rad);

R = the radius of the pick-up-finger seat (100~150 mm);

γ = the angle between line section FG of the guard plate (pushing station) and the horizontal surface (0.08~0.70 rad);

e = the base circle deviation of the involute section of the guard plate (0~10 mm);

L_1 = the maximum extension length of the pick-up finger out of the guard plate (100 mm), and

θ = the angle between the line from the pick-up-finger hinge point with the main axis and the X axis at the end of the pushing station.

Optimization method and analysis of results

This problem is a multi-objective function optimization problem, and the non-dominated sorting genetic algorithm II (NSGA-II) compiled in the C language is used for multi-objective optimization. The initial population is set to 50, the number of generations is set to 500 generations, the crossover factor is 0.8, the crossover distribution index is 20 and the variation distribution index is 20. Through NSGA-II iterations, 100 sets of parameters of feasible multi-objective Pareto-optimal solutions were obtained, and 20 sets of solutions were selected (Table 1).

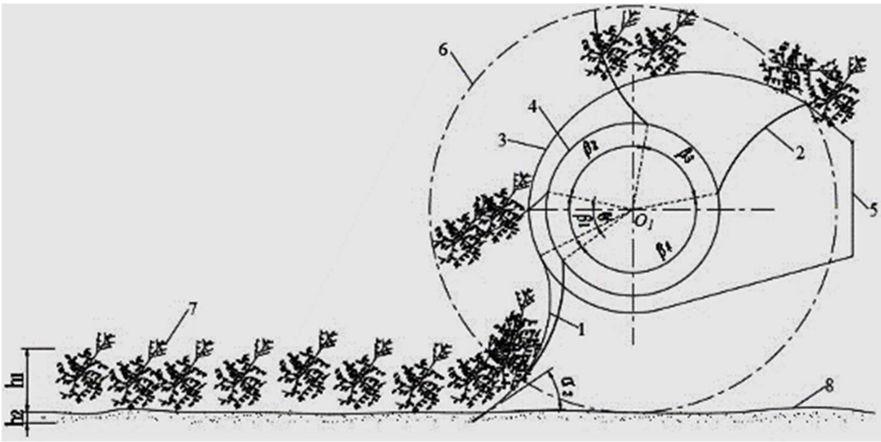
As shown in Table 1, after 500 generations of evolution for the mechanism parameters, there is no change in the installation angle β of the pick-up finger, the arc radius of the pick-up-finger working surface R_3, the radius of the pick-up-finger seat R, the angle γ between the line segment FG of the guard plate (pushing station) and the horizontal surface and the objective functions f_1(x) and f_2(x).The pressure angle α_1 at point F of the involute section of the guard plate and the base circle deviation e of the involute section of the guard plate vary slightly, but this has little influence on the objective function. After the optimization of the base circle deviation e of the involute section of the guard plate, most of the values are concentrated between 3.0 and 4.0, and the eleventh group of values are selected as the picking mechanism parameters.

The two objective function values were concentrated around 0.895 rad and 120 mm, respectively, and they did not change with changes in the mechanism parameters e and α_1. According to the variation rules of the mechanism parameters and objective functions shown in Table 1, the optimized mechanism parameter solution set was close to the optimal solution, and the optimized results were reasonable.

TABLE 1. Multi-objective optimization set.

No.	Installation angle of pick-up finger β (rad)	Arc radius of pick-up-finger working surface R_3 (mm)	Pressure angle at point F of involute section of guard plate α_1 (rad)	Radius of pick-up-finger seat R (mm)	Angle between line segment FG of guard plate (pushing) and horizontal surface γ (rad)	Base circle deviation of involute section of guard plate e (mm)	f_1（x）(rad)	f_2（x）(mm)
1	0.604	175.000	1.309	100.000	0.698	0.754	0.859	120.000
2	0.604	175.000	1.309	100.000	0.698	1.027	0.859	120.000
3	0.604	175.000	1.309	100.000	0.698	2.173	0.859	120.000
4	0.604	175.000	1.309	100.000	0.698	2.724	0.859	120.000
5	0.604	175.000	1.342	100.000	0.698	3.018	0.859	120.000
6	0.604	175.000	1.309	100.000	0.698	3.140	0.859	120.000
7	0.604	175.000	1.637	100.000	0.698	3.263	0.859	120.000
8	0.604	175.000	1.309	100.000	0.698	3.279	0.859	120.000
9	0.604	175.000	1.309	100.000	0.698	3.310	0.859	120.000
10	0.604	175.000	1.309	100.000	0.698	3.503	0.859	120.000
11	0.604	175.000	1.309	100.000	0.698	3.538	0.859	120.000
12	0.604	175.000	1.367	100.000	0.698	3.820	0.859	120.000
13	0.604	175.000	1.319	100.000	0.698	4.489	0.859	120.000
14	0.604	175.000	1.309	100.000	0.698	4.744	0.859	120.000
15	0.604	175.000	1.309	100.000	0.698	5.030	0.859	120.000

As shown in Figure 8, the main mechanism parameters of the shovel finger are determined according to the optimized maximum radial distance L_1 of the pick-up finger past the guard plate; the thickness h_1 of the peanut strip is 100–150 mm, the depth h_2 that the shovel finger is inserted into the soil is 10–20 mm, and the angle α_3 at which the shovel finger is inserted into the soil is 0.349–0.610 rad. After optimization, the parameters of the combined peanut-picking mechanism with a shovel finger and cylinder are rounded, as shown in Table 2.



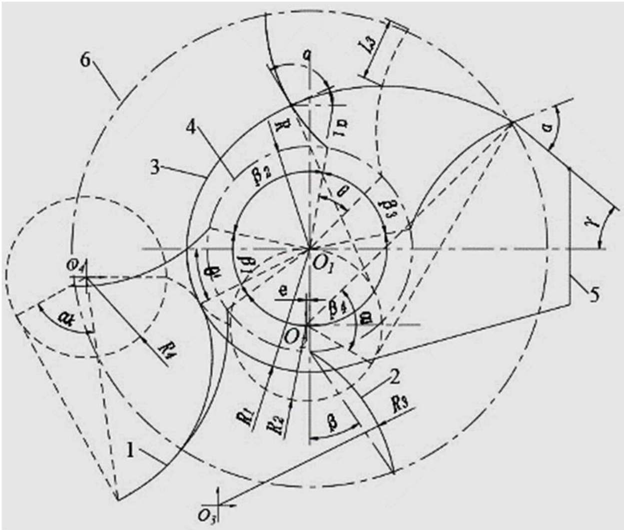
1. Shovel finger. 2. Pick-up finger. 3. Cylinder guard plate. 4. Pick-up-finger seat. 5. Rear-side plate. 6. Finger-end trajectory. 7. Peanut strip spread. 8. The Earth's surface.

FIGURE 8. Parameter analysis diagram for the shovel finger.

TABLE 2. Picking mechanism parameter optimization.

Parameter	Value
Installation angle of pick-up finger β (rad)	0.60
Arc radius of pick-up-finger working surface R_3 (mm)	175.00
Pick-up-finger-arc central angle δ (rad)	0.86
Pressure angle at point F of involute section of guard plate α_1 (rad)	1.31
Radius of pick-up-finger seat R (mm)	100.00
Radius of guard plate R_1 (mm)	120.00
Angle between line segment FG of guard plate (pushing) and horizontal surface γ (rad)	0.70
Base circle deviation of involute section of guard plate e (mm)	3.54
Base circle radius of shovel finger R_4 (mm)	78.20
Installation angle of shovel finger θ' (rad)	0.53
End pressure angle of shovel finger α_k (rad)	1.21
Penetration angle of shovel finger α_3 (rad)	0.51

The movement diagram of the optimized pick-up mechanism was established according to the optimized mechanism parameters (Figure 9); the corresponding center angle β_3 of the pushing station was 68.7°. Figure 10 shows the relationship between the working angle α between the pick-up finger and guard plate and the angle θ of the pick-up finger at the pushing station (Lim et al., 2016). It can be seen that as the angle θ gradually increased, the angle α gradually decreased. When the pushing station ends, α is 56.8°, which is larger than the clamping angle of the pick-up finger and the guard plate on peanut plants.



1. Shovel finger. 2. Pick-up finger. 3. Cylinder guard plate. 4. Pick-up-finger seat. 5. Rear-side plate. 6. Finger-end trajectory.

FIGURE 9. Diagram of the optimized picking mechanism.

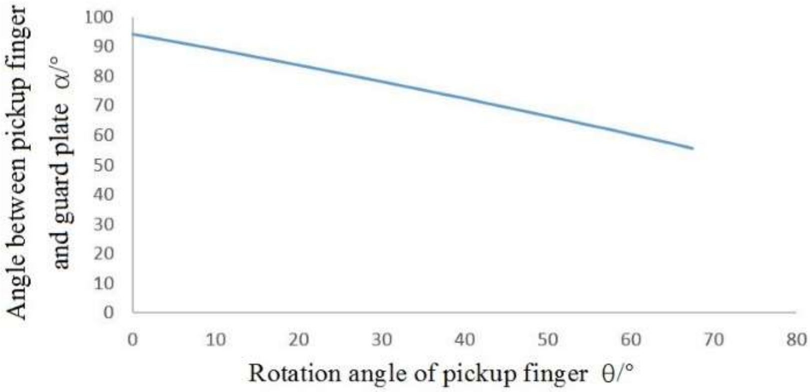


FIGURE 10. α parametric curve.

Figure 11 shows the change in the length L_3 of the pick-up finger extending past the guard plate at the pushing station. As the pick-up-finger angle θ gradually increases, L_3 gradually decreases. When θ = 68.7°, L_3 becomes 0, and the pick-up finger is completely retracted into the cylinder guard plate. Figure 12 shows the change in the angle α_1 between the tangent line and the horizontal direction of the intersection point of the pick-up finger on the projection surface of the guard plate. As the pick-up-finger angle θ gradually increases, α_1 gradually decreases. When the pick-up-finger angle θ = 34.9°, α_1 becomes negative. When θ was 0°~34.9°, the pick-up finger pushed peanut plants backwards and upward; the L_3 range was 61.2~94.4 mm, and the α range was 74.5°~94.1°. Therefore, when θ was 0°~-34.9 °, the pick-up finger could push peanut plants backwards, and there was no clamping problem. When θ ranged from 34.9° to 68.7°, L_3 gradually decreased to 0, and α_1 was negative. The downward tilt of the guard plate, continuous pushing of the pick-up finger and subsequent squeezing effect caused the peanut plants to continue to move downward.

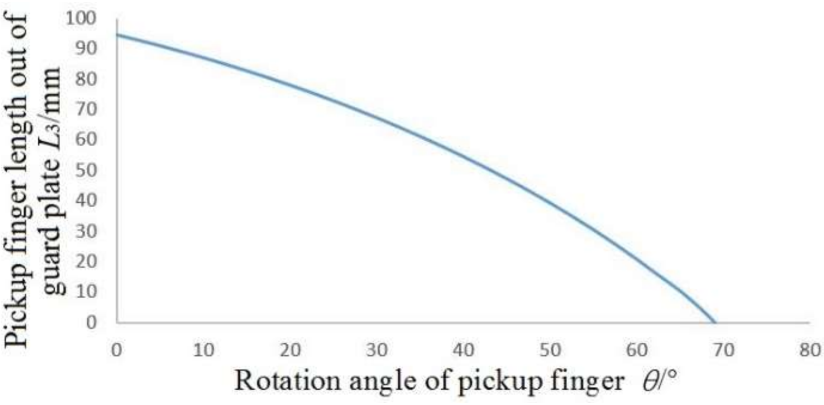


FIGURE 11. L_3 parametric curve.

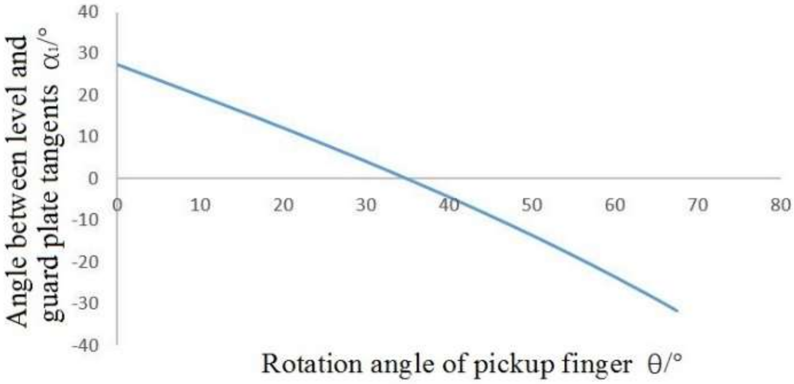
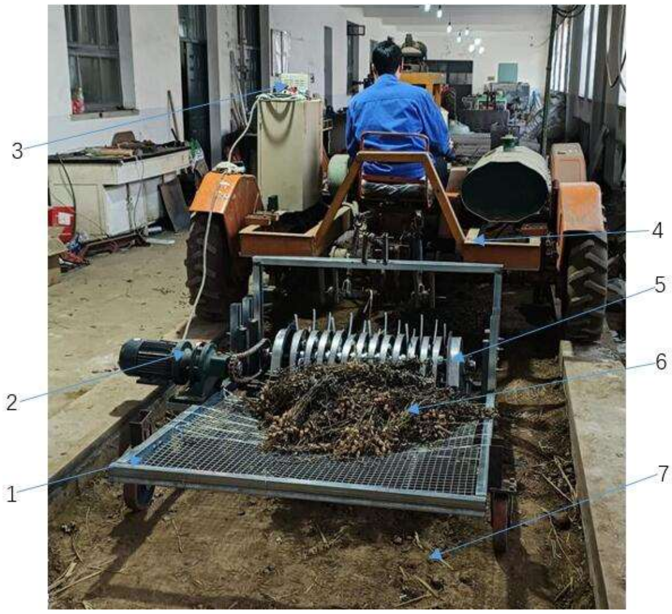


FIGURE 12. α_1 parametric curve.

Pick-up device performance test

According to the above theoretical analysis and optimization design results, a prototype of the peanut-picking device with a shovel finger and cylinder was designed and manufactured. Preliminary tests were carried out in the Soil Trough Laboratory of the College of Engineering at Shenyang Agricultural University (Figure 13).



1. Rack. 2. Motor. 3. Frequency converter. 4. Soil tanker. 5. Pick-up device. 6. Peanut plant. 7. Soil trough.

FIGURE 13. Picking test device.

The experimental material was Huayu 30, the main cultivated peanut variety in Liaoning Province; the moisture content of the straw was 15–17%, the pod was oriented on one side of two ridges and one spread, and the peanut strip was 20 m in length in each experiment (Guan et al., 2015 a; Lu et al., 2019 b). The main test is the adjustment of the forward speed of the soil tanker from 10 to 100 m/minute. The picking device is powered by a 1.1 kW motor, and the speed is adjusted by a frequency converter. Other test instruments and tools include the RM722 laser tachometer, electronic stopwatch, meter stick and scale (Gao et al., 2015; Guan *et al.*, 2015 b; Guo et al., 2021).

By referring to the relevant standards, the pick-up rate and loss rate were chosen as the main test indicators (Xu, 2016). According to a combination of response surface analysis (RSM) and the Box-Behnken design (BBD), the forward speed of the unit V, the rotary speed of the cylinder N and the depth of the shovel end H were selected as test factors, and a three-factor and three-level test design was carried out (Table 3), with 17 groups in total and each group repeated three times. The test protocol and results are shown in Table 4. X_1, X_2 and X_3 are factor coding values (Xu et al., 2016; Lu et al., 2019 c).

TABLE 3. Experiment factors and levels of response surface analysis.

Horizontal	Unit forward speed X_1 (m/min)	Cylinder rotary speed X_2 (r/min)	Depth of shovel end X_3 (mm)
-1	35	40	-30
0	45	50	-15
1	55	60	0

A total of 17 groups of tests were carried out, and each group was repeated three times to determine the average value (Yao, 2017). The test results for the pick-up rate and loss rate are shown in Table 4.

TABLE 4. Experiment factors and results of response surface method.

No.	X_1	X_2	X_3	Pick-up rate (%)	Loss rate (%)
1	-1	-1	0	98.6	2.4
2	1	-1	0	98.2	3.3
3	-1	1	0	98.4	3.5
4	1	1	0	97.4	3.9
5	-1	0	-1	99.4	2.4
6	1	0	-1	99.2	2.5
7	-1	0	1	97.8	3.4
8	1	0	1	97.0	4.7
9	0	-1	-1	99.3	2.1
10	0	1	-1	98.4	3.5
11	0	-1	1	96.8	3.9
12	0	1	1	96.8	4.5
13	0	0	0	99.0	2.9
14	0	0	0	98.9	3.2
15	0	0	0	98.9	2.8
16	0	0	0	98.7	3.1
17	0	0	0	98.8	3.0

Using the Design-Expert software for analysis, the optimal pick-up rate of 98.9% and loss rate of 2.8% (better than the national industry standard) were obtained with the following parameter values: the unit forward speed V is 48.0 m/minute, the cylinder rotary speed N is 45.3 r/minute and the shovel-finger-end depth H is -18 mm. The experimental values are close to the theoretical values (Yao et al., 2017; Wang et al., 2019 b).

CONCLUSIONS

(1) Based on the characteristics of upright peanut plants in China, a new type of peanut-picking device with a shovel finger and cylinder was invented and developed. The fixed shovel finger and the cylinder's pick-up finger completed the picking of peanut plants step by step. According to the role and orientation of the arc of the pick-up finger for each pick-up station, the working surface of the guard plate outside the cylinder is designed as a combination of a curved surface and a plane to avoid the clamping effect of the device on peanut plants.

(2) A mathematical model of the combined peanut-picking mechanism of the shovel finger and cylinder was established using the objective function method. NSGA-II was used to analyze the installation angle β of the pick-up finger, the pick-up-finger working arc radius R_3, the pressure angle α_1 at point F of the involute section of the cylinder guard, the pick-up-finger seat radius R, the cylinder guard straight line FG and horizontal angle γ, the base circle deviation e of the involute section of the guard plate, etc. The influence of the parameters on the objective function was analyzed, and the parameters of the mechanism were optimized.

(3) According to the optimization results, a prototype was developed and a soil tank test was carried out. Through the comprehensive test analysis of the multi-index response surface, the following optimal working parameters of the picking device were obtained: the forward speed V of the unit is 48.0 m/minute, the rotary speed N of the cylinder is 45.3 r/minute and the penetrating depth H of the end of the shovel finger is -18 mm. Under this parameter combination, the pick-up rate is 98.9% and the loss rate is 2.8%, which are slightly better than the values of operating quality for peanut harvesters specified by NY/T502-2016 (NY/T502-2016, 2016).

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