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DESIGN AND EXPERIMENT OF MULTICHANNEL CAMELLIA-FRUIT-PICKING DEVICE

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KEYWORDS

camellia fruit, flower bud, layered picking, multichannel, response surface method.

ABSTRACT

To address the low efficiency and high flower bud damage rate in camellia-fruit-picking machines, a multichannel camellia-fruit-picking device was designed. Three factors and levels of the quadratic orthogonal rotation combination test method were used in the test. The experimental results show that the fruit picking and bud damage rates were affected most by the roller speed, followed by the distance between rollers, and, finally, the roller diameter. The optimal parameter combination was determined to be the roller speed of 130 mm/s, distance between rollers of 21 mm, and roller diameter of 30 mm, as verified by outdoor experiments. The average camellia-fruit-picking and bud damage rates were 95.68% and 3.92%, respectively. Compared with a rotating rubber roller picking device, the average flower bud damage rate of the multichannel camellia-fruit-picking device was reduced by 14.71 percentage points.

INTRODUCTION

Camellia is a traditional woody oil species in China and is one of the four largest woody oil crops worldwide (Chen et al., 2021; Wang et al., 2020a). In recent years, with increasing support for the camellia industry policy in China, the number of camellia trees has increased from 50 million in 2008 to 1 billion in 2019 (Huang, 2020). However, camellia fruit picking is time consuming, whereas the harvest cycle is short. If the fruit is not picked in time, the camellia oil quality is seriously affected (Hung & Rao, 2019). At present, the picking of camellia fruit in China is mainly manual, labor-intensive, and inefficient, seriously restricting the development of the camellia industry (Pang et al., 2019). Therefore, practical and efficient camellia-fruit-picking machines must be developed (Xie, 2019).

Developed countries in Europe and the United States mechanized and automated the picking of citrus fruit, cherries, blueberries, apples, and other fruits (Bora & Ehsani, 2009; Láng, 2003; Láng, 2006; Mehta et al., 2016; Pacheco & Rehkugler, 1980; Onishi et al., 2019). In recent years, the mechanical picking of camellia, a unique source of woody oil in China, has been continuously researched by universities and other scientific institutions (Li & Yang, 2016; Rao et al., 2021; Wu et al., 2021b). Wu et al. (2021a) designed a twist-comb end effector for picking camellia fruit that used the rotation of a twist-comb assembly to pick the fruit. The camellia-fruit-picking efficiency was high, but flower bud damage was severe. Gao et al. (2013) designed a tooth-comb-type camellia-fruit-picking machine and established the spatial motion equation of the picking actuator by the D–H matrix transformation. The leakage rate of camellia fruit was the lowest, while the flower bud damage rate was less than 3% when the rising speed of the picking head was approximately 0.8 m/s and the revolving speed of the picking tooth was approximately 15 r/min. A vibratory camellia fruit harvester was developed by the Forestry Machinery Institute (Wang et al., 2020b) in Harbin. The picking arm had a rotary design and good flexibility. This harvester performed better in terms of fruit picking rate and flower bud damage rate but might cause irreversible damage to trunks and roots. Rao et al. (2019) designed a hydraulically driven camellia-fruit-picking machine with an assembly of rubber rollers. The movement of the rotating frame was controlled by a hydraulic motor. Camellia fruit falls from the branch because of the collision and extrusion of the upper and lower rubber rollers. The picking form was novel, but the flower bud damage rate was as high as 11.3%.

For the aforementioned reasons, further research on camellia-fruit-picking machinery is necessary. In this study, a multichannel camellia-fruit-picking device was

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developed. First, a three-dimensional model of the camellia-fruit-picking device was established, and its picking principle was analyzed. A mechanical model of the interaction between camellia fruit and the picking device was established to analyze the camellia fruit's shedding characteristics, and the main factors affecting the shedding of camellia fruit were determined. Finally, numerous outdoor picking experiments were conducted, the experimental data were analyzed, and the optimal working parameters of the picking device were obtained.

In this article, a multichannel picking device is proposed to improve camellia-fruit-picking efficiency. The adjustable dipping angle of the picking head allows the picking device to effectively navigate the branches according to the fruit growth trajectory. Single-chip control was employed to manipulate the picking device. Therefore, the operability improves when this picking device is used.

OVERALL SCHEME DESIGN

Main structure

The multichannel camellia-fruit-picking device had a triangular track chassis. Its overall structure is shown in Figure 1. The device consists of many components, including a layered picking head, hydraulic drive system, control system, and frame. The layered picking head is a critical component of the picking device and comprises a layered picking mechanism, angle-adjusting mechanism, spacing-adjusting mechanism, sliding block, and guide rail. The layered picking mechanism is fixed at one end of a movable rod, which is used to control the clamping, picking, and feeding thickness of the fruit branch. The angle-adjusting mechanism is pinned to the movable rod, fixed frame, and is used to adjust the angle of the layered picking mechanism to the camellia branch. A spacing adjustment mechanism is installed on both sides of the layered picking mechanism. It can adjust the distance between two parallel rubber rollers to reduce damage to the flower bud and branch. Building upon the picking characteristics of a single-layered picking mechanism, the multiple-layered picking mechanisms are arranged in the vertical direction of the rack to improve the camellia-fruit-picking efficiency.

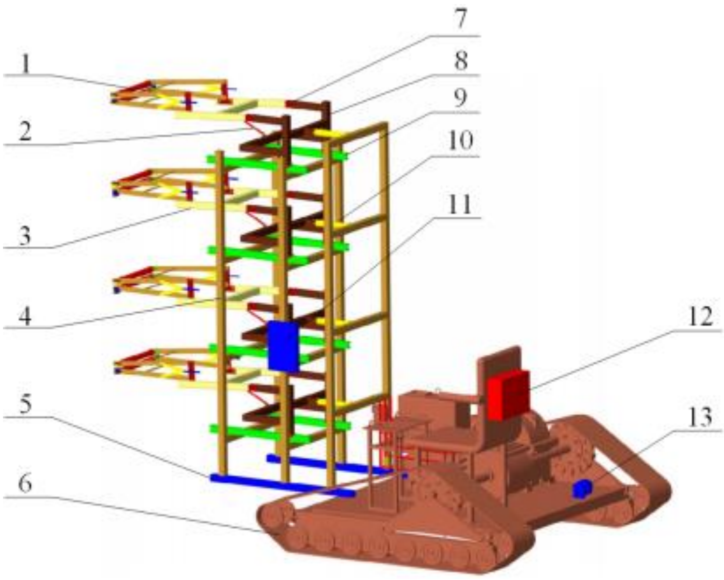


FIGURE 1. Diagram of machine structure: (1) layered picking mechanism, (2) angle adjustment mechanism, (3) active rod, (4) frame, (5) beam frame, (6) chassis, (7) hinge, (8) fixed frame, (9) guide, (10) hydraulic cylinder, (11) control box, (12) fuel tank, and (13) hydraulic motor.

Working principle

During picking, the machine is parked in front of camellia tree to be harvested. Through the serial port screen, the angle-adjusting mechanism adjusts the layered picking mechanism to the positive position of each camellia fruit branch layer. The electric push rod of the layered picking mechanism extends forward and drives the upper and lower layering frames to open at appropriate positions. The layered picking mechanism is driven by a hydraulic cylinder to engage with a camellia fruit branch, and the rubber rollers are driven close toward each other by the shrinking of an electric push rod to securely clamp a camellia branch. The layered picking mechanism is driven by the contraction of the piston rod in the hydraulic cylinder to move backward, while the camellia fruit is separated from the fruit branch by the impact of rubber rollers.

Abscission characteristics of camellia fruit

During picking, the camellia branch is placed between the parallel rubber rollers. The camellia fruit is subjected to the instant impact force of the rubber rollers. The forces acting between the camellia fruit and rubber rollers are complex because of the distinct nature of their contact surfaces. To facilitate the analysis of the force exerted by rubber rollers on camellia fruit, it is assumed that the fruit is positioned centrally in the gap between the rollers when it collides with them and is subjected to the symmetric force exerted by the two parallel rollers, as shown in Figure 2. When a collision occurs, the resultant force F_y of the roller on the fruit in the vertical direction is 0, and the resultant force F_x in the horizontal direction is

$$
\begin{aligned}
F_x &= F_{N1}\cos\theta + f_1\sin\theta + F_{N2}\cos\theta + f_2\sin\theta \\
&= 2(\cos\theta + \mu\sin\theta)F_{N1} \\
&= \frac{4l + 2\mu(L+D)}{D+d}F_{N1}
\end{aligned} \tag{1}
$$

Where:

F_{N1} and F_{N2} are the positive pressures of the upper and lower rollers on the fruit, respectively (N);

f_1 and f_2 are the friction forces between the fruit and the rollers (N);

D is the roller diameter (mm);

d is the fruit diameter (mm);

L is the distance between the upper and lower rubber rollers (mm);

l is the horizontal distance between the center of the fruit and that of the roller (mm);

μ is the coefficient of friction, and

θ is the angle between the positive pressure and the horizontal direction(°).

When the component force is greater than the binding force F, as shown in the following equation, the fruit falls off:

$$F_x \geq F \tag{2}$$

From the Pythagorean theorem, one obtains

$$l = \sqrt{\left(\frac{D+d}{2}\right)^2 - \left(\frac{L+D}{2}\right)^2} \tag{3}$$

From eqs (1)–(3), one obtains

$$F_{N1} \geq \frac{F}{2}\frac{\dfrac{D+d}{L+D}}{\sqrt{\left(\dfrac{D+d}{L+D}\right)^2 - 1} + \mu} \tag{4}$$

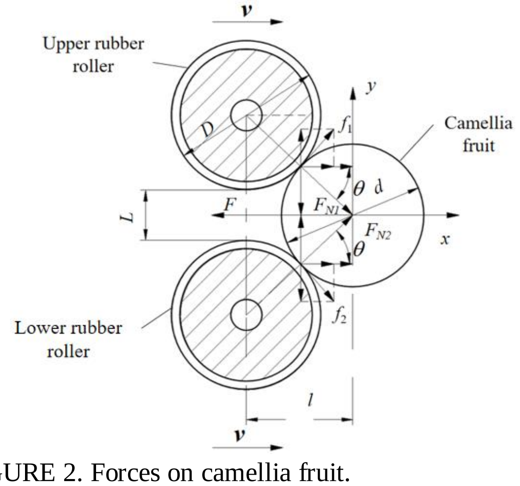


FIGURE 2. Forces on camellia fruit.

According to [eq. (4)], the critical force F_{N1} required for the camellia fruit to fall off is related to the binding force F, diameter D of the rubber rollers, distance L between the rollers, and diameter d of the fruit. When the variety of camellia is fixed, F and d are constant. Therefore, the factors that cause the fruit to fall are L and D.

With an increase in the rubber roller speed v, the interaction time Δt between the fruit and roller decreases. According to the momentum theorem,

$$
\begin{cases}
\Delta P = m(v - v_0) \\
F_1 = \dfrac{\Delta P}{\Delta t}
\end{cases} \tag{5}
$$

Where:

ΔP is the momentum change of the fruit before and after collision (g · mm/s);

v_0 is the speed of the fruit before impact (mm/s);

m is the mass of the fruit (g), and

F_1 is the resultant force of the fruit under the action of the rollers (N).

According to [eq. (5)], when the other conditions remain unchanged, the resultant force on the fruit increases when the speed of impact increases.

In conclusion, the main factors affecting the shedding of camellia fruit are the distance between rubber rollers, roller diameter, and roller speed.

DESIGN OF THE MAIN STRUCTURE AND SYSTEM

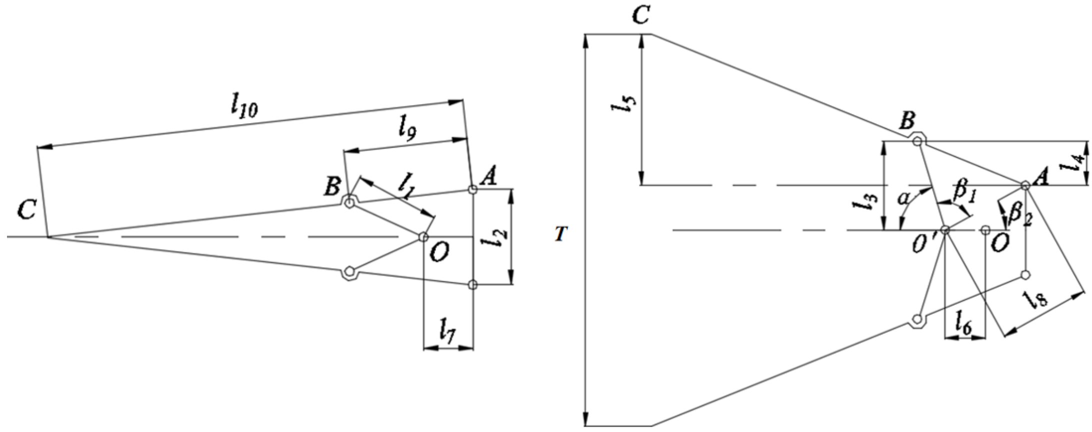
Layered picking head design

Layered picking mechanism

During picking, the thickness of the surface camellia branches determines the layered thickness of the layered picking mechanism. Its main parameters are listed in Table 1. To facilitate the analysis of the layered thickness of the layered picking mechanism, it was simplified into a geometric model, and its relationships were analyzed (Figure 3).

TABLE 1. Main parameters of layered clamping mechanism.

Parameter	Value
Layered shelf length l_{10}, mm	450
Length of rod l_9, mm	200
Layered connecting rod length l_1, mm	140
Length of T-plate l_2, mm	100
Push rod stroke	50
Initial installation distance of the push rod l_7, mm	50



(a) Closed state (b) Fully open state

FIGURE 3. Geometric model of the layered picking mechanism.

In the initial state, the layered picking mechanism is closed, as shown in Figure 3a. When the stroke distance of the push rod is maximal, the layered picking mechanism is fully open (Figure 3b). The equations are

$$\begin{cases} l_3 = l_1 \sin \alpha \\ l_4 = l_3 - \dfrac{l_2}{2} \\ l_5 = \dfrac{T}{2} - \dfrac{l_2}{2} \end{cases} \tag{6}$$

Where:

l_3 is the vertical distance between points B and D (mm);

l_4 is the vertical distance between points A and B (mm);

l_5 is the vertical distance between points A and C (mm);

T is the layer thickness (mm), and

α is the horizontal angle of the layered link (°).

According to the law of cosines,

$$\beta_1 = cos^{-1} \frac{l_1^2 + l_8^2 - l_9^2}{2 l_1 l_8} \tag{7}$$

$$\beta_2 = tan^{-1} \frac{l_2}{2(l_6 + l_7)} \tag{8}$$

Where:

β_1 is the angle between the layered link and the line connecting points A and O_2 (°),

β_2 is the angle between the horizontal and the line connecting points A and O_2 (°),

l_6 is the extension displacement of the push rod (mm), and

l_8 is the distance between point A and the hinge point of the push rod and layered link (mm).

The l_8 value must meet the following condition:

$$l_8 = \sqrt{(l_6 + l_7)^2 + \left(\frac{l_2}{2}\right)^2} \tag{9}$$

According to the triangle similarity theorem,

$$\frac{l_4}{l_5} = \frac{l_9}{l_{10}} \tag{10}$$

From eqs (6)–(10), one obtains

$$\begin{aligned} T &= l_2 + \frac{2 l_{10} l_1 \sin \alpha - l_{10} l_2}{l_9} \\ &= l_2 + \frac{2 l_{10} l_1 \sin(\pi - \beta_1 - \beta_2) - l_{10} l_2}{l_9} \end{aligned} \tag{11}$$

When the push rod reaches the maximum stroke, the layered thickness is 350 mm, according to [eq. (11)]. According to a thickness measurement test, the average surface thickness of single-layer camellia branches is approximately 291 mm, which is less than 350 mm and meets the picking requirements.

Angle-adjusting mechanism

The angle of the picking mechanism entering the camellia branches is adjusted by an angle-adjusting mechanism. Its simplified geometric model is shown in Figure 4, and the main operating parameters are listed in Table 2.

TABLE 2. Main parameters of angle-adjusting mechanism.

Parameter	Value
Rocker length L_4, mm	200
Initial putter length L_2, mm	210
Push rod stroke L_3, mm	150

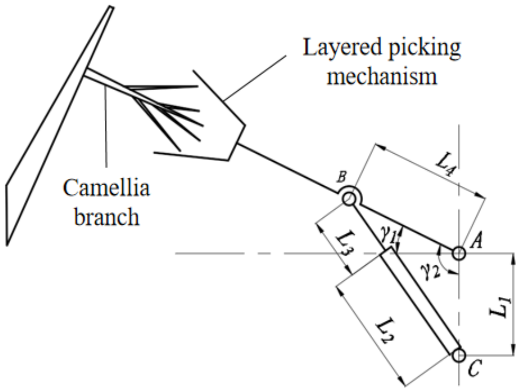


FIGURE 4. Geometric model of angle-adjusting mechanism.

The angle γ_2 between the pendulum and the vertical direction must satisfy

$$\gamma_2 = cos^{-1}\frac{L_4^2 + L_1^2 - 2(L_2 + L_3)^2}{2LL_1} \tag{12}$$

Where:

L_1 is the distance between hinge points A and C (mm).

The angle γ_1 between rocker L_4 and the horizontal direction satisfies

$$\gamma_1 = \gamma_2 - 90^{\circ} \tag{13}$$

The installation distance L_1 of the push rod is 190 mm, which can be substituted into eqs (12) and (13). The range of the angle-adjusting mechanism (the angle to the horizontal direction) is 0°–44.7°. Measurement of the angle between the fruit branches and the horizontal ground shows that the main distribution of the angle is 15°–35°, which meets the picking requirements.

Spacing-adjusting mechanism

During picking, the layered picking mechanism layers and clamps the camellia branches. The distance between the rubber rollers is crucial for the layered picking mechanism to hold and pick fruit without damaging the flower buds. If the distance is too small, the bud is easily damaged and falls off, which affects the camellia fruit production in the following year. If the distance is too large, the fruit can pass through the gap between the rollers without being picked (Zhang et al., 2018).

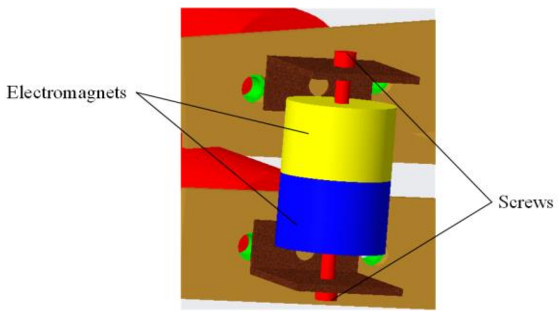


FIGURE 5. Adjustment mechanism of structure spacing.

The spacing-adjusting mechanism, as seen in Figure 5, comprises of electromagnets, screws, and brackets. When the electrical power is activated, the electromagnetic forces intensify the clamping force exerted by the parallel rollers. This effectively mitigates any potential impact on fruit harvesting caused by variations in the distance between the rollers, particularly when higher quantities of camellia fruit branches are being fed. The screw is used to adjust the distance between rollers, with an adjustable range of 0–35 mm. The average camellia fruit diameter is 31.34 mm, and the average flower bud diameter is 14.47 mm (Rao et al., 2017). The distance adjustment range between rollers should be greater than the bud length diameter and smaller than the fruit diameter so that flower buds may slip from the gap between the rollers when fruit is picked.

Hydraulic system design

The hydraulic system of the picking device has several components, including an oil tank, gear pump, manual reversing valve, throttle valve, pressure gauge, and hydraulic cylinder. A manual reversing valve controls the expansion and unloading of the hydraulic cylinder, and a throttle valve adjusts the contraction speed of the piston rod in the cylinder. The system has four independently moving hydraulic cylinders distributed from top to bottom on the rack to control the forward or backward movement of the layered picking heads. A schematic diagram of the hydraulic system is shown in Figure 6.

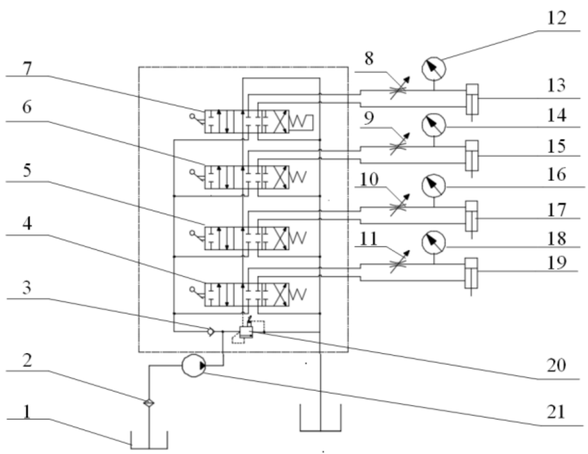


FIGURE 6. Schematic diagram of hydraulic system.

Selection of hydraulic cylinder

The retraction speed and stroke of the piston rod in the cylinder are important for picking efficiency. Based on the response speed, load, weight, and other factors of the hydraulic cylinder, the working pressure selected for the system is 16 MPa. The inner diameter of the cylinder is

$$D_W = \sqrt{\frac{4F_W}{\pi\eta(p_1 - 0.5p_2)}} \tag{14}$$

Where:

D_W is the inside diameter of the cylinder (mm);

F_W is the load on the piston rod (N);

p_1 is the working pressure of the cylinder (MPa);

p_2 is the back pressure of the return chamber of the cylinder (MPa), and η is the cylinder working efficiency.

The retraction speed v of the piston rod is

$$v = \frac{4qm_1}{\pi(D_1^2 - d_1^2)} \tag{15}$$

Where:

q is the cylinder flow rate (L/min);

m_1 is the cylinder volumetric efficiency;

D_1 is the cylinder inner diameter (mm), and

d_1 is the cylinder inner diameter (mm).

The stroke S of the cylinder is related to the distance ΔS between the rollers and the branches to be picked, the surface distribution depth S_1 of the fruit, and the free extension length S_2 of the branches during clamping and picking (Figure 7).

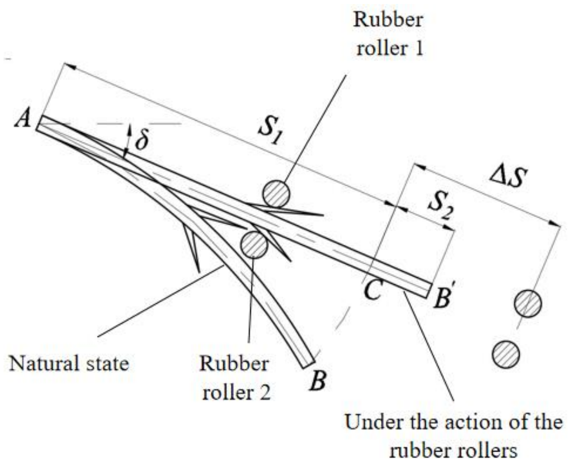


FIGURE 7. Interaction diagram of rubber rollers and fruit branches.

Stroke S of the hydraulic cylinder must satisfy

$$\begin{cases} S \geq (S_1 + \Delta S)\cos\delta \\ \Delta S \geq S_2 \end{cases} \tag{16}$$

Where:

δ is the angle between the horizontal direction and fruit branches under roller action (°).

Camellia fruit is typically distributed 200 to 300 mm apart on camellia branches in their natural state (Gao et al., 2012). To take into account the elongation of the branches under the action of the rubber roller and the distance between the rollers and the branches to be harvested, a hydraulic cylinder of type HSG40 with a stroke length of 600 mm is used. The cylinder inner diameter is 40 mm, and the piston rod diameter is 25 mm.

Hydraulic pump selection

To ensure the safety of the hydraulic system, the selected hydraulic pump should have a rated pressure higher than the system pressure (An et al., 2020). The rated pressure p_n must satisfy

$$p_n \geq (1.25 \sim 1.6)p_p \geq p \sum \Delta p_{max} \tag{17}$$

Where:

p_p is the highest working pressure of the hydraulic pump (MPa);

$p_{\max}$ is the maximum operating pressure of the actuator (MPa), and

($\sum \Delta p$) is the total pipeline pressure loss (N).

The rated flow q_n of the hydraulic pump must satisfy

$$q_n \geq K \sum^{\Sigma} q_{max} \tag{18}$$

Where:

K is the system leakage coefficient, valued between 1.1 and 1.3, and

$\sum q_{\max}$ is the maximum value of the sum of the flows of simultaneously operating actuators (L/min).

Regarding the efficiency of general picking machinery, the maximum contraction speed of the piston rod in the hydraulic cylinder is 200 mm/s, the volume ratio is 0.92, the pressure loss in the oil pipe is 0.3 MPa, the rated pressure of the pump is 1.3 times the system pressure, and the leakage coefficient is 1.1. Based on eqs (15), (17), and (18), the rated pressure of the hydraulic pump is 21.19 MPa, and the rated flow is 16.61 L/min. According to the rated pressure and flow of the hydraulic pump, a CBN-G314-CPR gear pump was chosen based on the hydraulic component catalogs.

Control system design

The picking device has four picking heads that work independently. Each must complete three actions: angle adjustment, branch layering, and clamping picking. To facilitate control and operation, a control system was designed that includes a controller (51&AVR MCU), motor drive module (L298N), and serial screen (USART HMI). As a human–computer interface and input equipment, the serial screen can directly control the start and stop of the DC motor, realizing collaborative human–machine operation.

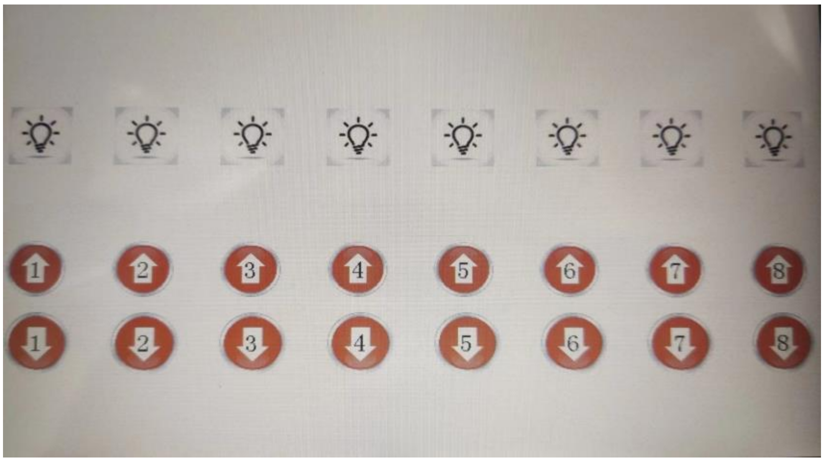


FIGURE 8. Serial port screen displaying a physical image of the control terminal.

During operation, the controller sends commands to the serial screen to display the eight groups of touch keys, as shown in Figure 8. Key 1 is used to control the angle adjustment of the first-layer layered picking head, key 2 is used to control the branch layering and clamping picking of the first-layer layered picking head, and the control of other layered picking heads is deduced in turn. A schematic diagram of the electrical control system is shown in Figure 9.

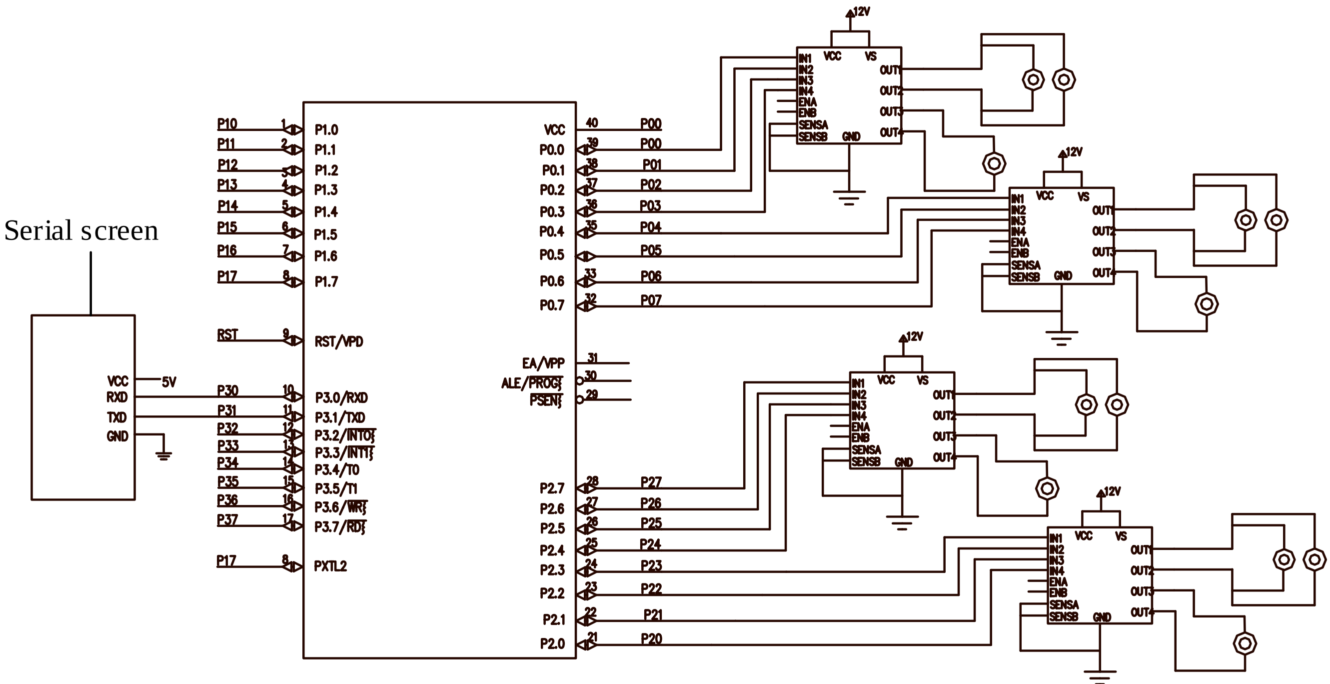


FIGURE 9. Circuit diagram of the control system.

OUTDOOR PICKING TEST

Test materials

The test site was at the Academy of Forestry camellia plantation base in Nanchang City, Jiangxi Province, China. The variety used was a Gan-wu 1 camellia tree with fruit and flower buds. The tree heights were 3–5 m, distance between plants was 3 m, and row spacing was 4 m. The test was conducted on October 16, 2021 (Figure 10).

FIGURE 10. Field test of the multichannel camellia-fruit-picking device.

The dimensions of the picking machine were $3 \times 1.5 \times 3.3$ m (length × width × height), layered picking heads were 0.45 m, hydraulic cylinder stroke was 1 m, and picking range was 0.5–5 m. The picking machine head is shown in Figure 11.

FIGURE 11. Head of the multichannel camellia-fruit-picking device under test.

Test factors and response indices

Based on the theoretical analysis of the interaction between the camellia fruit and the rubber rollers, the identified test factors include roller speed, distance between rollers, and roller diameter. The cylinder contraction speed was measured using a speedometer, and cylinder contraction speeds of 100, 130, and 160 mm/s were calibrated on a pressure gauge before the test. Because of the agronomic demands of camellia fruit picking in actual production, the fruit picking rate (Y_1) and flower bud damage rate (Y_2) were used as evaluation indices of picking. The fruit picking rate is based on the number of fruits collected and the number of fruits on the branches before picking. The bud damage rate is the ratio of the number of dropped flower buds to the number of buds on the branches before picking.

Three factors and levels of the quadratic orthogonal rotation combination test were used (Wang et al., 2018). Table 3 shows the factor-level coding.

TABLE 3. Coding table of factor levels.

Level	Factors		
	Roller speed, mm/s	Roller distance, mm	Roller diameter, mm
1	100	18	27
0	130	21	30
−1	160	24	33

Test results and analysis

The response surface method in Design-Expert 8.0.6 was used to conduct 17 groups of tests, and each group was performed three times to obtain the average value. The test scheme and results are listed in Table 4 (X_1, X_2, and X_3 are the coding values of the factors).

TABLE 4. Test scheme and results.

Test no.	Roller speed X_1, mm/s	Roller distance X_2, mm	Roller diameter X_3, mm	Picking rate of camellia fruit Y_1, %	Damage rate of flower buds Y_2, %
1	−1	−1	0	91.65	3.98
2	1	−1	0	97.51	6.97
3	−1	1	0	88.65	3.27
4	1	1	0	96.49	5.02
5	−1	0	−1	89.33	3.28
6	1	0	−1	97.02	5.58
7	−1	0	1	90.69	4.37
8	1	0	1	97.69	6.28
9	0	−1	−1	95.34	4.19
10	0	1	−1	93.54	3.31
11	0	−1	1	97.43	4.86
12	0	1	1	94.02	3.75
13	0	0	0	96.82	3.42
14	0	0	0	96.18	3.36
15	0	0	0	96.32	3.91
16	0	0	0	96.53	3.65
17	0	0	0	96.66	3.58

As Table 4 shows, the average picking rate of fruit was 94.82%, and the average flower bud damage rate was 4.28%. When first layering and then picking camellia fruit with a rotating rubber roller, a camellia fruit layered picking device test in 2020 resulted in an average bud damage rate of 18.99% (Wang et al., 2022). Compared with that picking device, the average bud damage rate of the multichannel camellia-fruit-picking device was reduced by 14.71 percentage points.

Effect of test factors on fruit picking rate

The test data in Table 4 on the picking rate of camellia fruit were analyzed using Design-Expert 8.0.6 (Ge, 2015). The regression model of each factor coding value and the fruit picking rate Y_1 were obtained according to [eq. (19)].

$$Y_1 = 96.5 + 3.55X_1 - 1.55X_2 + 0.57X_3 + 0.49X_1X_2 - 0.17X_1X_3 - 0.4X_2X_3 - 2.16X_1^2 - 0.76X_2^2 - 0.66X_3^2 \quad (19)$$

A variance analysis was performed. The results are shown in Table 5.

TABLE 5. Variance analysis of camellia-fruit-picking rate.

Model items	Mean square	F value	P value	Significance
Model	15.73	183.64	<0.0001	**
X_1	100.75	1176.08	<0.0001	**
X_2	10.65	124.31	<0.0001	**
X_3	2.65	30.88	0.0009	**
X_1X_2	0.98	11.44	0.0117	*
X_1X_3	0.12	1.39	0.2770	
X_2X_3	0.65	7.56	0.0285	*
X_1^2	19.71	230.06	<0.0001	**
X_2^2	2.45	28.65	0.0011	**
X_3^2	1.81	21.15	0.0025	**
Lack of fit	0.11	0.32	0.3040	

Note: * indicates significance of $p < 0.05$; ** indicates high significance of $p < 0.01$.

The results presented in Table 5 reveal that the observed relationship between the fruit picking rate and the test factors is statistically significant ($p < 0.01$), and the lack of fit is statistically insignificant ($p > 0.05$). This indicates that other factors in the study did not produce any significant effect, and the regression model is reasonable. In the single-factor effect, all single terms ($p < 0.01$) had a highly significant effect on the fruit-picking rate. In the two-factor interaction effect, the interaction between distinct factors had different effects. The interaction between roller speed X_1 and roller distance X_2 and the interaction between roller distance X_2 and roller diameter X_3 ($p < 0.05$) had significant effects on the fruit picking rate, but the effect of other interactions was not significant ($p > 0.05$). A response surface chart of the interaction terms X_1X_2 and X_2X_3 was obtained (Figure 12).

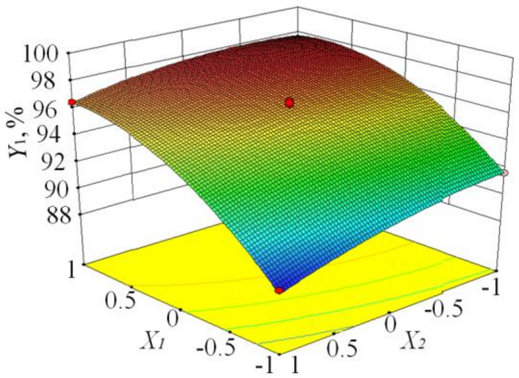


FIGURE 12. Effect of speed and distance of rubber rollers on picking rate of camellia fruit.

As Figure 12 shows, when the rubber roller diameter was centrally at 30 mm the fruit picking rate increased with an increase in roller speed, and the change was more significant whereas the change was softer with an increase in roller distance. The response surface line changed more rapidly along the roller speed direction. At the center level, the roller speed had a more significant effect on the fruit picking rate than the roller distance.

Figure 13 reveals that, when the roller speed was set at the optimum level (130 mm/s), the fruit picking rate decreased with an increase in roller distance, and the change was more obvious, whereas the change was gentler with an increase in roller diameter. The response surface line changed faster along the roller distance direction than that for the roller diameter direction. At the center level, the roller distance had a more significant effect on the fruit picking rate than did the roller diameter.

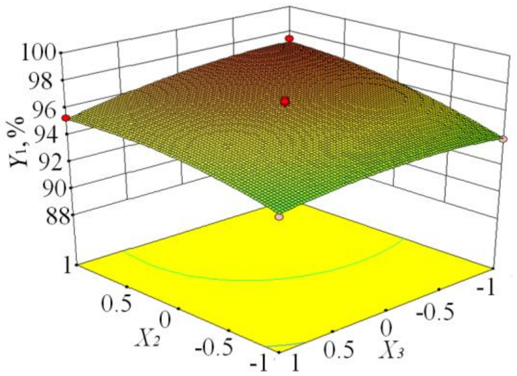


FIGURE 13. Effect of distance and diameter of rubber rollers on picking rate of camellia fruit.

Effect of test factors on flower bud damage rate

The test data of the camellia-fruit-picking rate in Table 4 were analyzed using Design-Expert 8.0.6. The regression model of each factor coding value and fruit picking rate Y_2 was obtained as in [eq. (20)].

$$Y_2 = 3.58 + 1.12X_1 - 0.58X_2 + 0.36X_3 - 0.31X_1X_2$$
$$-0.098X_1X_3 - 0.057X_2X_3 + 1.04X_1^2 + 0.19X_2^2 + 0.26X_3^2 \quad (20)$$

A variance analysis was performed. The results are shown in Table 6.

TABLE 6. Variance analysis of flower bud damage rates.

Model items	Mean square	*F* value	*P* value	Significance
Model	2.16	44.88	<0.0001	**
X_1	10.01	208.14	<0.0001	**
X_2	2.70	56.18	0.0001	**
X_3	1.05	21.85	0.0023	**
X_1X_2	0.38	7.99	0.0255	*
X_1X_3	0.038	0.79	0.4035	
X_2X_3	0.013	0.27	0.6162	
X_1^2	4.54	94.30	<0.0001	**
X_2^2	0.15	3.09	0.1220	
X_3^2	0.27	5.71	0.0481	*
Lack of fit	0.050	1.06	0.4594	

Note: * indicates significance at $p < 0.05$; ** indicates high significance of $p < 0.01$.

The results presented in Table 6 reveal that the relationship between the flower bud damage rate and the test factors is statistically significant ($p < 0.01$), and the lack of fit is insignificant ($p > 0.05$), indicating that there was no significant effect of other factors in the study and the regression model is reasonable. In the single-factor effect, the single term of roller speed X_1 ($p < 0.01$), the single term of roller distance X_2 ($p < 0.01$), the single term of roller diameter X_3 ($p < 0.01$), and the quadratic term of roller speed X_1 ($p < 0.01$) had highly significant effects on the bud damage rate, and the quadratic term of roller diameter X_3 ($p < 0.05$) had a significant effect. In the two-factor interaction effect, the interaction between the two factors differed. The interaction between roller speed X_1 and roller distance X_2 ($p < 0.05$) had a significant effect on the bud damage rate, whereas the effect of the other interaction items was not significant ($p > 0.05$). A response surface chart of the influences of X_1 and X_2 was obtained (Figure 14).

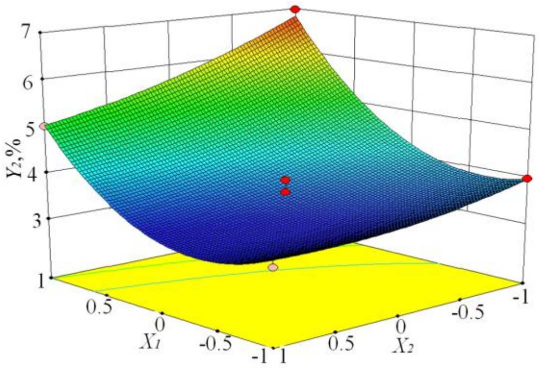


FIGURE 14. Effect of speed and distance of rubber rollers on damage of flower buds.

As shown in Figure 14, when the roller diameter was at the optimum level (30 mm), the bud damage rate increased with increasing roller speed, and the change was more obvious, whereas the change was gentler with an increasing roller distance. The response surface line changed more rapidly along the roller speed direction. At the center level, the roller speed had a more significant effect on the bud damage rate than did the roller distance.

Optimal parameters and experimental verification

The regression model examining the relationship between fruit picking rate and body damage rate was analyzed using the optimization function in Design-Expert 8.0.6 software. The objective was to determine the regression model that maximized the picking rate while minimizing the damage rate. The optimal set of parameters was obtained when the roller speed was 130 mm/s, roller distance was 21 mm, and roller diameter was 30 mm.

To verify the reliability of the best parameter combination, an outdoor picking experiment was conducted at the Academy of Forestry camellia plantation base in Nanchang City, Jiangxi Province, China, on October 22, 2021. To eliminate the influence of random errors on the test results, three camellia trees were selected, and the test was repeated four times. The test results are listed in Table 7.

TABLE 7. Test verification results.

Test no.	Factors			Y_1, %	Y_2, %
	X_1, mm/s	X_2, mm	X_3, mm		
1				94.12	3.45
2				91.89	4.35
3	130	21	30	96.55	3.23
4				95.83	5.56
5				100	3.03

As Table 7 shows, the average fruit picking rate was 95.68%, and the average bud damage rate was 3.92%.

CONCLUSIONS

1) A multichannel camellia-fruit-picking device was designed. The device was equipped with four-layered picking heads, which made multilayer independent picking of camellia trees possible. The device not only improved the picking efficiency of camellia fruit but also reduced flower bud damage.

2) Based on the distinct characteristics of camellia stems and branches, a mechanical model of the interaction between camellia fruit and parallel rubber rollers was established and analyzed. The primary factors affecting the shedding of camellia fruit were the roller speed, distance between rollers, and roller diameter.

3) According to the control requirements of the entire machine, a single-chip microcomputer control system was designed. It employed a serial screen as the human–machine interface to control the angle of the layered picking heads when entering the camellia fruit branches to achieve layered clamping picking in the picking areas.

4) To analyze the factors influencing picking performance, three factors and levels of a quadratic orthogonal rotation combination experiment were implemented. The factors affecting the fruit picking rate and bud damage rate, in descending order, were the roller speed, distance between rollers, and roller diameter. The fruit picking rate was 95.68%, and the bud damage rate was 3.92% when the roller speed was 130 mm/s, distance between rollers was 21 mm, and roller diameter was 30 mm. Compared with a rotating rubber roller picking device, the flower bud damage rate of the multichannel camellia-fruit-picking device was reduced by 14.71 percentage points.

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