DESIGN AND EXPERIMENT OF END EFFECT FOR KIWIFRUIT HARVESTING BASED ON OPTIMAL PICKING PARAMETERS
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基于最优采摘参数的猕猴桃采摘末端执行器设计与试验

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***Keywords:** Kiwifruit, harvesting, robot, end effector, response surface*

ABSTRACT
A kiwifruit harvesting end effector was designed and developed to improve the efficiency of mechanized kiwifruit harvesting. Firstly, the automated kiwifruit picking process was determined according to the kiwifruit orchard working environment. Secondly, the end effector was designed and analyzed based on the principle of kiwifruit picking. Finally, an orchard experiment was conducted with the clamping force, rotation angle and rotation speed of the end effector as test factors, and the separation success rate, separation time and damage rate of kiwi fruit as test indicators. A regression model between the test factors and test indicators was established using a quadratic fitting equation to analyze the influence between the test factors and indicators. The experimental results showed that the optimal parameter was a clamping force of 3.05 N, a separation angle of 65.75°, and a separation speed of 60.03°/s. The results of the study provide theoretical basis and technical support for automated kiwifruit harvesting.

摘要
为提高猕猴桃机械化收获效率，设计并开发了一款用于猕猴桃采摘的末端执行器。首先，根据猕猴桃果园作业环境，确定出猕猴桃机械化采收作业原理。其次，根据猕猴桃采摘机理，对末端执行器的结构进行设计和分析。最后，进行果园试验，以末端执行器的夹持力，旋转角度和旋转速度为试验因素，以猕猴桃果实的分离成功率，分离时间和损伤率为试验指标，采用二次拟合方程建立试验因素和试验指标之间的回归模型，分析试验因素和指标间的影响。试验结果表明最优参数中夹持力为 3.05N，分离角度为 65.75°，分离速度为 60.03°/s。研究结果为实现猕猴桃自动化高效采摘提供理论依据和技术支持。

INTRODUCTION
China has the largest area and production of kiwifruit in the world, with a cultivation area of 193,000 hectares and an annual yield of 2.2 million tons (*Li et al., 2022; Suo et al., 2020*). Compared to other industries in the agricultural field, kiwifruit picking is still a labor-intensive industry, especially in the time-consuming and laborious harvesting process (*Mu et al., 2018; Fu et al., 2020*). Therefore, the development of kiwifruit harvesting robots is crucial to reduce the risk of artificial injury and promote the development of the kiwifruit industry (*Jin, 2020*).

In recent years, harvesting robots have achieved remarkable results in the design of end effectors (*Li et al., 2020*), picking mechanism research (*Liu et al., 2022; Bu et al., 2020*), fruit identification (*Mu et al., 2019*). However, the harvesting efficiency has always been affected by the long picking cycle of the single fruit. At present, fruit information perception is mainly studied in the mechanized picking operation of kiwifruit (*Zhou et al., 2020*), improving the mechanized picking efficiency with the improvement of fruit recognition accuracy. The existing research on kiwifruit harvesting robots reflects the problems of long picking time and low picking efficiency of kiwifruit (*Williams et al., 2020*). However, less research on improving operational efficiency is on motion control of kiwifruit harvesting robots.

In this paper, the kiwifruit picking end effector was designed and developed to solve the low efficiency of mechanized harvesting of kiwifruit. The field experiment was carried out.

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The response surface method was used to determine the optimal range of picking parameters to improve the picking efficiency of the robotic arm in the fruit separation stage, taking the success rate, separation time and damage rate of kiwifruit fruit separation as the dependent variable, and the clamping force, rotation angle and rotation speed of the end effector as independent variables.

MATERIALS AND METHODS

The working principle of the kiwifruit harvesting robot

Kiwifruit adopts the planting management mode of scaffolding cultivation as shown in Figure 1(a). The trellis canopy is suitable for mechanized harvesting due to its large and flat bottom (4 m wide× 2 m spacing between fruit trees× 1.8 m high). In addition, kiwifruit show a natural drooping state due to their own gravity, as shown in Figure 1(b).

(a)Pergola planting mode *(b)Clusters of kiwifruit*

Fig.1 – Kiwifruit planting patterns

The harvesting robot was built according to the Kiwifruit harvesting operation environment as shown in figure 2. Harvesting robots mainly included the main components such as a six-degree-of-freedom robotic arm, a mobile platform, an end effector and a depth camera. The mobile platform moves the harvesting robot to the picking position. At the same time, the depth camera sends this coordinate information to the controller by obtaining the three-dimensional spatial coordinate information of the kiwifruit. Then, the robotic arm drives the end effector to pick according to the joint movement trajectory planned by the controller.

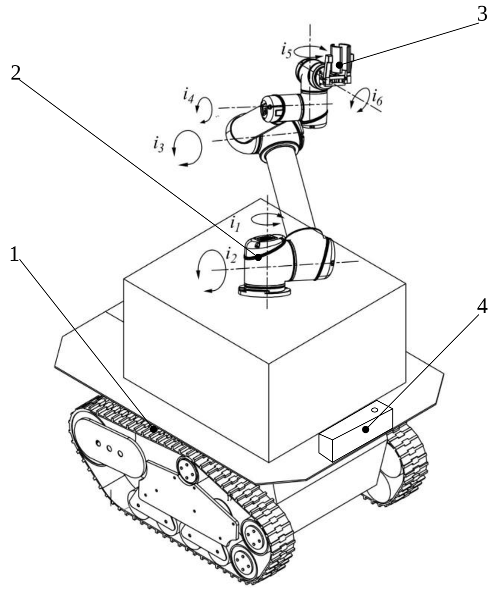

Fig. 2 – Overall structure diagram of kiwifruit harvesting robot

1 Mobile chassis; 2 Robotic arm with six degrees of freedom; 3 End effector; 4 Depth camera

The principle of kiwi fruit picking

During the manual picking operations, the separation of kiwifruit and fruit stem is often achieved by bending the fruit stalk. The resulting shear force separates the fruit from the peduncle by holding the fruit body and rotating it in an arc motion. So, inspired by the above manual picking methods, the separation law between the kiwifruit and the fruit stalk was studied in the early stage.

The results show that when the angle between kiwifruit and fruit stalk is 60°-90°, the separation force required for the fruit is the smallest (*Mu et al., 2020*). The separation process is shown in Figure 3, the separation of fruit and stem is realized, when the kiwifruit stalk moves from point B to point B1, the bending angle of the fruit stem α reaches the separation threshold.

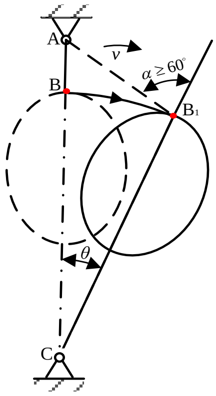

Fig. 3 – Geometric model of the kiwifruit picking method

Note: Line AB is the initial position of fruit stem of kiwifruit under natural growth; Point B is the connection point between the fruit stem and the fruit; Point C is the rotation center point of the end actuator finger; V - is the rotation speed of the end actuator around point C; θ - Rotation angle for end actuator.

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The overall structure design of the end effector

The end effector is mainly composed of three parts: mounting base, pneumatic hand claw and clamping device as shown in Figure 4. The mounting base forms a fixed connection between the end effector and the sixth joint of the robotic arm through screws; Under the control of the solenoid valve, the pneumatic hand claw realizes the effective grasp of kiwi fruits by driving the clamping device; The clamping device is made using 3D printing to minimize the mass of the picking end effector mechanism itself and achieve lightweight processing. The finger dimensions of the picker end effector gripper are designed to be 75 mm long× 65 mm wide × 5 mm thick.

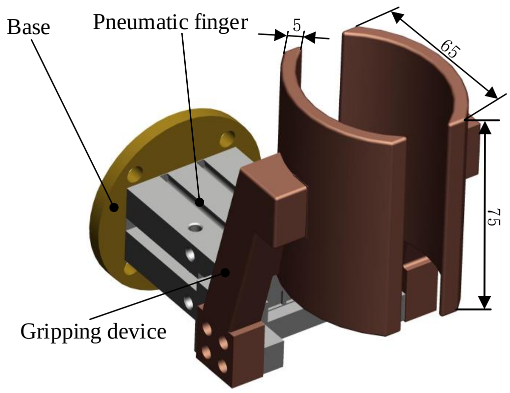


Fig. 4 – Overall Structure of End Actuator

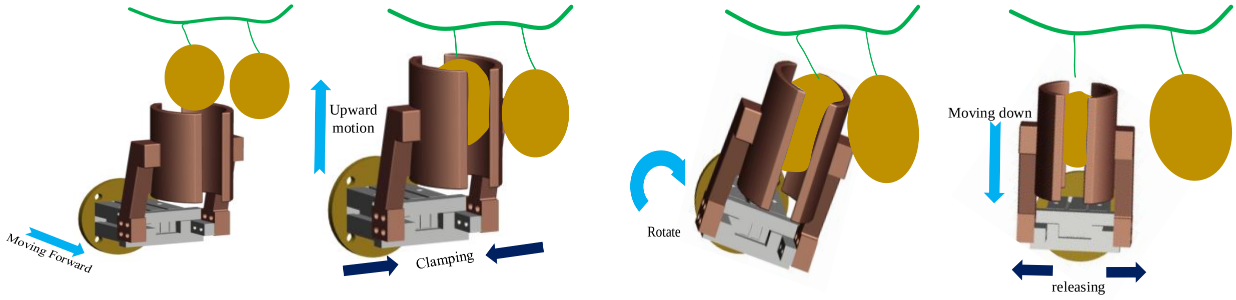
As shown in Figure 5, the kiwi fruit is spherical-like, and the kiwifruit is harvested by bottom-up picking. The process of harvesting kiwifruit with an end effector can be described as:

(1) Close to the fruit. The robotic arm moves the end effector to the base of the kiwifruit so that the center of the finger aligns with the center of the fruit.

(2) Grab the fruit. The end effector moves upwards and the fingers are closed under the drive of the cylinder to achieve the purpose of grabbing the fruit.

(3) Pick the fruit. The end effector rotates to achieve separation of fruit and stem, according to the kiwifruit picking mechanism. The kiwifruit stalk and fruit are successfully separated, when the bending angle of the kiwifruit stem reaches the separation threshold.

(4) Unload the fruit. Spread your fingers to finish picking the fruit. Then get the coordinates of the next target space to be picked.

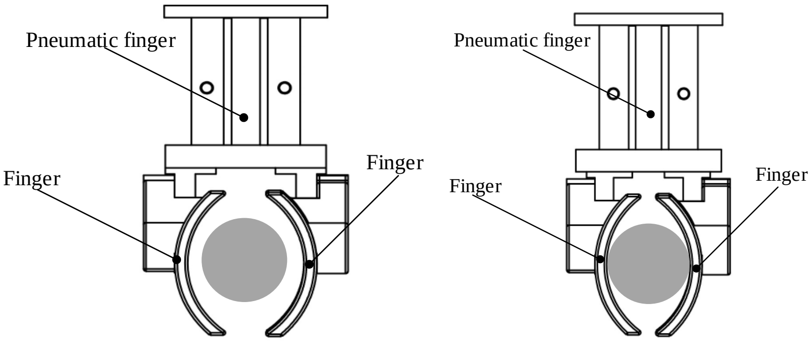


(a) Close to the fruit (b) Grab the fruit (c) Pick the fruit (d) Unload the fruit

Fig. 5– Picking Diagram of End Actuator

Dynamic analysis of the clamping mechanism

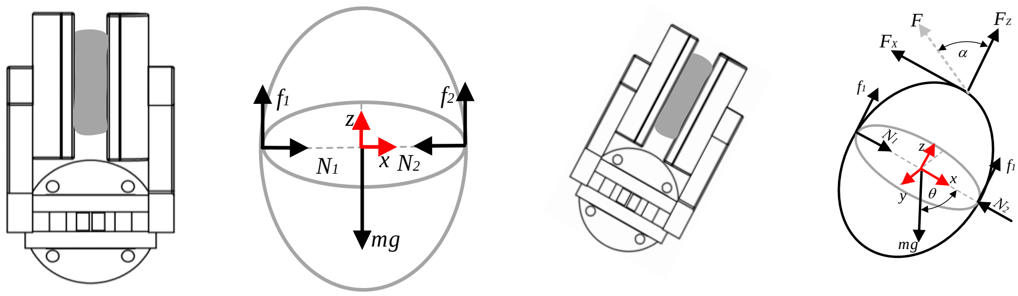
The clamping mechanism consists of two fingers, as a part in direct contact with the fruit. As shown in Figure 6, it has two open and gripping states under the drive of pneumatic hand jaws. The mechanical gripping device cannot apply dynamic pressure through the soft and hard state of the fruit, unlike manual gripping. Therefore, it is necessary to adjust the finger support force, by calculating the movement law of the grasping mechanism and by analyzing the dynamics of the grasping mechanism.



(a) Open state (b) Grasping state

Fig. 6 – Operating schematic diagram of the clamping device

The grasping device needs to complete the two actions of grasping the fruit and separating the fruit, according to the picking mechanism of kiwifruit. The force on the kiwifruit itself is analyzed, during of grasping and separating the kiwi fruit with the designed end effector. The fruit force of the two stages is shown in Figure 7. In the grasping of the fruit, there are two contact points between the fingers and the fruit, the positive pressure between the two contact points is $N_1$and N_2 , and the friction in the vertical direction is $f_1$andf_2. In the fruit separation stage, the rotation angle of the grasping mechanism is θ , and the separation force between the fruit and the peduncle is F.



(a) Grab the fruit (b) Fruit force analysis (c) Separate the fruit (d) Fruit force analysis

Fig. 7 – Kinetic analysis of end effector

In the fruit grasping stage, to ensure that there is no slippage between the fingers and the fruit, it is necessary to meet:

$$\begin{cases} N_1 = N_2 \\ f_1 + f_2 = mg \end{cases} \tag{1}$$

To ensure that there is no relative movement between the fruit and fingers, the friction force is expressed as:

$$\begin{cases} f_1 = \mu N_1 \\ f_2 = \mu N_2 \end{cases} \tag{2}$$

Where:

μ is coefficient of friction, m is fruit mass, N_1, N_2 is normal force, f_1, f_2 is frictional force.

It can be concluded from Formula (1) and Formula (2) that the normal force between fingers and fruit should meet:

$$N_1 \geq \frac{m \cdot g}{2\mu}$$

As shown in Figure 7(d), the fruit breaks apart from the peduncle under tangential shear force by rotating the end effector until the angle between the fruit and the peduncle reaches the separation threshold.

The separation process of the fruit is a uniform movement, so all directions need to meet:

$$\begin{cases} F\cos\alpha + f_1 + f_2 = mg\cos\theta \\ F\cos\alpha + N_1 = N_2 + mg\sin\theta \end{cases} \tag{3}$$

Where:

F is separation force, θ is rotation angle, α is separation threshold.

In addition, considering that kiwifruit is a non-rigid body, it is prone to deformation during the picking process. Therefore, in order to successfully separate the fruit and achieve the purpose of non-destructive harvesting, the gripping force of the fruit needs to meet:

$$N_1 \geq \frac{mg\sin(\alpha - \theta)}{2\mu\sin\alpha} \tag{4}$$

Experimental conditions

The test site was selected at the Kiwifruit Experimental Station of Meixian County of Northwest A&F University (geographical location is 34°07'39" north latitude, 107°59'50" east longitude, altitude 648 m). The test was carried out using a prototype of a kiwifruit harvesting robot as shown in Figure 8. The prototype mainly included end effectors (pneumatic claws: SMC, MHZL2-20D; Solenoid valve: OLK, 4V210-08), depth camera Kinect 2.0 (Microsoft, USA), mobile platform with tracked chassis (Guoxing Intelligence, China), robotic arm UR5 (Universal Robot, Denmark).

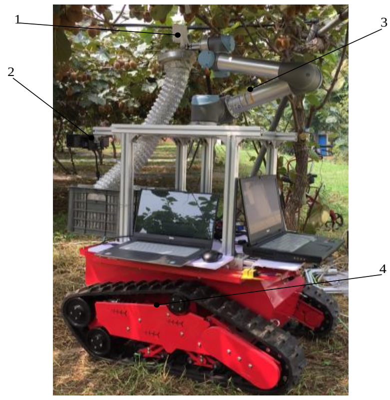


Fig. 8 – Kiwi fruit harvesting robot
1 - End effector; 2 - Kinect camera; 3 - UR5 Mechanical arm; 4 - Mobile chassis

Test parameters and methods

To optimize and determine the optimal conditions for fruit separation, picking tests of scaffolding cultivated kiwifruit were carried out. Firstly, the picking area is randomly selected, the picking area is 600mm*650mm. Secondly, the number of kiwifruits in the picking area was counted.

Each group of experiments operated on 5 picking areas, 20 kiwifruits were picked in each area. If there are less than 20 kiwifruits, the next picking area is selected. Then, the end effectors are set up and adjusted for picking. Finally, the number of successful separations, separation time and damage during the picking process is counted.

The harvesting robot adjusts and sets the end effector before the kiwifruit harvest. Firstly, the air pressure of the pneumatic grip is adjusted to control the clamping force of the fingers. Secondly, the rotation angle and speed of the end effector are adjusted by planning the joint angle movement of the sixth joint of the robotic arm. Finally, positioning accuracy in picking operations is improved by hand-eye calibration and calibration of the end effector dimensions.

The factors affecting the separation efficiency of the robot mainly include finger clamping force, end effector rotation angle and speed. Experimental studies are carried out on finger gripping force, end effector rotation angle and speed to obtain the best parameters. Taking the success rate of fruit separation, fruit separation time and damage rate as evaluation indexes, according to the agronomic requirements of kiwifruit harvesting process. The success rate of fruit separation is the ratio of the number of successfully picked fruits to the total number of fruits that can be picked. The separation time is the time spent in the four stages of fruit picking at the end effector; The damage rate is the ratio of the number of damaged fruits to the total number of fruits successfully picked. The previous studies have shown that when the pressure is less than 15N and the corresponding pressure is 18.8KPa, the fruit is not damaged at this time, so the pressure sensor is used to judge the measured pressure value to judge the fruit damage during the picking process.

Experiment design and analysis

The quadratic regression orthogonal rotation combination test scheme was adopted. The quadratic regression orthogonal rotation combination test scheme was adopted. Finger clamping force X1, end effector rotation angle X2 and rotation speed X3 were taken as test factors, success rate of fruit separation Y1, fruit separation time Y2 and harvesting damage rate Y3 were taken as the evaluation indicator of the test. Table 1 shows the controlling factors and their levels. Quadratic regression equations for the test factors and test indicators are established, using Design-Expert software and experimental design schemes and results. The experimental design scheme and results are shown in Table 2.

The regression equation is:

$$\begin{aligned} Y_1 &= 84.40 + 2.13X_1 + 1.88X_2 - 0.25X_3 - 0.25X_1X_3 \\ &\quad - 0.25X_2X_3 - 1.95X_1^2 - 1.45X_2^2 - 1.20X_3^2 \end{aligned}$$

$$\begin{aligned} Y_2 &= 1.89 - 0.04X_1 + 0.4963X_2 - 0.5738X_3 + 0.08X_1X_2 \\ &\quad - 0.015X_1X_3 - 0.2075X_2X_3 + 0.0323X_1^2 \\ &\quad + 0.1398X_2^2 + 0.4447X_3^2 \end{aligned}$$

$$\begin{aligned} Y_3 &= 7.2 + 4.13X_1 + 0.375X_2 + 3.0X_3 + 0.50X_1X_2 \\ &\quad + 1.25X_1X_3 + 0.25X_2X_3 + 3.15X_1^2 - 0.85X_2^2 + 0.40X_3^2 \end{aligned}$$

Table 1

Experimental factor coding

Code	Finger clamping force (N)	End effector rotation angle (°)	Rotation speed (°/s)
-1	1N	50	30
0	3N	65	60
1	5N	80	90

Table 2

Experimental design and protocol

Serial No	factor			index		
	X1	X2	X3	Y1	Y2	Y3
1	-1	-1	0	77	1.74	5
2	1	-1	0	81	1.51	13
3	-1	1	0	81	2.45	5
4	1	1	0	85	2.54	15
5	-1	0	-1	79	2.94	5
6	1	0	-1	84	2.82	10
7	-1	0	1	79	1.88	9

Serial No	factor			index		
	X1	X2	X3	Y1	Y2	Y3
8	1	0	1	83	1.82	19
9	0	-1	-1	80	2.34	4
10	0	1	-1	84	3.87	4
11	0	-1	1	80	1.49	9
12	0	1	1	83	2.19	10
13	0	0	0	85	1.65	6
14	0	0	0	84	1.95	7
15	0	0	0	83	1.71	9
16	0	0	0	87	2.01	7
17	0	0	0	83	2.12	7

The analysis of variance of the experimental results is shown in Table 3. The significance level of the experimental index model is in a state of extremely significant difference, and the misfit term is greater than 0.05. Experimental results show that the three regression equations have high fitting degree and the model is statistically significant.

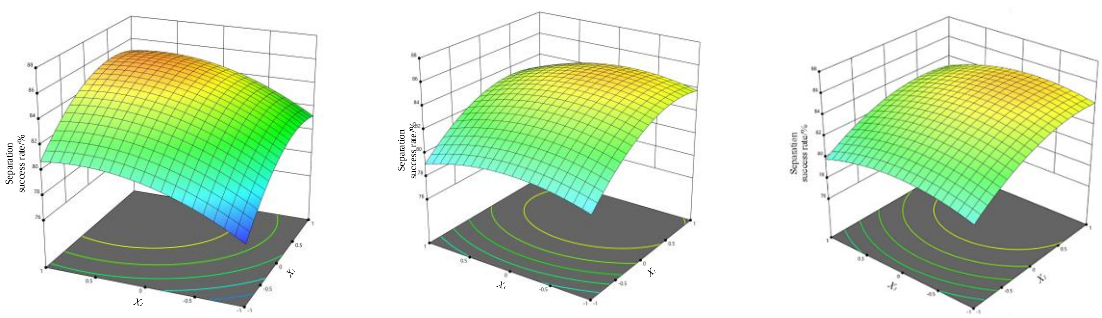
In the Y_1 model, X_1 and X_2 had a significant impact on the model, X_1^2 had a significant impact on the model, and other factors had no significant impact on the model. In the Y2 model of separation time, X_2, X_3 and X_3^2 had a significant effect on the model, while other factors had no significant influence on the model. In the Y_3 model of damage rate, X_1, X_2 and X_1^2 had a significant impact on the model, X_2X_3 factors had a significant impact on the model, and other factors had no significant influence on the model.

Table 3

Analysis of variance

variance source	Separation success rate Y_1				Separation time Y_2				Damage rate Y_3			
	Sum of squares	Free degree	F	p	Sum of squares	Free degree	F	p	Sum of squares	Free degree	F	p
model	99.61	9	6.77	0.0098**	5.78	9	20.52	0.003**	261.69	9	31.07	<0.0001**
X1	36.13	1	22.09	0.0022**	0.0128	1	0.4097	0.5425	136.13	1	145.48	<0.0001**
X2	28.13	1	17.19	0.0043**	1.97	1	63.06	<0.0001**	1.13	1	1.20	0.3091
X3	0.5000	1	0.3057	0.5976	2.63	1	84.29	<0.0001**	72.00	1	76.95	<0.0001**
X1 X2	0.0000	1	0.0001	1.0000	0.0256	1	0.8194	0.3955	1.0000	1	1.07	0.3356
X1 X3	0.2500	1	0.1528	0.7075	0.0009	1	0.0288	0.8700	6.25	1	6.68	0.0362*
X2 X3	0.2500	1	0.1528	0.7075	0.1722	1	5.51	0.0513	0.2500	1	0.2672	0.6212
X12	16.0105	1	9.79	0.0166*	0.0044	1	0.1402	0.7192	41.78	1	44.65	0.0003**
X22	8.8526	1	5.41	0.0529	0.0822	1	2.63	0.1488	3.04	1	3.25	0.1144
X32	6.0632	1	3.71	0.0956	0.8329	1	26.66	0.0013**	0.6737	1	0.7200	0.4242
residual	11.45	7			0.2187	7			6.55	7		
Misfit term	0.2500	3	0.0298	0.9920	0.0578	3	0.4792	0.7140	1.75	3	0.4861	0.7101
error	11.20	4			0.1609	4			4.8	4		
sum	111.06	16			6.00	16			268.24	16		

Note : indicates significant difference (P<0. 05); **Indicates a very significant difference (P<0. 01)*



(a) (b) (c)

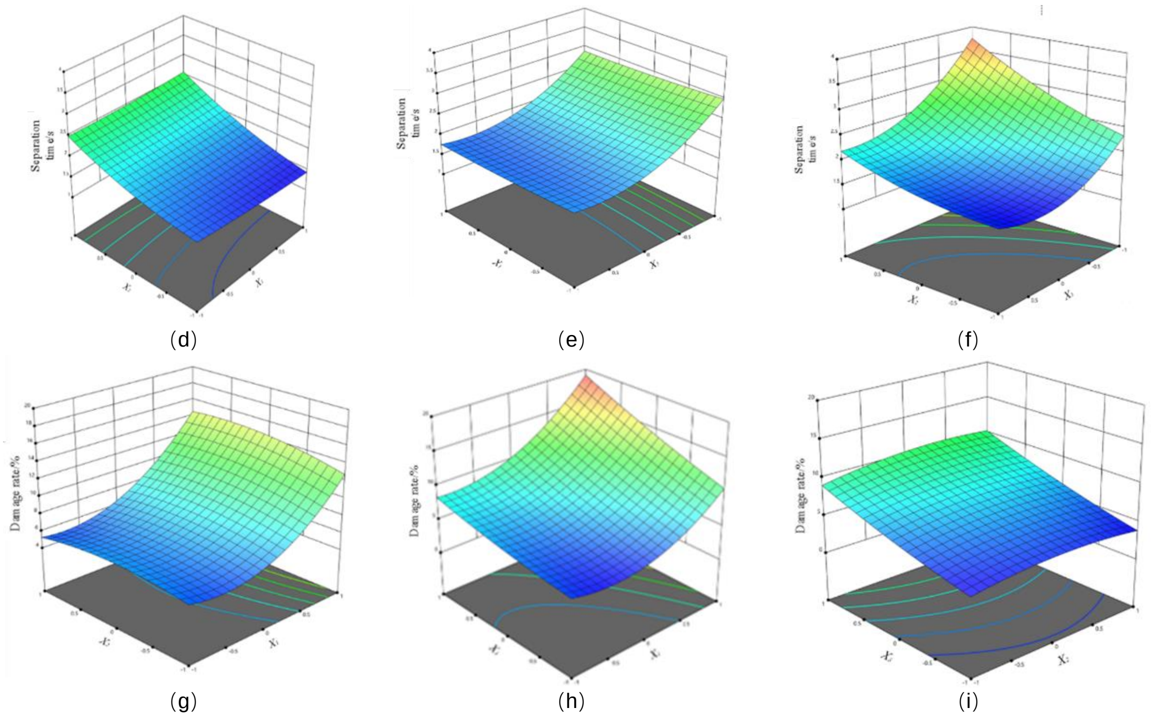


Fig. 9 – Response surface of interaction factors to performance indicators

Analysis of the effect of interaction factors on performance

Fig. 9(a)(b)(c) shows the influence of interaction factors on the success rate of fruit separation. Overall, the end effector rotation speed is moderate, and the higher the clamping force and rotation angle, the higher the success rate of fruit separation. The greater the clamping force, the fewer times the kiwifruit will slip during the separation process and the higher the success rate of separation. In addition, kiwifruit stalks and trunks are non-rigid materials. Deformation occurs during fruit separation: the rotation angle of the end effector is too small to make the separation angle not reach the separation threshold. As a result, the kiwifruit peduncle is not separated. The greater the rotation angle, the greater the success rate of separation between the stem and the kiwifruit. The rotation speed has no effect on the success rate of fruit separation.

Figure 9(d)(e)(f) shows the effect of interaction factors on fruit separation time. In general, the lower the angle of rotation of the end effector, the faster the rotation speed and the less time for kiwifruit separation. In addition, the size of the clamping force has no effect on the kiwifruit separation time.

Figure 9(h)(i)(j) shows the effect of interaction factors on fruit damage rate. In general, the greater the end effector clamping force, the faster the rotation speed, and the higher the kiwifruit damage rate. The greater the clamping force, the greater the pressure per unit area of the kiwifruit, resulting in damage during the harvesting process. In addition, if the rotation speed is too large, it will cause the surrounding branches and fruits to vibrate in the moment of separating the fruit. This vibration causes fruit to collide with fruit. During the next harvesting process, the vibrating fruit and the end effector are prone to collision. The effect of rotation angle on damage rate is not obvious.

Optimal parameter combination solution

The separation success rate, separation time and damage rate of each parameter are optimized to improve the fruit separation efficiency and determine the optimal picking parameters of the kiwifruit harvesting robot.

According to the module Numerical, the optimal combination of picking parameters is solved, where the optimization constraints are:

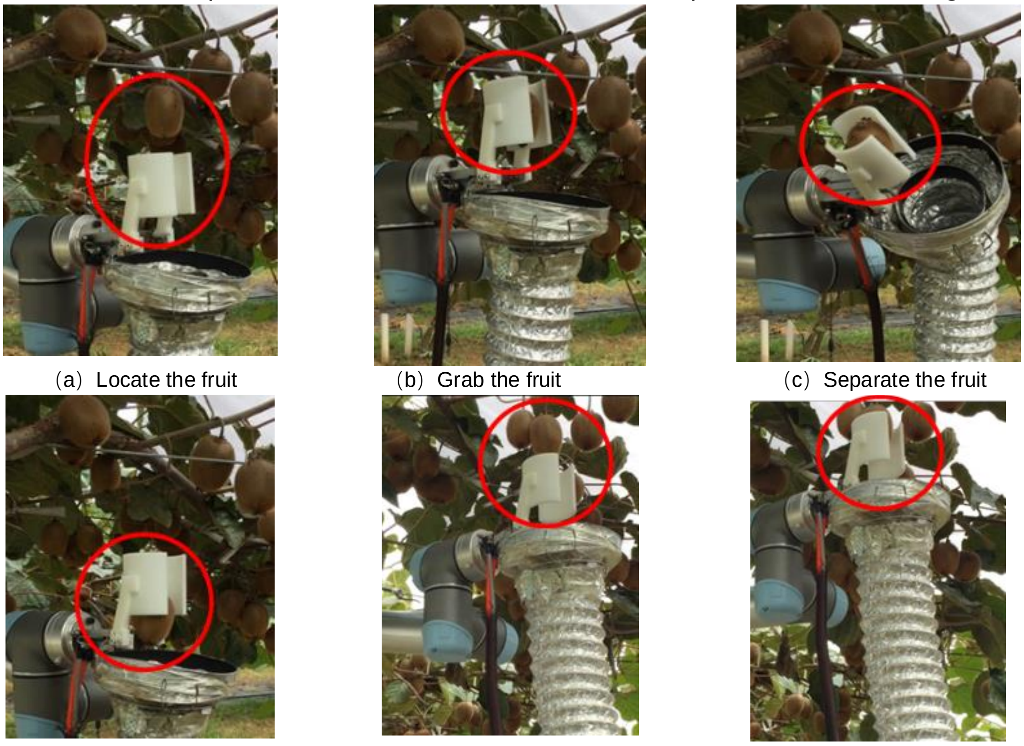
$$\begin{cases} \max Y_1(X_1, X_2, X_3) \\ \min Y_2(X_1, X_2, X_3) \\ \min Y_3(X_1, X_2, X_3) \\ s.t. \begin{cases} -1 \le X_1 \le 1 \\ -1 \le X_2 \le 1 \\ -1 \le X_3 \le 1 \end{cases} \end{cases}$$

The optimal value occurs when the clamping force level is -0.027, the rotation angle level is -0.045, and the rotation speed level is 0.001. The corresponding working parameters are 3.05 N, the rotation angle is 65.75°, the rotation speed is 60.03°/s, the separation success rate is 84.253%, the separation time is 1.866 s, and the damage rate is 7.077%.

Validation test

Experiments are carried out to verify that the obtained combination of picking parameters is optimal. The picking process is shown in Figure 10, the robotic arm moves to the picking position of the fruit to be picked according to the planned path, the end effector grabs the fruit and separates the fruit and the stem. After the harvesting is completed, the robotic arm moves to the next picking target for operation. A total of five groups of picking experiments were carried out, and 20 kiwifruits in the selected area were picked and averaged.

The verification results show that under the optimal combination of picking parameters, the separation success rate is 83%, the separation time is 1.95 s, and the damage rate is 8%. The relative error between the experimental value and the optimized value is less than 5%, and the optimization result is significant.



(a) Locate the fruit (b) Grab the fruit (c) Separate the fruit

(d) Unload fruits (e) Move to the next fruit position (f) Pick the next fruit

Fig. 10 – Kiwifruit picking process

CONCLUSIONS

A kiwifruit picking end effector was designed and developed through the basic parameters and bending picking mechanism of kiwifruit. This end effector enables continuous kiwifruit picking.

The response surface method was used to determine the optimal range of picking parameters, where the fruit separation time, damage rate and harvest success rate in the experiment were taken as indicators. The test results show that when the clamping force is 3.05 N, the separation angle is 65.75°, and the separation speed is 60.03°/s, the harvesting robot has the best picking effect.

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