TRIZ-AIDED DESIGN AND EXPERIMENT OF KIWIFRUIT PICKING END-EFFECTOR / TRIZ 辅助猕猴桃采摘末端执行器设计与试验

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ABSTRACT

Currently kiwifruit picking process mainly leverages manual labour, which has low productivity and high human effort, meanwhile the existing kiwifruit picking machinery also has low picking efficiency and easily damages fruits. In this regard within this paper, a multi-fruit envelope-cutting kiwifruit picking end-effector was designed by applying TRIZ assistance. Firstly, a common kiwifruit picking end-effector was selected as the prototype system. The functional analysis method of TRIZ was applied to identify the functional defects of the system. TRIZ solution tools such as technical contradiction analysis, substance-field analysis, and trimming were utilized to improve and innovate the system, resulting in the design of a kiwifruit picking end-effector that recognizes fruits, envelops fruit clusters, cuts and separates fruit stalks, and is capable of picking kiwifruit in clusters. Then, simulation software ADAMS was applied to perform gait simulation of the end-effector picking action to verify the smoothness and coherence of the picking process. Finally, a kiwifruit picking test stand was set up to conduct picking tests in the form of fruit clusters. The results showed that the average time to pick each cluster of fruits was 8.8 s, the picking success rate was 89.3%, and the picking damage rate was 6.0%. All the indicators were better than the prototype and met the expected design requirements.

摘要

目前，在猕猴桃收获过程中多采用人工采摘作业，生产率低、劳动强度大，而现有的猕猴桃采摘机械也存在采摘效率低、易损伤果实等问题。对此，本文应用 TRIZ 理论辅助设计了一种多果包络切割式的猕猴桃采摘末端执行器。首先，选取一种常见的猕猴桃采摘末端执行器为原型，应用 TRIZ 的功能分析方法识别其存在的功能缺陷，并应用技术矛盾分析、物场分析、裁剪等 TRIZ 解题工具进行改进创新，设计了一种自动识别果实-包络果实簇-切割分离果梗的猕猴桃采摘末端执行器，可对猕猴桃成簇采摘。然后，应用仿真软件 ADAMS 对末端执行器的采摘动作进行步态仿真，验证采摘过程的平稳连贯性。最后，搭建猕猴桃采摘试验台，以果实簇的形式进行采摘试验。结果表明，该末端执行器采摘每簇果实平均用时为 8.8s，采摘成功率为 89.3%，采摘损伤率为 6.0%，各项指标均优于原型系统，符合预期设计要求。

INTRODUCTION

Kiwifruit is rich in nutritional value, known as the "king of fruit", and has a very large market demand. China is the world's largest agricultural country in terms of kiwifruit planting area and production, with its annual yield exceeding 3 million tons *(Fazayeli et al., 2019)*. The kiwifruit industry in China is still labour-intensive compared to developed countries, which especially manifests in the time-consuming and laborious harvesting process *(Yuan et al., 2020)*. With the scale-up of the kiwifruit planting industry, the traditional manual picking method is difficult to meet the current market demand. Therefore, the study of kiwifruit picking robots not only helps to reduce labour costs, and improve picking operation efficiency and kiwifruit high quality rate but is also of crucial importance for realizing the mechanization and standardization of the kiwifruit industry *(Guo et al., 2022; Li et al., 2022)*.

In recent years, scholars have conducted a series of studies on fruit and vegetable picking robots such as kiwifruit *(Williams et al., 2019; Williams et al., 2020)*, citrus *(Sun et al., 2023; Yin et al., 2023),* apple *(Yan et al., 2021; Hu et al., 2022),* cucumber *(Mao et al., 2020; Kim et al., 2023)*, tomato *(Feng et al., 2018; Wang et al., 2023)* and so on. However, improving fruit-picking efficiency and ensuring non-destructive fruit picking are two key criteria of fruit-picking robots, in which non-destructive picking is mainly ensured by the end-effector. For example, *Fu et al., (2015),* designed a clamp-type kiwifruit picking end-effector in which the fruit was held by the clamping mechanism and automatically rotated to separate the fruit from the stalk.

Silwal et al. (2017), developed a clamping-type apple picking end-effector, consisting of three drivers and three fingers. After gripping the fruit with the three fingers, the base drove the fruit to rotate until it separated from the stalk. *Xu et al., (2018),* designed a suction-type navel orange picking end-effector, which utilized a suction cup to hold the fruit and a cutting blade to separate the fruit from the stalk. *Xiong et al. (2019),* designed a clamping-type strawberry picking end-effector, which separated the fruit from the stalk by pulling when the fruit was sucked. *Mu et al., (2020),* designed a clamp-type kiwifruit picking end-effector that used two bionic fingers to separate the fruit from the stalk by repeatedly bending the fingers after the fruit was clamped. *Xu et al., (2023),* designed a clamp-type broccoli picking end-effector to harvest broccoli by clamping-cutting method.

The above studies provide useful insights for the development of harvesting techniques for kiwifruit and other fruits and vegetables. However, the current kiwifruit picking end-effector is mostly of single-fruit clamping or sucking structure, which is prone to two problems during the fruit picking process: ① Picking kiwifruit by clamping or sucking is unstable when gripping the fruit, therefore leading to fruit loss. ② Approximately 87% of kiwifruit are distributed in clusters in the canopies *(Fu et al., 2018)*, and the use of single-fruit picking is highly possible to disturb neighbouring fruits, therefore leading to fruit drop.

TRIZ (Theory of Inventive Problem Solving) is a systematic and structured innovation methodology (*Altshuller et al., 1984*). The process of applying TRIZ to innovation design can be divided into four parts. Part I is problem description: The function, working principle, composition, and existing issues in the prototype system is described. Part II is problem analysis: TRIZ analytical tools such as functional analysis and cause analysis are utilized to find the functional deficiencies of the prototype system, and to explore the root causes of the problems. Then starting point can be caught to resolve these issues. Part III is problem- solving: problem-solving tools such as contradiction analysis and substance-field analysis are used to find innovative solutions. Part IV is scheme decision-making: all conceptual schemes are cross evaluated in terms of economy and implementability, etc, and the final implementation schemes are determined after selection and synthesis. It has been demonstrated in practice (*Yang et al., 2018; Azammi et al., 2018; Kang et al., 2022*), that TRIZ is applied to product design that can assist designers in triggering inspiration from different dimensions, finding solutions in a broader field, and improving the quality and efficiency of design.

Considering that the current kiwifruit picking robots lack design theory guidance in structure and usually have long design cycles as well as low product success rates, TRIZ was used to guide the conceptual design of a kiwifruit-picking end-effector. First, TRIZ tools were applied to analyse the problems of the prototype system and to improve and innovate it, and a multi-fruits envelope-cutting-type kiwifruit picking end-effector was designed. Then, ADAMS was applied to perform a gait simulation of the end-effector picking action to verify the effectiveness of the expected operation. Finally, a kiwifruit-picking test stand was set up to verify the working effect of the kiwifruit-picking end-effector.

MATERIALS AND METHODS

Background

Kiwifruit belongs to vine plants, and the trellis planting mode is mostly used in orchards, as shown in Figure 1. The fruit hangs down on the vine of the fruit tree in a clustered distribution, with a large bottom space and no interference from branches, leaves, etc., which is conducive to the implementation of the picking action *(Fu et al., 2015)*. The average lateral spacing of the trellis is 4 m, the longitudinal spacing is 2 m and the height is 2 m. The fruits are generally distributed within a spatial range of 1.5~1.8 m above the ground, with a cluster of 3~7 fruits.

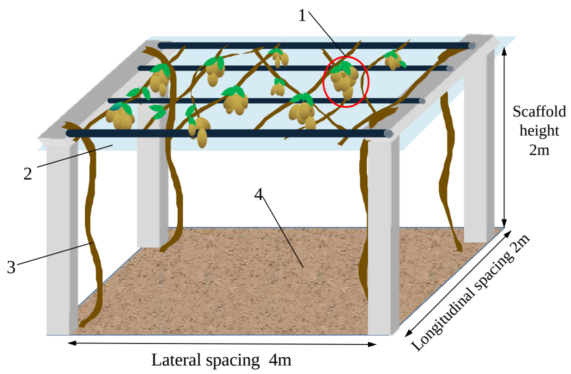


Fig. 1 - Equivalent model of trellis space

1. kiwifruit cluster; 2. trellis model; 3. kiwifruit tree; 4. ground level

According to the growth characteristics and planting environment of kiwifruit in the orchard, the expected picking indicator of the kiwifruit picking end-effector is a fruit picking speed of 7-10 s/cluster, with a success rate of over 90% and a fruit damage rate of less than 10%.

The kiwifruit-picking robot is mainly composed of an end-effector, a mobile device, a support device, and a collection device. During the robot working process, the end-effector plays a key role, which directly affects the picking efficiency and fruit damage rate of the picking robot. While the existing picking end-effector has the problem of low picking efficiency and easy fruit damage. To solve the above problems, a common kiwifruit picking end-effector was selected as a prototype in this paper, and TRIZ theory was applied to analyse the key structural defects and an improvement scheme was proposed.

Problems of the Prototype

1) Overall Structure: A common structure of clamped-type picking end-effector *(Rong et al., 2019)*, as shown in Figure 2, is mainly composed of a clamping support frame, drive screw, ball screw, fruit stalk clamping fingers, identification sensor, V-shaped gripper, stepper motor, frame.

2) Working Principle: First the position of the fruits is detected by the recognition sensor, and the V-shaped gripper is driven by the stepper motor to clamp the fruit with a preset clamping force. Then, the clamping stepper motor drives the fruit stalk clamping fingers to clamp the fruit stalk, and the linear stepper motor drives the clamping support frame forward by the drive screw (The fruit stalk clamping fingers are installed on the clamping support frame). Finally, the stalk is separated from the fruit by the pulling force of the fruit stalk clamping fingers and the fruit is picked completely.

3) Experimental indicators of the prototype *(Rong et al., 2019)*: The success rate of fruit picking is 86%, the fruit damage rate is 8%, and the average picking time of a single fruit is 17±0.5 s.

4) Existing problems: The pulling force on the fruiting stalk is excessive, which may easily damage the fruit. There are also problems during the picking process such as the weak ability to recognize fruits and the insufficient ability to clamp fruits.

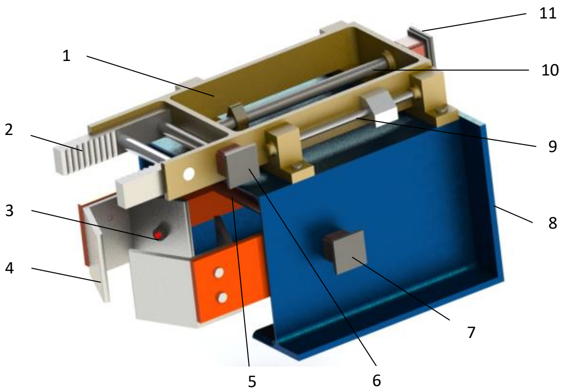


Fig. 2 - Clamp-type kiwifruit picking end-effector

1. clamping support frame; 2. fruit Stalk clamping fingers; 3. recognition sensor; 4.v-shaped gripper; 5. ball screw; 6. clamping stepper motor; 7. drive stepper motor; 8. frame; 9. guide rail slider; 10. drive screw; 11. linear stepper motor

TRIZ-Aided Design of End-Effector

The end-effector is installed at the front end of the robotic arm, and its main function is to pick fruit. It is mainly composed of three parts: a fruit clamping device, a fruit and stalk separation device and a recognition device.

System Function Analysis of the Prototype

System function analysis is one of the most important tools in TRIZ for analysing problems, where the interactions of system components are analysed for accomplishing function *(Fu et al., 2021).* In this paper, the system function model of the end-effector was established by the system function analysis, the functional relationship between the components in the system was clarified, and the functional defects of the end-effector were found, which provided the direction for the subsequent improvement and innovation.

Name of technical system: picking end-effector.

Function of the system: separation of the fruit from the stalk.

The objects of the system: fruit and stalk.

Components of the system: V-shaped gripper, recognition sensor, ball screw, drive stepper motor, fruit stalk clamping fingers, clamping stepper motor, clamping support frame, guide rail slider, linear stepper motor.

Components of super-system (Super-system is external components that exist outside the system and have an impact on the current system): Frame.

The functional relationship among functional objects, system components, and super-system components was analysed, and the system function model was established in Figure 3.

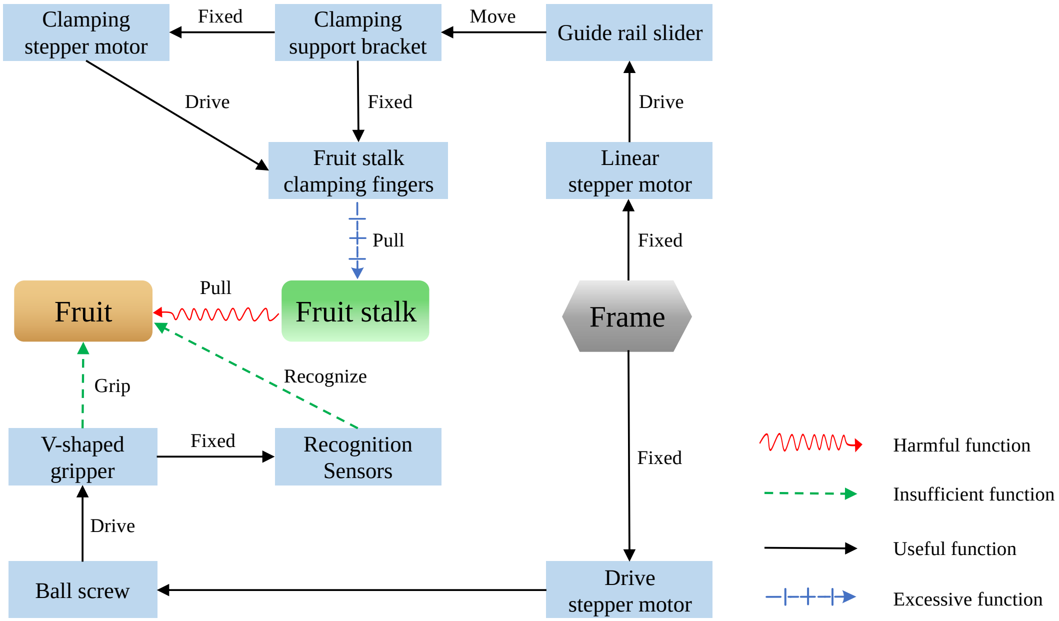


Fig. 3 - System function model of the prototype

As shown in Figure 3, the prototype has three functional defects: ① the V-shaped gripper has insufficient ability to grip fruits, which can easily cause fruit detachment. ② insufficient recognition of fruits by recognition sensors, resulting in low fruit-picking efficiency. ③ in the process of pulling off the stalk by the fruit stalk clamping fingers, the stalk can easily cause damage to the fruit skin.

Next, for the functional defect ① of the prototype, the technical contradiction analysis tool in TRIZ was applied to improve and innovate the design of the fruit clamping device; For the functional defect ②, the substance-field analysis tool in TRIZ was applied to improve and innovate the design of the recognition device; For the functional defect ③, the trimming tool in TRIZ was applied to improve the innovative design of the fruit and stalk separation device.

Design of Fruit Clamping Device

The technical contradiction analysis is one of the tools for problem-solving in TRIZ and refers to the contradiction where one parameter of a technical system is improved and causes another parameter to deteriorate. Technical contradictions are defined by TRIZ through 39 general engineering parameters and then the problem is solved according to the innovation principles recommended by the contradiction matrix table *(Fu et al., 2021)*.

For functional defect ①, the technical contradiction was defined: If the size of the V-shaped gripper was increased, then kiwifruits with different shapes could be adequately gripped, but it increased the weight of the end effector, which led to inconvenient movement and reduce fruit picking efficiency; If the size of the V-shaped gripper was reduced, then the weight was reduced, but it couldn't adequately grip various shapes of kiwifruit.

In this technical contradiction, the improved parameter is NO.35 (adaptability or versatility), and the deteriorated parameter is NO.1 (weight of moving object). Finding the contradiction matrix table to obtain the reference innovative principles: NO1 (Segmentation), NO6 (Universality), NO15 (Dynamicity), and NO8 (Counterweight). To address the lack of adaptability and versatility of the end-effector, valuable inventive principles were screened, and 2 conceptual solutions were proposed, as shown in Table 1.

Table 1

Analysis of valuable inventive principles

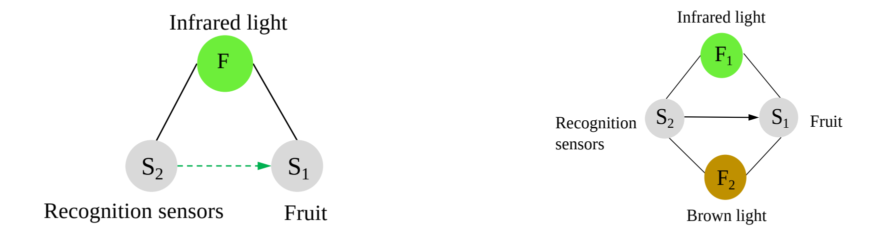
Serial number	Principle	Valuable content in detail	Conceptual solution
1	Universality	Enabling an object to perform many different functions	A device that could both adequately pick kiwi fruit of all shapes and assist in the collection of the fruit was installed to reduce the complexity of the mechanical system when picking the fruit.
2	Dynamicity	Increasing the motion of an object by turning its immobile parts into moving ones	Making the clamping device movable, and when picking kiwifruits of various shapes, the range of fruits surrounded could be adjusted by moving the clamping device.

From the above analysis, synthesizing conceptual solutions 1 and 2, a fruit clamping device was designed, as shown in Figure 5. The clamping device was designed as an envelope-type picking bin structure. During the picking process, the end effector moves upwards from the bottom of the kiwifruit, surrounding a cluster of fruits into the picking bin, achieving full clamping of the picked fruits. Meanwhile, a fruit collection end was added to the lower end of the picking bin, which could assist in the collection of fruits and improve the picking efficiency.

Design of Recognition Device

The substance-field analysis is one of the tools for problem-solving in TRIZ. The most basic substance field model is composed of three basic elements: S2 represents the tool (functional performer), S1 represents the object of action (functional receiver), and F is the interaction field between them. The problematic substance-field model is solved with 76 standard solutions from TRIZ *(Fu et al., 2021)*.

For the functional defect ②, the substance-field model of the problem was established, as shown in Figure 4(a). The light Field generated by S2 (the recognition sensors) couldn't adequately recognize S1 (the fruits). The TRIZ standard solution S2.1.2 was applied, and the substance-field model of the solution was shown in Figure 4(b).



(a) substance-field model of the problem *(b) substance-field model of the solution*

Fig. 4 - Substance-field analysis model

F-field, S1-object of action, S2-tool.

Conceptual solution 3 was proposed by the substance-field analysis: A colour detection sensor was installed on the baffle at the port of the picking bin and the detected colour was set to tan (the colour of the fruit is tan, and the colour of the fruit stalk is dark green). Meanwhile, two fruit recognition sensors were installed on the side panel of the picking bin, as shown in Figure 5. After the fruits were recognized by fruit recognition sensors, the end-effector moved upward to envelop the fruits into the picking bin. When the colour detection sensor detected that all the picked fruits had entered the picking bin, the end effector stopped moving.

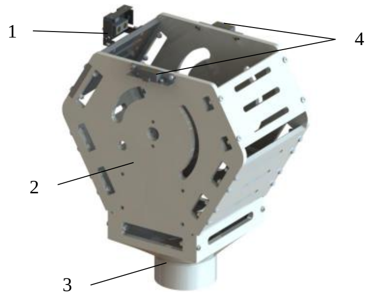


Fig. 5 - Structure of envelope-type picking bin

1. colour detection sensor; 2. envelope picking bin; 3. fruit collection end; 4. fruit recognition sensor

Design of Separation Device for Fruit Stalks

Trimming is one of the important tools for problem-solving in TRIZ. The principle of trimming is to optimize the functional structure of the system and improve the ideality by deleting or replacing the problematic components and redistributing the useful functions *(Fu et al., 2021)*.

For the functional defect ③, the TRIZ trimming tool was applied to analyse and solve the problem. In the process of pulling off the stalk by the fruit stalk clamping fingers, the stalk would pull on the fruit and cause damage to it. Therefore, the fruit stalk clamping fingers were identified as the trimming object, but their useful function needed to be retained. According to the trimming rule, "the function of the problematic component is replaced by the newly added component", a rotating cutter device was used to replace the fruit stalk clamping fingers to complete the useful function of pulling the stalk.

Conceptual solution 4 was proposed by the trimming tool as shown in Figure 6. The rotary cutter rotated clockwise at a preset speed to cut off the stalks of the fruits in the picking bin. Then, driven by the rotary stepper motor, the rotary cutter continued to rotate until it stopped at 180° from the initial position, waiting for the next picking. The rotary cutter device rotated one circle and could complete two cutting operations on the fruit stalks.

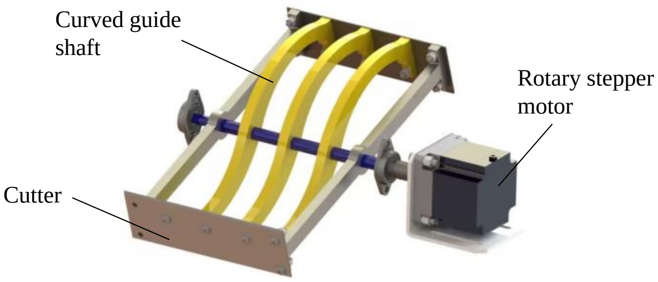


Fig. 6 - Schematic diagram of the rotary cutter structure

Structure and Working Principle of End-Effector

Synthesizing the above conceptual solutions, a multi-fruit envelope-cutting-type kiwifruit picking end-effector was designed, as shown in Figure 7. First, the end effector was delivered by the robotic arm to the appropriate kiwifruit picking area, then the recognition sensor started to scan the surrounding fruits. After recognizing the fruits, the robotic arm with the end-effector moved upward to envelop the fruit into the picking bin. Then, when the colour detection sensor detected that all fruits had entered the picking bin, the robotic arm stopped moving. The rotary cutter rotated clockwise to cut off the fruit stalks in the picking bin. Finally, the fruits slowly passed through the picking bin along the curved guide shafts and fell into the fruit collection end, completing a single picking process. The end-effector adopts the operation mode of enveloping the fruits - cutting the fruit stalks, it could realize the continuous picking of multiple fruits, improve the picking efficiency, and reduce the damage rate of the fruits.

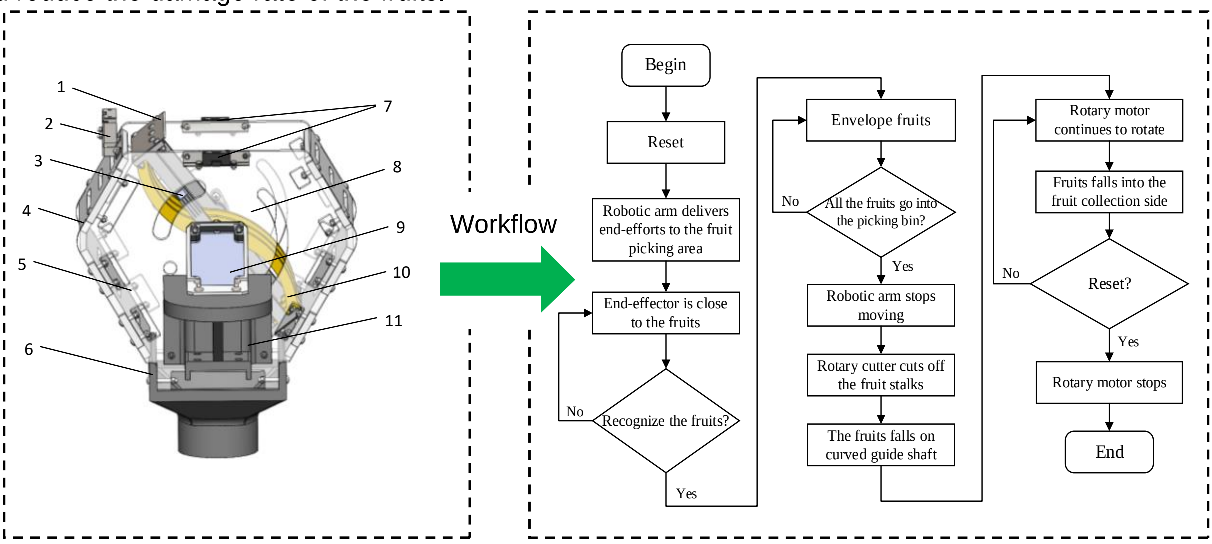


Fig. 7 - Schematic diagram of the end-effector structure and workflow

1. blade; 2. colour detection sensor; 3. hall sensor; 4. Baffle; 5. side plate; 6. fruit collection end; 7. fruit recognition sensor; 8. picking bin; 9. rotary stepping motor; 10. curved guide shaft; 11. connector.

The parameters of the kiwifruit-picking end-effector are shown in Table 2.

Table 2

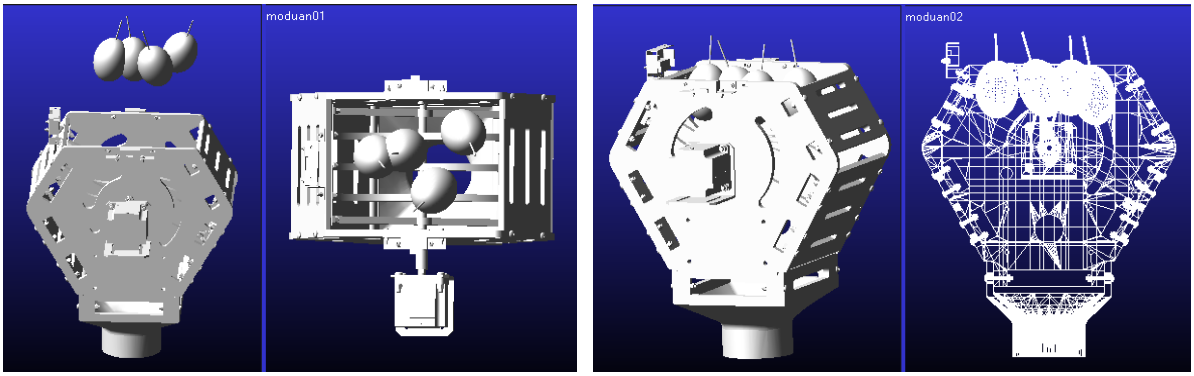
Parameters of the kiwifruit picking end-effector

Parameters	Numerical value
Weight of end-effector/kg	4
Lifting height of robotic arm/m	0~0.9
Operating speed of robotic arm/ (m.s-1)	1.5
Speed of stepper motor/(r.min-1)	6

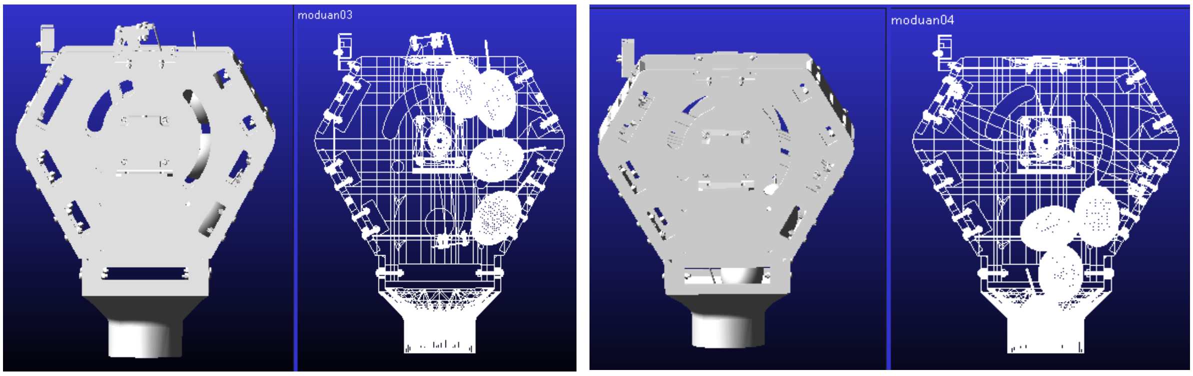
RESULTS

Dynamics Simulation Analysis

To verify whether there is interference between the various mechanisms of the kiwifruit-picking end-effector and whether the picking action is smooth and coherent during the fruit-picking process, a fruit cluster of four kiwifruits was selected, with each kiwifruit having approximate dimensions of 65 mm in length, 52 mm in width, and 45 mm in thickness. ADAMS was used to simulate and analyse the picking action of the end-effector, including four motion gaits of identifying the fruits, enveloping the fruits, cutting off the fruit stalks and resetting the end-effector. The simulation results are shown in Figure 8.



(a) recognizing fruits *(b) enveloping fruits*



(c) cutting fruit stalks *(d) resetting the end-effector*

Fig. 8 - Simulation of end-effector picking action

STEP1: The end-effector recognized the kiwis by the fruit recognition sensors. STEP2: The robotic arm with the end-effector moved upward to envelop the fruits into the picking bin. STEP3: After the colour detection sensor detected that all fruits had entered the picking bin, the rotary cutter rotated clockwise to cut off the fruit stalks in the picking bin; STEP4: During resetting the end-effector, the fruits slowly passed through the picking bin along the curved guide shafts and fell into the fruit collection end. The simulation results showed that during the process of picking the fruit clusters, the various mechanisms of the end-effector were coordinated and non-interfering with each other, and the operation was smooth and coherent, which was in line with the expected design requirements.

Test Stand Set Up

A picking test stand was set up in a laboratory conducting picking trials as shown in Figure 9. The test stand mainly includes: the AUBO-E5 robotic arm test stand, trellis model, the kiwifruit picking end-effector and its control system, Lenovo R7000P portable computer, collection device, etc.

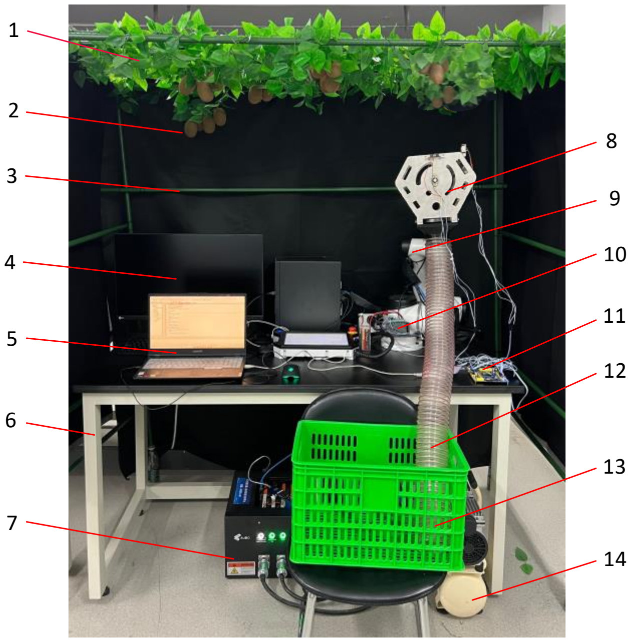


Fig. 9 - Kiwifruit picking test stand

1. vine; 2. kiwifruit; 3. trellis model; 4. upper computer; 5. portable laptop; 6. test stand; 7. control box; 8. end-effector; 9. robotic arm; 9. motor driver; 11. micro-controller control board; 12. hose; 13. fruit collection box; 14. compressed air pump

Test Method

The picking experiment was carried out on 20 July 2023. The AUBO-E5 robotic arm was used to support the end-effector for the picking operation, and the picking operation flow as shown in Figure 9, 75 kiwifruits of different shapes were selected for testing. The dimensions of the selected kiwifruit were measured to be a maximum of 72.7 mm and a minimum of 61.4 mm for the length, a maximum of 56.7 mm and a minimum of 49.5 mm for the width, and a maximum of 48.3 mm and a minimum of 44.6 mm for the thickness of the fruit. Based on the characteristics of kiwifruit clusters, 75 fruits were divided into 5 groups according to the number of fruits per cluster: 3, 4, 5, 6 and 7, and each group had 3 clusters with the same number of fruits. In this section, the picking success rate, average picking time per picking, and picking damage rate are used as the evaluation indexes for fast and non-destructive picking. The definitions are as follows:

$$T = \frac{t_0 - t_1}{c} \tag{1}$$

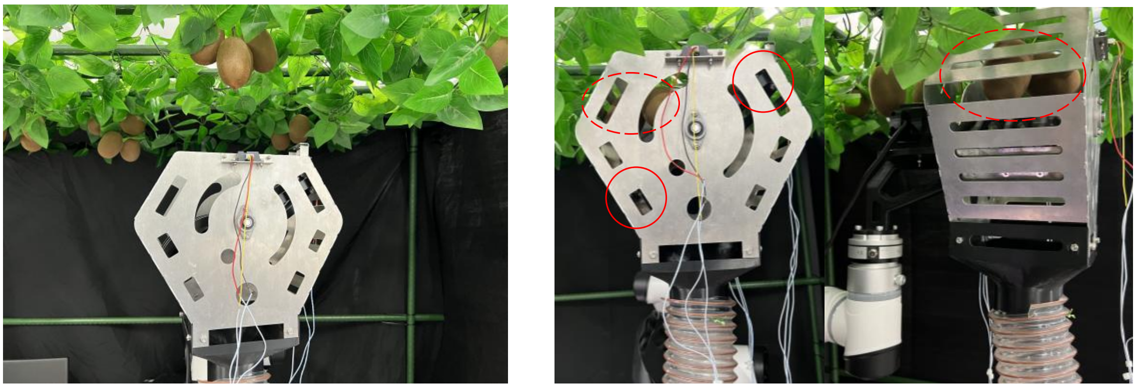
$$S = \frac{n}{h} \times 100\% \tag{2}$$

$$D = \frac{m}{n} \times 100\% \tag{3}$$

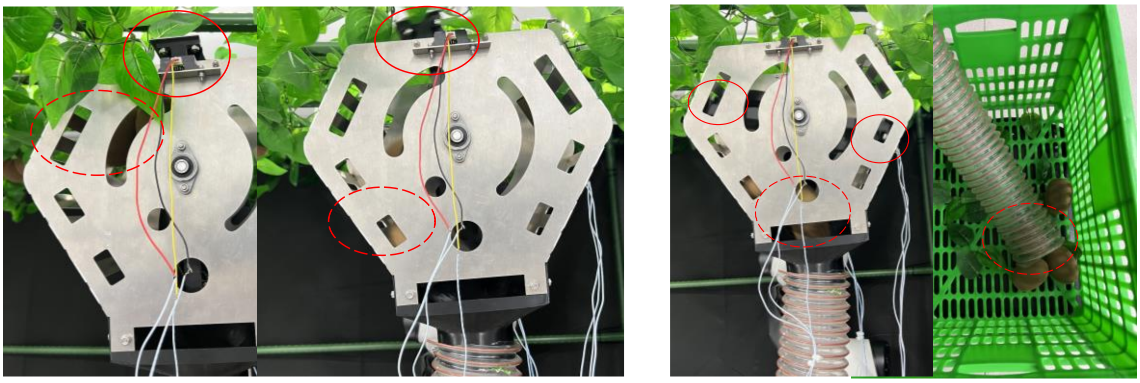
where: T - Average picking time, s;
S - Success rate, %;
D - Damage rate of fruits picked successfully, individual;
t_0 - Time of the start of picking, s;
t_1 - Time of the end of picking, s;
c - Number of fruit clusters, individual;
n - Number of fruits picked successfully, individual;
h - Total number of fruits, individual;
m - Number of damaged fruits, individual.

Analysis of Results

In this paper, picking experiments were carried out on 5 groups of 15 clusters of fruits respectively, as shown in Figure 10. The robotic arm first sent the end-effector to the area suitable for picking fruits, and after the fruits were recognized by the recognition sensor, the robotic arm carried the end-effector upwardly to envelope and pick the fruits, and the picked fruits fell into a fruit collection box through a hose.



(a) recognizing fruits *(b) enveloping fruits (front view and side view)*



(c) picking fruits (start of the picking and after the picking) *(d) collecting fruits (fruit falling into the collection hose and fruit falling into the collection box*

Fig. 10 - Kiwifruit picking process

where: Real-time status of rotary cutter

Real-time status of fruit position

During the above fruit-picking process, the robotic arm carried the end-effector picking operation at a speed of 1.5 m/s, and the stepper motor carried the rotary cutter at a speed of 6 r/min to separate the fruits from the fruit stalks, the results of the picking experiments being shown in Table 3.

Table 3

Results of picking experiments

Group	Number of fruits per cluster	Number of fruit clusters per group	Total number of fruits	Number of picking successes	Number of picking failures	Number of fruit damage	Picking success rate (%)	Fruit damage rate (%)	Average picking time per cluster (s)
1	3	3	9	9	0	0	100	0	6.5
2	4	3	12	12	0	0	100	0	7.3
3	5	3	15	14	1	1	93.3	14.3	8.5
4	6	3	18	15	3	1	83.3	13.3	10.2
5	7	3	21	17	4	2	81.0	17.6	11.5
	Total	15	75	67	8	4	89.3	6.0	8.8

According to Table 3, the average time for picking each cluster of fruits was 8.8 seconds, with a success rate of 89.3% and a damage rate of 6.0%. When the number of fruits picked in each cluster was 3~4, the picking success rate was 100%, and the fruit damage rate was 0. When the number of fruits picked in each cluster was 5~7, the more fruits picked in each cluster, the lower the picking success rate, and the higher the fruit damage rate.

The causes of fruit damage were analysed as follows:

① Fruit leaves interfered with the colour detection sensor, resulting in damage to one or more fruits by the rotary cutter before they reached the picking bin.

② During the picking or collection process, collisions between fruits could lead to damage to the skin of overripe fruits. (Note: Typically, when kiwifruit is picked in an orchard, the fruit is not yet fully ripe and is firmer, making the skin less likely to be damaged).

CONCLUSIONS

(1) For orchard scaffold-grown kiwifruit, TRIZ was applied to assist in the design of a new kiwifruit-picking end-effector. A multi-fruit picking method of automatically recognizing fruits - fully enveloping fruits - and Non-destructive separating fruit stalks was proposed for picking kiwifruit in clusters. The designed picking end-effector aggregates the fruit clusters into the picking bin by means of enveloping, separates the fruits and stalks using a rotating cutter and sets a curved guide shaft to buffer and guide the picked fruits.

(2) A kiwifruit picking test stand was established in a laboratory. Seventy-five fruits were selected and divided into five groups in the form of fruit clusters. The robotic arm was set at 1.5 m/s and the stepper motor at 6 r/min running speed for the picking test. The results showed that the average time to pick each cluster of fruits was 8.8 s, the picking success rate was 89.3%, and the picking damage rate was 6.0%. Compared with the picking experimental data of the prototype, the kiwifruit picking end-effector designed in this paper not only improved the fruit picking success rate and reduced the fruit damage rate, but also shortened the fruit picking time and thus improved the fruit picking efficiency.

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REFERENCES

[1] Altshuller, G. S. (1984). Creativity as an exact science, the theory of the solution of inventive problems. *Gordon and Breach Science Publishers*: New York, USA, pp.5-25.

[2] Azammi, A. N., Sapuan, S. M., Ishak, M. R., & Sultan, M. T. (2018). Conceptual design of automobile engine rubber mounting composite using TRIZ-Morphological chart-analytic network process technique. *Defence Technology*, 14(4), 268-277.

[3] Fazayeli, A., Kamgar, S., Nassiri, S. M., Fazayeli, H., & de la Guardia, M. (2019). Dielectric spectroscopy as a potential technique for prediction of kiwifruit quality indices during storage. *Information Processing in Agriculture*, 6(04), 479-486.

[4] Feng, Q., Zou, W., Fan, P., Zhang, C., & Wang, X. (2018). Design and test of robotic harvesting system for cherry tomato. *International Journal of Agricultural and Biological Engineering*, 11(01), 96-100.

[5] Fu, L., Tola, E., Al-Mallahi, A., Li, R., & Cui, Y. (2019). A novel image processing algorithm to separate linearly clustered kiwifruits. *Biosystems Engineering*, 183, 184-195.

[6] Fu, L., Zhang, F., Yoshinori, G., Li, Z., Wang, B., & Cui, Y. (2015). Development and experiment of end-effector for kiwifruit harvesting robot (猕猴桃采摘机器人末端执行器设计与试验). *Transactions of the Chinese Society of Agricultural Machinery*, 46(3).

[7] Fu M. (2021). *Systematic Innovation Approach - TRIZ Practical Tutorial* (系统化创新方法 - TRIZ 实用教程). Northeast Forestry University Press: Harbin, China, pp.5-10.

[8] Hu, G., Chen, C., Chen, J., Sun, L., Sugirbay, A., Chen, Y., et al. (2022). Simplified 4-DOF manipulator for rapid robotic apple harvesting. *Computers and Electronics in Agriculture*, 199, 107177.

[9] Kang, C. Q., Ng, P. K., & Liew, K. W. (2022). A TRIZ-Integrated Conceptual Design Process of a Smart Lawnmower for Uneven Grassland. *Agronomy*, 12(11), 2728.

[10] Kim, S., Hong, S. J., Ryu, J., Kim, E., Lee, C. H., & Kim, G. (2023). Application of a modal segmentation on cucumber segmentation and occlusion recovery. *Computers and Electronics in Agriculture*, 210, 107847.

[11] Guo, L., Rui, S., Zhao, G., Gao, C., Fu, L., Shi, F., Dhupia, J., Li, R., & Cui, Y. (2022). Real-time detection of kiwifruit flower and bud simultaneously in orchard using YOLOv4 for robotic pollination. *Computers and Electronics in Agriculture*, 193, 106641.

[12] Li, C. E., Tang, Y., Zou, X., Zhang, P., Lin, J., Lian, G., & Pan, Y. (2022). A novel agricultural machinery intelligent design system based on integrating image processing and knowledge reasoning. *Applied Sciences*, 12(15), 7900.

[13] Mao, S., Li, Y., Ma, Y., Zhang, B., Zhou, J., & Wang, K. (2020). Automatic cucumber recognition algorithm for harvesting robots in the natural environment using deep learning and multi-feature fusion. *Computers and Electronics in Agriculture*, 170, 105254.
[14] Mu, L., Cui, G., Liu, Y., Cui, Y., Fu, L., & Gejima, Y. (2020). Design and simulation of an integrated end-effector for picking kiwifruit by robot. *Information Processing in Agriculture*, 7(1), 58-71.
[15] Rong H. (2019). *Development of kiwifruit picking end-effector based on fruit stem separation picking method* (基于果梗分离采摘方式的猕猴桃采摘末端执行器研制). [Thesis of Master, Northwest Agriculture and Forestry University]. China Campus Repository.
[16] Silwal, A., Davidson, J. R., Karkee, M., Mo, C., Zhang, Q., & Lewis, K. (2017). Design, integration, and field evaluation of a robotic apple harvester. *Journal of Field Robotics*, 34(6), 1140-1159.
[17] Sun, Q., Zhong, M., Chai, X., Zeng, Z., Yin, H., Zhou, G., & Sun, T. (2023). Citrus pose estimation from an RGB image for automated harvesting. *Computers and Electronics in Agriculture*, 211, 108022.
[18] Williams, H. A., Jones, M. H., Nejati, M., Seabright, M. J., Bell, J., Penhall, N. D., et al. (2019). Robotic kiwifruit harvesting using machine vision, convolutional neural networks, and robotic arms. *Biosystems Engineering*, 181, 140-156.
[19] Wang, T., Du, W., Zeng, L., Su, L., Zhao, Y., Gu, F., Liu, Li., Chi, Q. (2023). Design and Testing of an End-Effector for Tomato Picking. *Agronomy*, 13(03), 947.
[20] Williams, H., Ting, C., Nejati, M., Jones, M. H., Penhall, N., Lim, J., et al. (2020). Improvements to and large-scale evaluation of a robotic kiwifruit harvester. Journal of Field Robotics, 37(02), 187-201.
[21] Xiong, Y., Peng, C., Grimstad, L., From, P. J., & Isler, V. (2019). Development and field evaluation of a strawberry harvesting robot with a cable-driven gripper. *Computers and electronics in agriculture*, 157, 392-402.
[22] Xu, H., Yu, G., Niu, C., Zhao, X., Wang, Y., & Chen, Y. (2023). Design and Experiment of an Underactuated Broccoli-Picking Manipulator. *Agriculture*, 13(4), 848.
[23] Xu, L., Liu, X., Zhang, K., Xing, J., Yuan, Q., Chen, J., ... & Yu, C. (2018). Design and test of end-effector for navel orange picking robot (脐橙采摘机器人末端执行器设计与试验). *Transactions of the Chinese Society of Agricultural Engineering*, 34(12), 53-61.
[24] Yan, B., Fan, P., Lei, X., Liu, Z., & Yang, F. (2021). A real-time apple targets detection method for picking robot based on improved YOLOv5. *Remote Sensing*, 13(09), 1619.
[25] Yang, L., Yi, S., Mao, X., & Tao, G. (2018). Innovation design of fertilizing mechanism of seeder based on TRIZ theory. *IFAC-PapersOnLine*, 51(17), 141-145.
[26] Yin, H., Sun, Q., Ren, X., Guo, J., Yang, Y., Wei, Y., et al. (2023). Development, integration, and field evaluation of an autonomous citrus-harvesting robot. *Journal of Field Robotics*.
[27] Yuan J. (2020). Research progress analysis of robotics selective harvesting technologies (选择性收获机器人技术研究进展与分析). *Transactions of the Chinese Society of Agricultural Machinery*, 51(09), 1-17.