DESIGN AND EXPERIMENT OF AN END-EFFECTOR FOR HARVESTING SWEET PEPPER IN COMPLIANT OBSTACLE ENVIRONMENT
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柔顺障碍环境下收获甜椒末端执行器的设计与试验

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ABSTRACT
Picking sweet peppers by hand is often time-consuming and laborious. To overcome this, in the current study, we developed an end effector for mechanized and non-destructive harvesting of sweet pepper. The design includes grip modules, shear modules and control systems. Based on the establishment of an approximate mathematical model of sweet pepper fruit and the analysis of the biomechanical characteristics of sweet pepper fruit, a pinch finger was proposed. The proposed mechanism is able to successfully achieve non-destructive and stable fixation of sweet pepper and fruit bunches. Key parameters of peduncles cutting were obtained by the cutting test. A cutting mechanism was then designed to achieve efficient separation of the fruit and fruit stem. The designed end effector achieves precise control through a single-chip microcomputer and multi-sensor integrated control system to achieve mature target fruits. The test results showed that the picking success rate, damage rate and picking time of peppers were 93.3%, 1.6% and 5 seconds, respectively. The end effector designed for sweet pepper picking has a simple and reliable structure, which provides a reference for further research on sweet pepper picking robots.

摘要
手工采摘甜椒通常既费时又费力。为了克服这一点，在目前的研究中，我们开发了一种用于机械化和无损采摘甜椒的末端执行器。该设计包括夹紧模块、剪切模块和控制系统。在建立甜椒果实近似数学模型的基础上，结合对甜椒果实生物力学特性的分析，提出了夹指。所提出的机制能够成功地实现甜椒和果簇的无损稳定夹紧。通过对果穗的扦插试验，获得了果穗扦插的关键参数。然后设计了一种分离机构来实现果实和果柄的有效分离。所设计的末端执行器通过单片机和多传感器集成控制系统实现精确控制，获取成熟的目标果实。试验结果表明，辣椒的采摘成功率、损伤率和采摘时间分别为 93.3%、1.6%和 5s。所设计的甜椒采摘末端执行器结构简单可靠，为后续甜椒采摘机器人的研究提供了参考。

INTRODUCTION
Besides high vitamin A and C contents, sweet peppers are also rich in vitamin B and E, and minerals such as calcium, potassium, iron, and phosphorus (*Guo et al., 2016*). The content of many nutrients can increase up to five times following the maturity of sweet peppers (*Djurovic et al., 2015; Ferreira et al., 2016*). This vegetable also has a characteristic taste (*Lee et al., 2019*). The planting area of sweet peppers in China, which is second only to cabbage, accounts for 35% of the world's planting area of sweet peppers. In addition, Chinese sweet pepper production ranks first in the world (*Shi et al., 2017*). Picking is considered to be the most labor-intensive task in agricultural production (*Li et al., 2008; Graham et al., 2018*). The replacement of manual picking by robots has become a recent trend (*Chen et al., 2019*) following the popularization of agricultural technology (Kondo et al., 2009), the gradual reduction of rural labor and other related factors (*Fan et al., 2016; Bac et al., 2017*). As an integral component of fruit and vegetable picking robots, the end-effector is in direct contact with the fruit and plays an important role in improving the picking efficiency (*Song et al., 2006*) and operational stability of the picking robot (*Chiu et al., 2013; Jiang et al., 2017*).

Non-Chinese automatic sweet pepper picking robots have been developed over the past two decades, demonstrating great success in picking targets without affecting the environment of other crops (*Ji et al., 2014; Lehnert et al., 2017*). The grasping element of the "sweet pepper gripper" proposed by German crops team includes a passive adaptive FinRay finger, with a blade driven by the cylinder used to cut the sweet pepper from the plant (*Hemming J. et al., 2014*). The development of the end-effector is based on bionics and is able to protect the sweet pepper fruit.

Yet the bionic materials proved to be both difficult and expensive to process due to the complex structure of the gripping fingers, preventing the development of domestic promotion. Gauchel et al. designed a "lip-shaped end-effector" in 2012 that was placed close to the suction cup in order to stabilize the fruit without the requirement of holding fingers. However, the force exerted on the fruit during stalk cutting by the lip ring may break the fruit from the suction cup, while the large range of motion of the lip ring may damage the plant (*Bac et al., 2016*). FF Robotics, an Israeli company, simulated the manual picking process and designed a 3-degree-of-freedom Cartesian Coordinate Robot equipped with a telescopic three-finger underdriven end-effector, with the fingers coated with flexible material, which grasps the apple and rotates it by 90°, after which the robot arm retracts by a few inches, the fruit stalk is tugged and broken, and the end-effector lets go of the apple at the collection point to complete the picking of the apple (*Avigad et al., 2020*). Dogtooth Technologies in the UK designed an end-effector that utilizes a unique hooking of the strawberries by means of a broken shank gripping of the fruit stalk (*Robertson et al., 2020*). MetoMotion of Israel company designed a two-degree-of-freedom closed-chain string tomato stalk shear gripper for separating touching alibi bunches and gripping the target bunch tomato fruit stalks for robust and non-destructive harvesting (*Adi NIR et al., 2020*). LU RF developed a newly vacuum-based robotic apple harvesting system, using the twist-and-pull fruit picking method (*Renfu Lu et al., 2022*).

Despite the relatively limited research on fruit and vegetable picking robots in China (in the 1990s) (*Liu et al., 2017*), much progress has been made (*Lin et al., 2015*). For example, for low-destructive picking, a soft mechanism on the end-effector was set to achieve the constant output force required for low-destructive fruit clamping by Yubin Miao (*Miao et al., 2020*). Xinjiang currently employs self-propelled sweet pepper harvesters and Gansu uses traction sweet pepper pickers (*Liu, 2014*). Yi Wang et al. who simulated the head mechanism of snake designed an end-effector with the bite mode for citrus harvesting robot and suggested an optimization method of harvesting postures (*Wang et al., 2019*). Zhiguo Li et al. investigated the factors of affecting the human hand grasp type in picking tomato which provided theoretical basis for multi-finger end-effectors intelligent picking grasp planning algorithm (*Li et al., 2019*). However, studies on sweet pepper picking in China are limited, with marked differences in the methodology and results of existing research: (1) picking robot to separate pepper fruit clusters and fruit stalks of the influence of more factors, in the actual growth environment, the thickness of the fruit stalks, the degree of lignification is randomized, in addition to the plant in China planting methods, varieties, fruit maturity, fruit bunches and the distance between the branches and trunks of the fruit will have a direct impact on the effect of the separation of chili peppers and fruit stalks. (2) The skin of ripe chili peppers is brittle and easily damaged during mechanical picking, making it difficult to store. (3) Environmental problems of robotic operation. In the actual environment of the pepper plant, the distance between the main branches and lateral branches, the spatial distribution of the fruit, the weight of the fruit, the length of the fruit stalk, the leaf shade and other parameters change randomly, resulting in difficulty in identifying the specific cutting position of the fruit stalk.

The purpose of the current study was to design a flexible end-effector suitable for the reliable picking of sweet pepper while avoiding mechanical damage. The working environment of a picking robot is non-structural, while picking objects are generally tender and complex (*B et al., 2014; Fu et al., 2015; Yu et al., 2017*). Thus, end-effectors must be soft, stable during clamping, inexpensive and easy to control, and should consider the biological, physical and mechanical characteristics of the picking object (*Zhang, 2014; Shi et al., 2018; Xiong et al., 2018*). The aforementioned factors were considered to produce an end-effector prototype, which was then verified in order to provide technical support for the design of future sweet pepper picking robots.

MATERIALS AND METHODS

Sweet pepper fruit picking

In order to determine the most suitable robot sweet pepper picking method, the characteristics of several manual picking methods were tested in the field. In Fig. 1(a), the stem could be twisted with ease by simply rotating it, without pulling the target fruit; in Fig. 1(b), pulling the fruit straight down affected the machine vision positioning; in Fig. 1(c), the direct lifting of the fruit did not completely break the stalk; in Fig. 1(d), the target fruit was pulled down while rotating, with a relatively large motion range of the robotic arm and damage to surrounding plants; in Fig. 1(e), the fruit stem was cut to simulate artificial plucking. Fig. 1(f) proved to be suitable for the sweet pepper picking by the robot. Cutting the fruit peduncles directly avoided damage to surrounding fruits, stems, leaves, etc. The range of movement was also relatively small, greatly reducing the damage to the surrounding plants and resulting in minimal fruit stalk wounds. Therefore, the clamping and shearing method was employed to separate the fruits from the plants.

（a） Twisting without pulling (b) Pulling straight down (c) Direct lifting

(d) Rotating 90° while pulling downward (e) Manual picking (f) Shearing

Fig. 1 – Common sweet pepper picking methods

Robot end-effector structure

The principal components of the proposed end-effector were the mechanical parts (Fig. 2), control system (Fig. 3) and vision system, which were installed on the mechanical arm (Fig. 4). The end-effector adopted a two-finger clamping mechanism, which was composed of the clamping fingers, stepping motor, positive and negative screws, buffer material, timing belt and pulley, force sensor, stopper, coupling, etc. Two stepping motors were used as the power output. The sweet pepper picking process (Fig. 5) can be described as follows: 1) The machine vision recognized and located the target fruit. 2) The robotic arm drove the end-effector to the fruit location. 3) The control system sent out a clamping command to rotate the motor and generate a driving force that was transmitted to the gripping fingers. 4) The gripping fingers began to move closer to the sweet pepper fruit and subsequently clamp it. 5) The control system continuously monitored the force between the sweet pepper and the gripping finger measured by the force sensor within the gripping finger. Once the safety threshold set by the finger surface film force sensor was reached, the clamping finger stopped moving in the clamping direction and the clamping state was maintained. 6) The control system sent a message to the motor to start rotating the scissors. The output power was then transmitted to the scissors, closing them until the required position was detected by the stopper. 7) The motor controlling the gripping finger movement rotated in reverse, the gripping fingers and scissors moved to the outer limiter positions, the movement stopped, and picking was complete.

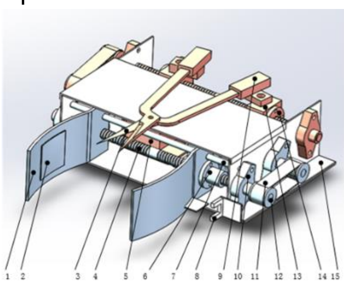


Fig. 2 – Overview of the end-effector structure

1. Clamping finger; 2. Force sensor; 3. Scissors; 4. Positive and negative screw; 5. Stepping motor; 6. Screw nut I; 7. Guide rod; 8. Stopper; 9. Scissors connector; 10. Bearing with seat; 11. Synchronous belt; 12. Pulley; 13. Nut seat; 14. Lead screw nut II; 15. Frame.

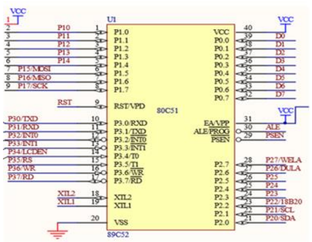


Fig. 3 – Microcontroller resource allocation

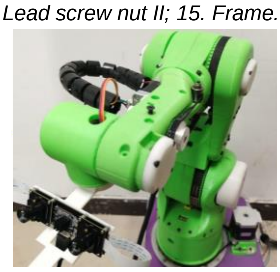


Fig. 4 - Mechanical arm

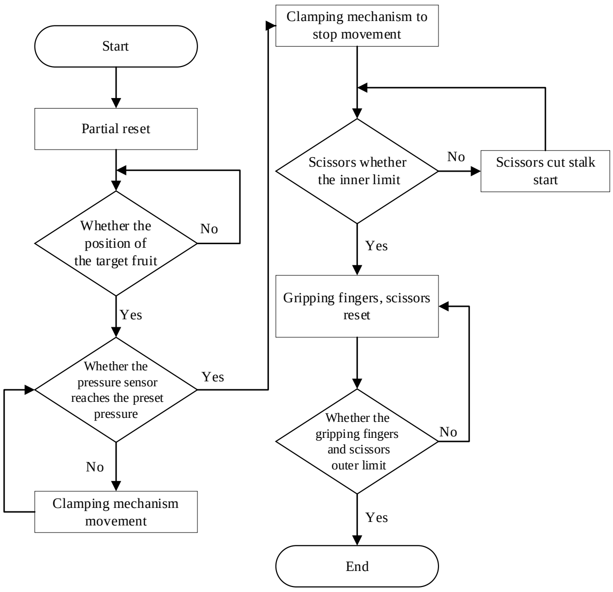


Fig. 5 – Flow diagram of sweet pepper picking

Sweet pepper mathematical model

Since the clamping mechanism was in direct contact with the fruit, the structural parameters of the clamping device were designed according to the physical size of the fruit (*Shi et al.,2018; Fengfeng et al., 2018*). "Rixwang 35132" was used as the experimental pepper fruit and was picked in the greenhouse of Lushou Green Garden in Luocheng, Shouguang, China. The appearance and size of this variety was taken as the design reference (Table 1). The fruit width range (the gap between the maximum and minimum values) was 39.22 mm, with multiple values of 79-83 mm; the thickness range was 32-90 mm, with multiple values distributed within 71-75 mm; and the fruit length range was 40-73 mm, with multiple values of 80-85 mm. The sweet pepper width and thickness direction ranges were observed to be smaller than that of the length direction. Thus, adjusting the clamping position via the width and thickness direction was more conducive to increasing the clamping success rate.

Table 1

Physical parameters of the Rixwang 35132 sweet pepper

Parameter	Max.	Min.	Average	Majority value	Extremums
Mass (g)	287.01	50.04	157.13	150-170	236.97
Width (mm)	102.54	63.32	80.06	79-83	39.22
Thickness (mm)	90.68	57.78	71.07	71-75	32.90
Fruit length (mm)	105.21	64.48	79.33	80-85	40.73
Length of fruit stalk (mm)	9.85	6.71	8.18	8.1-8.2	3.14

The sweet pepper fruit had the shape of an irregular cylinder with a larger diameter at the top than the bottom. The region of the fruit with the largest diameter was selected as the contact position between the sweet pepper and finger during clamping. Thus, the finger grip design was based on the largest diameter. Figure 6 presents a schematic diagram of a finger enveloped fruit. Compared with the straight grip, arc-shaped fingers are able to increase the contact point between the fingers and the fruit surface, improving the stability of the grip. In order to ensure the clamping effect, the circular curvature of the finger was less than the approximate circular minimum curvature of the sweet pepper fruit. The maximum fruit diameter corresponded to the minimum curvature. Measurement data reveals that the sweet pepper diameter did not exceed 110 mm. Thus, the approximate circle curvature of the sweet pepper fruit was greater than or equal to 0.018, and this value was used for the arc-shaped curvature of the finger.

The mechanism underlying the finger enveloping the target fruit was based on the sweet pepper fruit size in the longitudinal direction. In particular, a stable grasp of the sweet peppers requires a finger grip that is at least 50% larger than the fruit. The enveloping range of the gripping fingers was determined to be 55 mm and thus the arc length used to optimize gripping was set as 55 mm. Furthermore, the fruit height ranged within 64-106 mm. As the finger holding position was placed at the upper fruit region with the largest diameter, the finger height was able to meet the requirements when it reached half of the maximum fruit height. Thus, the finger height was set as 53 mm.

The final curved finger model was set as follows:

$$x^2 + y^2 = 3025 \ (-27.5 \ll x \ll 27.5) \quad (1)$$

$$z = 53 \quad (2)$$

where x denotes the finger motion range, mm; y is the finger wrapped range; and z is the finger height, mm.

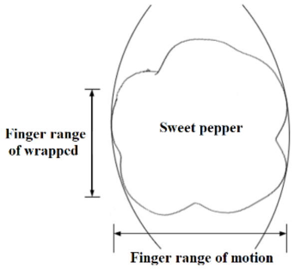


Fig. 6 – Diagram of the finger enveloping

Force analysis of gripping fingers

In order to demonstrate the wrapping of the fruit by the gripping fingers, the equatorial surface of the sweet pepper was taken as an example for force analysis (Figure 7). Due to the shape of the fruit, the force on the fruit can be considered to be concentrated in four points. The positive force of the fingers was denoted on the curved surface, the static friction force in the vertical direction, and the static friction force in the horizontal direction as Ni, fi and $f\,i'$, respectively.

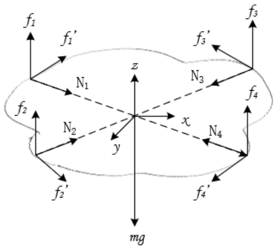


Fig. 7 – Mathematical model and stress analysis of sweet pepper

In Figure 7, fi is the static friction force in the vertical direction experienced by the i-th contact point, N; fi' is the static friction force in the horizontal direction experienced by the i-th contact point, N*;* Ni is the horizontal upward force experienced by the i-th contact point of the static friction force, N; and mg is the balance force of the sweet pepper, N. The balance force system in the horizontal direction is given as:

$$\sum_{i=1}^{n} N_i = F_x, \quad (3)$$

where N_i is the positive force of each point on the sweet pepper surface in contact with the gripping finger.
As the enveloping range of the fingers on both sides of the sweet pepper are approximately equal, the force-bearing area is approximately equal and the force in the horizontal direction can be considered symmetrical. More specifically, the magnitudes are equal while the directions are opposite. Therefore, in the horizontal direction, the resultant force F_x can be considered as zero.

When sweet pepper and the finger come into contact with the frictional point, the end-effector needs to hold the sweet pepper in a stable manner. The friction force generated by the clamping force must overcome the gravity of the sweet pepper, while the clamping force must avoid damage to the fruit (*Zhan et al., 2017*). These two requirements determine the size of the finger gripping force.

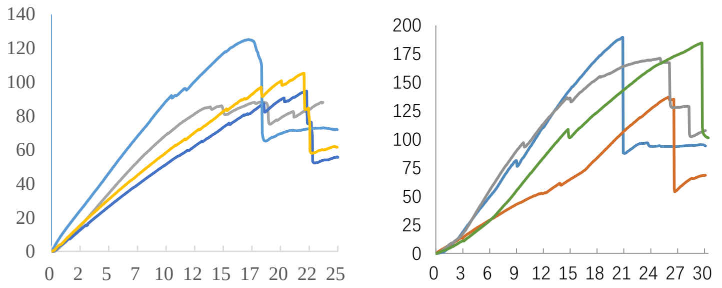
The resultant force of the static friction between the sweet pepper fruit and the gripping fingers in the vertical direction produced by the clamping force is greater than the gravity of the sweet pepper fruit:

$$\mathrm{F_{Clamping}} \geq \mathrm{mg}/2\mu \quad (4)$$

$$\mathrm{F_{Clamping}} < \mathrm{F_{broken}} \quad (5)$$

where $F_{clamping}$ is the clamping force of the finger, N; μ is the friction coefficient between the silica gel and the sweet pepper fruit; m is the maximum mass of the sweet pepper fruit, kg; and g is the acceleration of gravity, which was taken as 9.8 m/s^2.

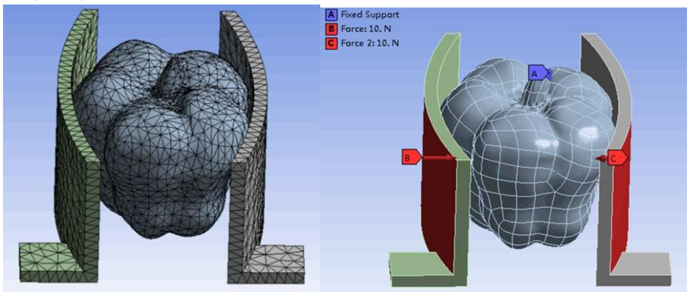
In order to determine the minimum positive force N min, the fruit quality was measured using Eq. (4), with a maximum fruit mass of approximately 287 g. Taking the variability of sweet pepper into account, taking 400 g fruits increases the margin coefficient of 28.25%, and the minimum positive force N_{min} was determined as 2.13 N. Furthermore, friction coefficient tests determined the friction coefficient between the silica gel and the sweet pepper fruit to be 0.92. In order to judge whether the positive force damages the biological tissues of the sweet pepper, a compression test was performed on the sweet pepper to determine the maximum positive force N_{min} for non-destructive picking. Eight randomly selected sweet pepper fruits were divided into 2 groups (4 in each group) and compressed horizontally and vertically to obtain the load displacement curves (Figure 8(a) and (b), respectively). The compression tests demonstrated that at a compression load less than 50 N, the load varied steadily with the displacement, and the sweet pepper was not damaged. The damage force of the sweet pepper was more than 50 N and thus the positive force ranged within 2.13-50 N.



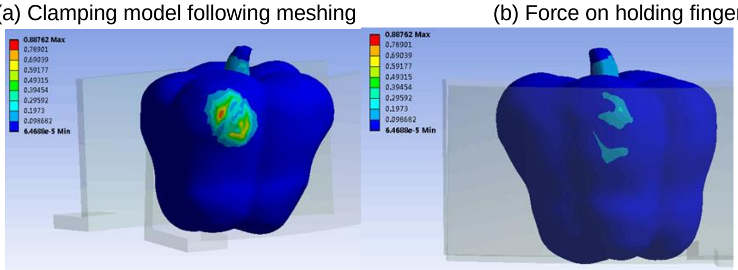
(a) Lateral compression (b) Longitudinal compression

Fig. 8 – Compressed displacement-load curve

The finite element analysis software ANSYS 17.0 was employed to simulate and analyze the clamping fingers in order to avoid damaging the target fruit. The mesh was divided into 21,735 nodes and 12,289 elements. Once the grid was divided, the loads and constraints were added to the gripping fingers and the red pepper. Previously, it was calculated that the appropriate range of gripping force for gripping fingers is 2.13-50 N. The clamping force of 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 N on sweet pepper skin was tested through preliminary experiments. The results of the pre-liminary experiments showed that the optimal clamping force was 10 N. During the clamping process, leftward and rightward pointing forces from the pepper and gripping fingers were added, respectively, and the rotation the gripping fingers was limited. Figure 9 presents the simulation analysis results. The maximum and rupture stress of the pepper fruit were determined as 0.375 MPa and 0.88762 MPa, respectively. This proved that the proposed clamping device had robust clamping performance without causing any mechanical damage to the chili fruit.



(a) Clamping model following meshing (b) Force on holding finger

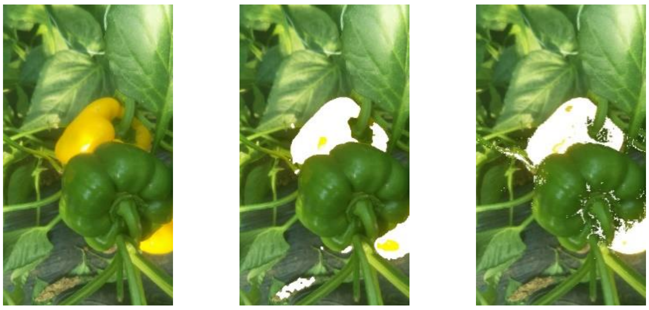


(c) Right-view of stress cloud diagram (d) Left-view of stress cloud diagram

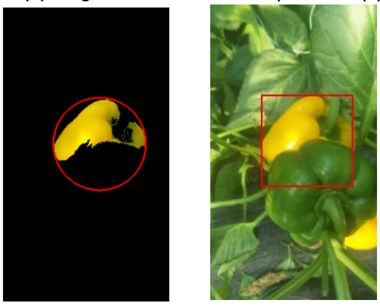
Fig. 9 – Clamping stress analysis diagram

Image segmentation of sweet pepper

Immature sweet peppers of the experimental sample were green, while mature sweet peppers varied in color and were significantly different from the background (Figure 10(a)). Therefore, color, area and shape feature screening was employed to divide the sweet pepper image. The color image was converted from an RGB to HSV color space. The mature sweet peppers exhibited gray values in the H (hue) and S (saturation) components that were distinct to the gray values of the branches and leaves in the background. The differences in gray values were used to apply a median filter to the H and S components. The segmentation threshold was then obtained through the Otsu automatic threshold segmentation (T). This threshold was adjusted based on the threshold determined from the image segmentation effect in order derive the segmentation thresholds in the H and S components as (0, 0.75T) and S (1.45T, 255), respectively. Figure 10(b) and (c) displays the segmentation effects in the H and S components, respectively. Noise within the image was removed using morphological opening and the holes were subsequently filled. The entire area was divided into different connected domains that were filtered according to the area and roundness of the pepper. The circular Hough transformation was applied to the occluded sweet pepper image, and the size was calculated and displayed in the form of a circumscribed rectangle. Figure 10(d) and (e) demonstrates the processing results.



(a) Original image (b) Segmentation of H component (c) Segmentation of S component



(d) Circular Hough transform (e) Processing results

Fig. 10 – Image segmentation of sweet pepper

Figure 11 compares the sweet pepper image segmentation effects of the H and S components. The threshold segmentation was optimal under the H component for greater occlusions in the image, and the connected domain was relative. The saturation of the leaves under strong light was similar to that of mature sweet peppers. The image segmentation in the S component was erroneous under this case. Thus, the H component of the HSV color space was selected for sweet pepper image segmentation.

(a) H component processing-1 (b) S component processing-1 (c) H component processing-2 (d) S component processing-2

Fig. 11 – Comparison of segmentation effects

Experimental implementation and results

Experimental implementation

The test materials included the end-effector prototype, a control box, an ASUS X550 laptop, and a tripod. The "Rixwang 35132" sweet pepper variety was picked in the Lushou Green Park greenhouse, Luocheng, Shouguang, China. The end-effector was supported by a height-adjustable tripod that was moved to the target fruit. The upper frame was removed during operation to facilitate debugging during testing. A total of 60 sweet peppers at 50% maturity or more were randomly picked. During the picking process, fruit that did not enter the gripping fingers, fallen fruit, uncut stalks, and broken sweet pepper were regarded as failures.

(a) Reset stage (b) Fruit is held

(c) Stalk is cut (d) Stem is cut

Fig. 12 – Picking process

RESULTS AND DISCUSSION

The growth environment of sweet peppers was shown in Figure 13. The picking target was "Rickswan 35132" normally growing sweet pepper fruit. The picking process consisted in the following operations: use the height to adjust the three tripod to support the end actuator; move the tripod to the target fruit; remove it during operation. Figures 2 and 3 are the picking process of different colors of pepper. From close to the plants, hold the fruit, cut the fruit handle, and cut.

Fig. 13 – Picking the field environment

Fig. 14 – The picking process of different colors of pepper

Table 2 reports the number of successful and failed fruit picking attempts. The experimental process of the developed device is shown in Figure 12. Sixty sweet pepper fruits were harvested using the developed device. The experimental results showed that 56 sweet pepper fruits were successfully picked (Figure 13), while 4 sweet pepper fruits were lost. The success rate of device picking was about 93.3%. Four failed cases include one fruit being pierced by scissors, one case where the handle failed to cut, and the other two cases where it failed to enter the grip area. The successful clamping of the target fruit by the designed clamping mechanism ensures that the end effector effectively separates the fruit and fruit stalks without damaging the target fruit. Therefore, this end effector can meet the current requirements for sweet pepper fruit picking.

Fig. 15 – Fruit picking effect

Table 2

Picking test results

Picking effect	Quantity
Successfully picked	56
Fruit did not enter the gripping fingers	2
Fruit stalk shear failure	1
Scissors pierced the fruit	1
Total	60

The fruit picking failures may be attributed to the following factors:

1) Some fruit had short and bent stems, resulting in stalks growing close to the end of the fruit. The gap between the fruit was very small and not wide enough to accommodate the scissors. Thus, the tip of the scissors may pierce the target fruit once the actuator is close.

2) In the greenhouse, the branches of the sweet peppers grow upward along the artificially pulled rope while the fruits and branches droop down due to gravity. These growth characteristics facilitate the clinging of individual sweet pepper fruits to the branches. This may result in the branches also entering the shear range of the scissors along with the sweet peppers, cutting off both the branches and fruit.

3) Two sweet peppers can grow from the same joint on the branch. In this case, when the end-effector approaches the target fruit from the front, the fingers also push the adjacent fruit, thereby moving the branch. This movement affects the target fruit, preventing it from entering the gripping region.

CONCLUSIONS

In the current study, a sweet pepper picking robot end-effector for the non-destructive picking of sweet peppers based on their biomechanical properties was designed. The device consists of a clamping module, a cutting module, and a control system. The clamping mechanism was able to successfully separate the fruit and fruit cluster, while the timely separation of the fruit and fruit stalk was achieved by the shearing mechanism. The control system integrated a single-chip microcomputer and multiple sensors. The proposed end-effector was centered around a single mechanical structure and multiple sensors. The picking and movement status was detected by the sensor and controlled by the single-chip microcomputer. The end-control principle was adopted to control the direction and pulse signals and enable the signal of the stepper motor driver to control the end-effector.

The proposed end-effector exhibits a simple structure and reliable performance. Test results demonstrate the ability of the end-effector to effectively realize the clamping of the fruit and the separation of the stalk, with a picking success rate of 93.3%, and an average picking time of 5 s per fruit. The proposed system was able to realize the non-destructive picking of the target fruit.

This study is based on the physical characteristics of sweet pepper fruit. In the structural design of the end effector, combined with machine vision, a testing device was successfully developed. The prototype was verified through picking experiments to meet the design requirements and achieve the functions of picking and positioning.

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