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Development of an Automatic Sweet Pepper Harvesting Robot and Experimental Evaluation

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Abstract— **The aging population and diminishing working population in agriculture motivate the development of autonomous harvesting robots. Although autonomous harvesting is expanding rapidly, the commercial application of sweet pepper harvesting robots still faces challenges. This paper presents the development of a sweet pepper harvesting robot and reports its experimental verification, which mainly includes end-effector design, visual perception, and grasping pose control. The end-effector adopts electrical control, mainly composed of a servo-electric two-finger parallel clamping module, a swing-cutting module, and a fruit recovery device. Equipped with a tactile sensor array, it can accurately sense the sweet pepper peduncle position and the end-effector state (harvesting failure) to complete the precise cutting. An end-effector grasping pose control algorithm of the manipulator is proposed, which can control the end-effector to grasp along the direction of the fruit peduncle and perpendicular to the tangent direction of the picking point by estimating the pose of the sweet pepper peduncle. Finally, the robot and proposed method were verified in a plant factory. The experimental findings demonstrate that the developed harvesting robot can complete robust detection of fruit peduncles and non-destructive picking of sweet pepper, with an average picking time of about 15 seconds.**

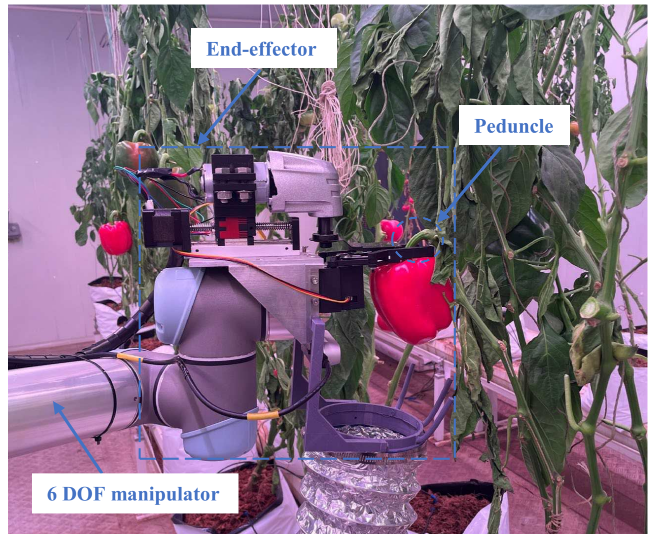

Fig. 1. The developed end-effector harvest sweet pepper in a plant factory.

I. INTRODUCTION

The reduction of the agricultural labor force is a worldwide problem. Due to the aging labor force and the flow of young and middle-aged labor to non-agricultural industries, agricultural labor resources are in short supply, and labor costs have risen sharply. All countries worldwide are faced with reducing agricultural costs and improving production efficiency, and there is a strong demand for agricultural automation technology. Therefore, it is crucial to improve the automation degree of agricultural robot equipment, change the traditional agricultural labor mode, reduce manpower dependence and improve labor productivity [1], [2].

Harvesting crops is among the tedious and manpower-intensive activities within the agricultural cycle, usually concentrated in a specific season, which can lead to a surge in labor demand for a short period, such as harvesting sweet peppers [3]. Sweet pepper is one of the fruit and vegetable varieties with a large planting area in facility horticulture, which is completed manually during the harvesting stage. Harvesting sweet peppers manually has a large workload, high labor intensity, and requires a lot of labor. The amount of labor in the picking process accounts for 40% to 50% of the labor in the entire production process. Therefore, the research and application of autonomous harvesting robots are significant for reducing labor costs, improving picking efficiency, and the profit of the sweet pepper industry.

In this study, our main contributions include the following three parts: (1) we develop an end-effector for automated sweet pepper harvesting and integrate it into a harvesting robot. Fig.1 shows the designed end-effector for automatic harvesting of sweet peppers, which can achieve non-destructive harvesting of sweet peppers. The end-effector is equipped with a tactile sensor array, which can sense the precise position of the fruit peduncle and complete the accurate cutting of the sweet pepper peduncle; (2) we propose a grasping pose control algorithm of the end-effector of the manipulator, which can grasp along the direction of the fruit peduncle and perpendicular to the tangent direction of the picking point for harvesting by estimating the sweet pepper peduncle pose. The success rate of picking sweet peppers at different grasping poses is evaluated using our designed end-effector; (3) we develop an efficient automated sweet pepper harvesting robot that can complete robust detection and localization of sweet pepper peduncle. Finally, a comprehensive feasibility experiments were carried out in a plant factory using the robot, and the picking time of a single fruit was about 15 seconds.

The rest of this article is organized as follows: Section

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II is about the summaries of the related work. Section III describes perception and control methods. The end-effector development and control, sweet pepper peduncle robust detection and localization, and grasping pose control are described in detail. Section IV is about the harvesting experimental platform and overall harvesting robot experiment and performance evaluation. Finally, the conclusion and prospect of this paper are elaborated.

II. RELATED WORK

At present, autonomous harvesting robots have been applied to various types of fruits and vegetables [4]. Such as tomatoes [5]–[8], strawberries [9]–[12], apples [13]–[17], etc. In autonomous harvesting robots, the non-destructive picking of fruits is one of the important indicators [18]–[20]. Therefore, automatic harvesting robots need to have intelligent end-effector design, robust visual perception capabilities and reasonable grasping control methods to achieve non-destructive picking of fruits. It is essential to design a dedicated end-effector based on the characteristics of fruits and vegetables. The configuration of the harvesting robot's end-effector is crucial in enhancing the picking success rate and fruit quality. To date, researchers have designed many end-effectors, which can be divided into the following categories: vacuum suction cups, electric grippers, soft pneumatic grippers, electromagnetic grippers, bionic grippers, etc. [21]–[29]. Gunderman et al. invented a soft robotic gripper driven by tendons with active contact force feedback control, which took advantage of the gripper's passive compliance to enable gentle harvesting of berries [30]. Gao et al. formulated a pneumatic finger end-effector for a tomato harvesting robot that can continuously and stably pick cherry tomatoes with an average picking cycle of 6.4 seconds per fruit [31]. Unlike these fruits and vegetables, sweet pepper harvesting requires cutting the peduncle. Additionally, the peduncles of sweet pepper plants are similar to the stems and have different poses. This brings significant challenges to the accurate identification and grasping of fruit peduncles. In recent years, researchers have also conducted related studies on sweet pepper harvesting robots [32]–[34]. But there are still some shortcomings. Bac et al. developed two end-effectors for sweet peppers [35]. The success rate of end-effectors is low, which is easy to cause damage to plants and fruits. Lehnert et al. developed a sweet pepper harvesting robot, which utilized a decoupling mechanism to divide harvesting into two independent parts: the grasping of sweet pepper and the cutting of fruit peduncle [36], [37]. The robot utilized a lightweight DCNN network to detect the region of interest (ROI) of sweet pepper peduncles and combined a three-dimensional filter to find the cutting position of the sweet pepper peduncle. However, the real-time performance and accuracy of the algorithm are suboptimal, and the picking time of a single fruit is relatively long. Arad et al. formulated a sweet pepper harvesting robot employing visual servoing for harvesting [38], which utilizes a vibrating knife to cut the sweet pepper peduncle, resulting in an average picking cycle of approximately 24 seconds. However, the picking efficiency remains low and lacks intelligent automation.

To solve these problems, a sweet pepper harvesting robot is designed, which can not only complete the precise cutting of sweet pepper peduncles but also protect the sweet pepper plants to the greatest extent and has a certain degree of intelligence. The robot identifies the ROI of the sweet pepper peduncle at close range. The pixel area of the sweet pepper peduncle is larger, and the pixel size of complex backgrounds is relatively reduced, which improves the robustness of fruit peduncle identification. In addition, we proposed an algorithm for controlling the grasping pose at the end-effect of the manipulator by estimating the pose of the fruit peduncle, which significantly improves the success rate of picking.

III. PERCEPTION AND CONTROL METHODS

Our work aims to design a robot that can automatically harvest sweet peppers. This section details the key technologies and methods. It mainly includes the design of the end-effector, the sweet pepper peduncle detection algorithm, and the proposed manipulator end-effector grasping pose control algorithm.

A. End-effector Development and Control

The agricultural end-effector's design is the embodiment of a critical technology in the automatic operation process of agricultural robots. In the agricultural environment, fruits are tender and fragile, and the traditional industrial robot grasping theory is no longer fully applicable. The agricultural picking scene is an unstructured environment, and the fruit's size and the fruit peduncle's length vary, so the end-effector needs to be small and flexible and have a certain degree of adaptability and intelligence. As shown in Fig. 2(a), the end-effector comprises five main parts: a servo-electric two-finger parallel gripper module, a shearing module, a tactile sensing module, a fruit recovery device, and a stepper motor lead screw slide table. The servo-electric two-finger parallel gripper module is employed to grasp the sweet pepper peduncle. The shearing module is installed on top of the stepper motor lead screw slide table and is controlled by a relay to start and stop. It moves forward and backward, utilizing a stepping motor. The array tactile sensor module consists of three resistive thin-film force sensors. The array tactile sensor module, installed at the end of the gripper, mainly serves two functions: sensing the precise position of the fruit peduncle and judging whether harvesting failure occurs.

The end-effector's overall hardware structure is shown in Fig. 2(b). The end-effector is controlled by the MCU STM32, which communicates with a laptop through serial communication. Fig. 3(a)-(d) shows the process of harvesting sweet peppers by the end-effector. The end-effector's control process is shown in Fig. 4. The grasping force F_e is about 17.3N during harvesting sweet peppers. Fig. 5(a)-(b) respectively show the situation when a tactile sensor is triggered and three tactile sensors are triggered. Fig. 5(c) shows the tactile sensor display. When the harvesting fails, such as at

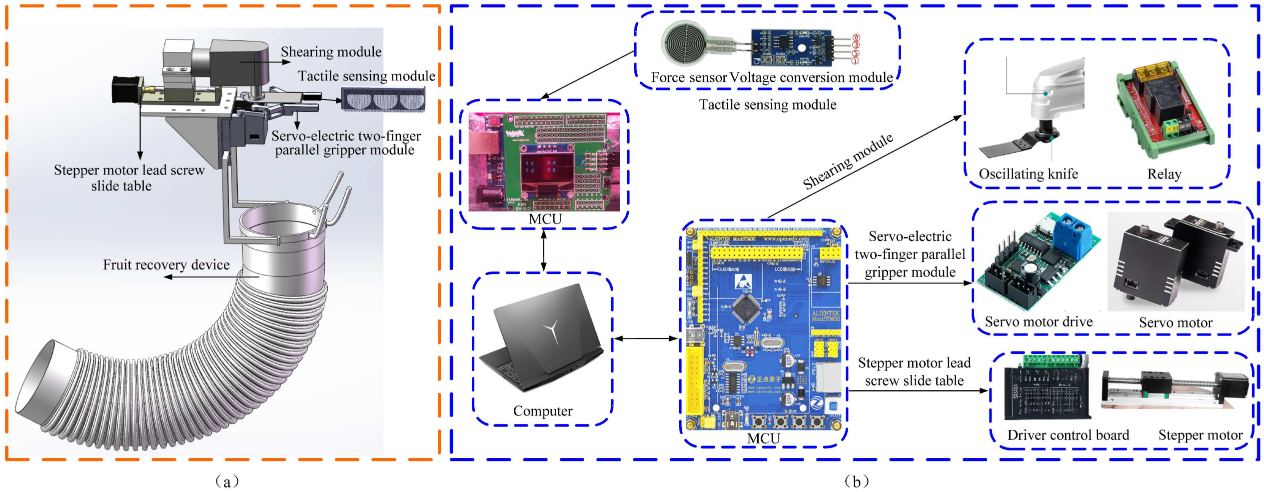

Fig. 2. Sweet pepper harvesting end-effector. (a) CAD model of the sweet pepper harvesting end-effector. (b) End-effector hardware structure.

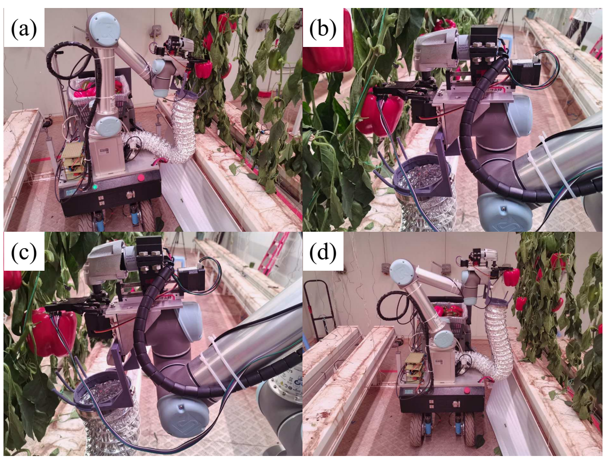

Fig. 3. Harvesting sweet pepper process using end-effector. (a) Move to the picking point with a grasping pose. (b) Grasp sweet pepper peduncle. (c) Cut sweet pepper peduncle. (d) Return to the initial position.

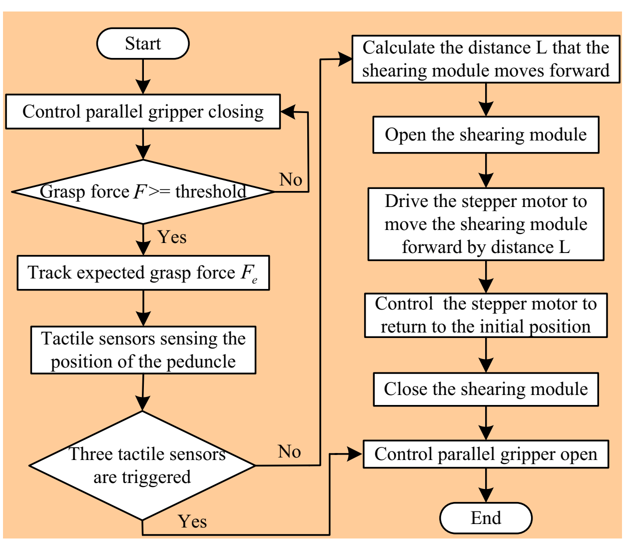

Fig. 4. Flow chart of the end-effector control algorithm.

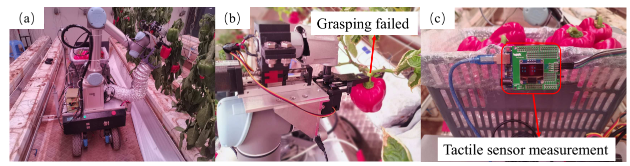

Fig. 5. Sensing the peduncle position and grasping status employing tactile sensors. (a) A tactile sensor is triggered. (b) Grasping failed and three tactile sensors are triggered. (c) Display of tactile sensor measurement.

the end of the gripper slides, the error caused by the visual recognition algorithm, etc., can be obtained by the tactile sensor. When three tactile sensors are triggered, the servo-electric two-finger parallel gripper opens and reverts to its original position. The swinging knife will cease operation, and the manipulator will return to its initial position for re-identification and harvesting.

B. Sweet Pepper Peduncle Robust Detection and Localization

Reliable and robust detection of sweet pepper peduncles is crucial for harvesting robots. Due to factors such as branch and leaf occlusion and changes in lighting, The precision of identifying fruit peduncles can be greatly affected. In addition, during the recognition process, the peduncle of the fruit is relatively thin compared to the fruit, making it challenging to identify accurately from a long distance. Therefore, the identification of sweet pepper peduncle is divided into two parts. Fig. 6(a) and (b) represent long-distance identification of sweet pepper and identification of sweet pepper peduncle at close range, respectively.

From a distance, the YOLOv5 is employed for the initial recognition of fruits to determine the picking order and improve picking efficiency. At close range, YOLOv5 is utilized to identify the sweet pepper, and the ROI of the sweet pepper peduncle is obtained based on the location of the sweet pepper. Finally, the YOLACT is employed to identify the ROI of the sweet pepper peduncle. Identifying the sweet pepper peduncle at close range, the pixel area of the sweet pepper peduncle is larger, and the pixel size of the complex background is relatively reduced. The above methods have significantly improved the accuracy and robustness of fruit peduncle recognition.

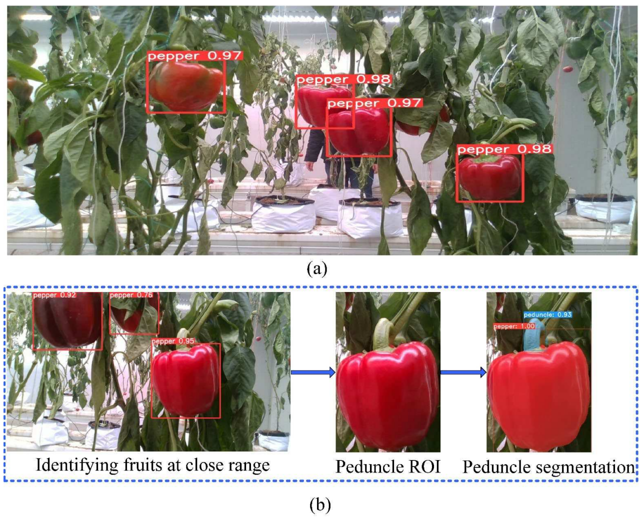

Fig. 6. Identification of sweet pepper peduncle. (a) Identifying sweet peppers from a distance. (b) Sweet pepper peduncle identification.

C. Grasping Pose Control Algorithm of the End-effector Manipulator

During the harvesting process, sweet pepper peduncle have various poses. Choosing the appropriate grasping pose can enhance the success rate of picking. Taking the camera coordinate system as a reference, the state of rotating the sweet pepper peduncle clockwise along the Y-axis direction is shown in Fig. 7(a), and the state of rotating counter-clockwise along the X-axis direction is shown in Fig. 7(b). Because of gravity, sweet peppers grow downward, and we do not take into account rotation along the Z-axis. An algorithm for grasping pose control at the end-effector of the manipulator is proposed, which can grasp along the direction of the fruit peduncle and perpendicular to the tangent direction of the picking point. First, the grasping pose perpendicular to the tangent direction of the picking point is calculated. The identified fruit peduncle pixels are binarized. The binarized fruit peduncle image is processed through the skeleton extraction algorithm to obtain the in the pixel coordinate system picking point(x_{cut}, y_{cut}) and two endpoints. The least squares method was employed to obtain the fitting curve of the fruit peduncle pixels (x_i, y_i) after skeleton extraction. The fitted curve is expressed by the following formula.

$$y = a_0 + a_1 x + a_2 x^2 \tag{1}$$

The grasping pose perpendicular to the tangent direction of the picking point is obtained in the following way. First, the picking point (x_{cut}, y_{cut}) and the fitted curve are employed to compute the tangent vector $\vec{n}_x$ at the picking point.

$$\vec{n}_x = [1, a_1 + 2a_2 \cdot x_{cut}, 0]^T \tag{2}$$

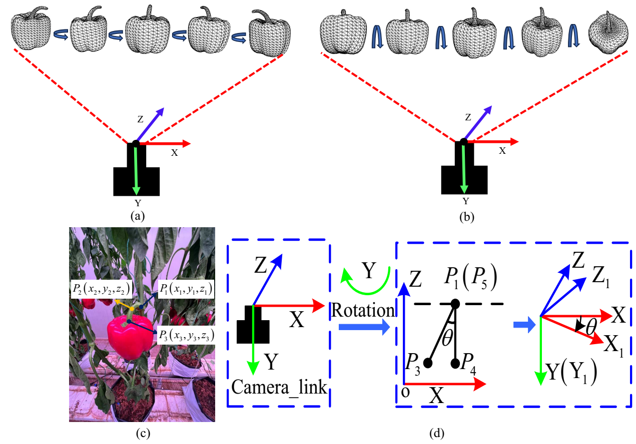

Fig. 7. (a) Rotating clockwise along the Y-axis direction. (b) Rotating counterclockwise along the X-axis direction. (c) The picking point P_2 and two endpoints P_1, P_3 of the peduncle. (d) Estimating the pose of sweet pepper peduncle.

Then calculate the vector $\vec{n}_z$ perpendicular to the tangent vector $\vec{n}_x$, and determine the grasping pose $(\vec{n}_x, \vec{n}_y, \vec{n}_z)$ perpendicular to the tangent direction of the picking point using the right-hand rule.

$$\vec{n}_z = [1, -\frac{1}{a_1 + 2a_2 \cdot x_{cut}}, 0]^T \tag{3}$$

$$\begin{cases} \vec{n}_y = [x_1, x_2, x_3]^T \\ \vec{n}_y \times \vec{n}_x = 0 \\ \vec{n}_y \times \vec{n}_z = 0 \end{cases} \tag{4}$$

The grasping pose along the direction of the fruit peduncle is calculated by estimating the yaw angle θ of the sweet pepper peduncle pose in the Y-axis direction. As shown in Fig. 7(c), the positions picking point $P_1\,(x_1, y_1, z_1)$ and the two endpoints $P_2\,(x_2, y_2, z_2)$, $P_3\,(x_3, y_3, z_3)$ in the world coordinate system are calculated according to pixel coordinate positions. The yaw angle θ of the fruit peduncle along the Y-axis direction in the camera coordinate system is computed following these steps. As shown in Fig. 7(d), the $P_1\,(x_1, y_1, z_1)$ and $P_3\,(x_3, y_3, z_3)$ are projected to form points P_5 and P_4. The yaw angle θ along the Y-axis direction can be calculated by the following formula.

$$\theta{=}\cos^{-1}\frac{P_1P_4}{P_3P_5}{=}\cos^{-1}\frac{z_1 - z_3}{\sqrt{(x_1 - x_3)^2 + (z_1 - z_3)^2}} \tag{5}$$

$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \tag{6}$$

Finally, the final grasping pose C_{pose} along the direction of the fruit peduncle and perpendicular to the tangent direction of the picking point is obtained through the camera coordinate system, $(\vec{n}_x, \vec{n}_y, \vec{n}_z)$, and $R_x(\theta)$ calculation.

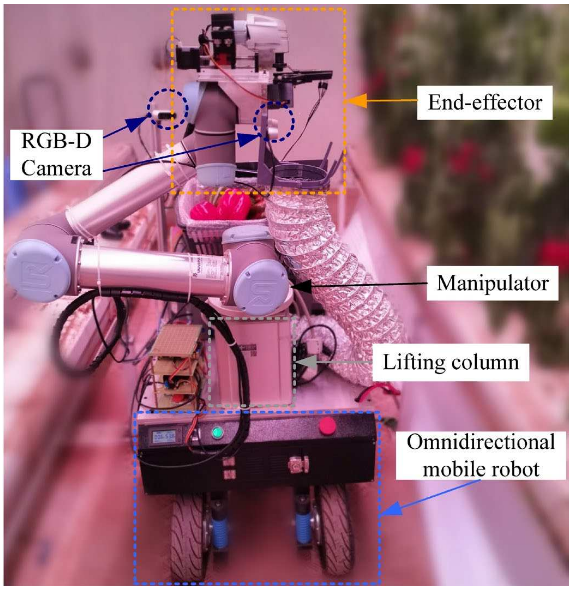

Fig. 8. Sweet pepper harvesting robot experimental platform.

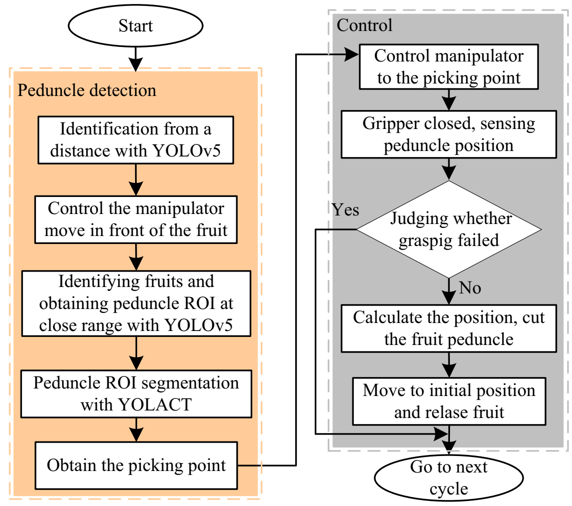

Fig. 9. Algorithm flowchart in a sweet pepper harvesting cycle.

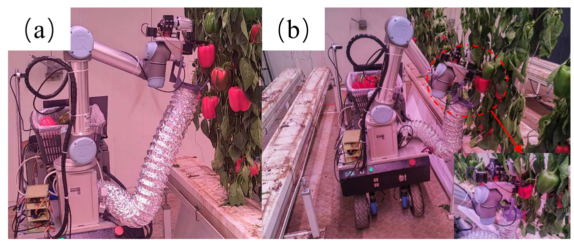

Fig. 10. (a) Grasping in a horizontal pose. (b) Grasping along the direction of the fruit peduncle.

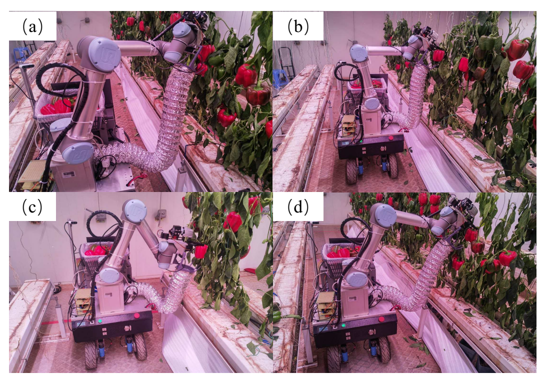

Fig. 11. Grasping along the direction of the fruit peduncle and perpendicular to the tangent direction of the picking point.

IV. Experiment and Performance Evaluation

In this section, the harvesting experiments were carried out in the Samsung ecological agriculture plant factory in Haicheng, Anshan City, Liaoning Province. First, the sweet pepper harvesting experimental platform is introduced. Then, The performance of the end-effector in different grasping poses was evaluated. Finally, field evaluation and tests were given to exhibit the overall performance of the harvesting robot.

A. *Sweet Pepper Harvesting Experimental Platform*

The structure of the sweet pepper harvesting robot is shown in Fig. 8, which is mainly comprised of a 6-degree of freedom manipulator UR5, two vision systems Intel RealSense D435i cameras, an omnidirectional mobile robot, and an end-effector. Two vision systems are employed. One is utilized for long-distance preliminary fruit position identification to determine the picking sequence. The other camera is mounted at the manipulator's end for precise identification of sweet pepper peduncles. All hardware is connected to a computer(Intel(R) Core(TM) i7-11800H CPU and NVIDIA GeForce RTX 3070 GPU). The Robot Operating System (ROS) is utilized to create a software framework for communicating and centrally controlling various components. Fig. 9 shows the algorithm flowchart of the harvesting robot software system for sweet peppers.

B. *Evaluation of Different Grasping Poses*

Fig. 10(a)-(b) and Fig. 11 show grasping in a horizontal pose, along the direction of the fruit peduncle, and along the direction of the fruit peduncle and perpendicular to the tangent direction of the picking point. To verify the end-effector's picking success rate under different grasping poses, we selected 90 pickable sweet peppers, each of which was a group of 30, and picked them with three different grasping poses. The picking success rates were 63.3%, 73.3%, and 90%, respectively, only considering the grasping pose. The experimental results show that grasping along the direction of the fruit peduncle and perpendicular to the tangent direction of the picking point can significantly enhance the picking success rate.

C. *Field Harvesting Experiment*

The automatic harvesting experiments were conducted by employing the end-effector without and with a fruit recycling device, referred to as "harvesting method 1" and "harvesting method 2," respectively. Fig. 12(a)-(f) shows the sweet pep-

TABLE I

PERFORMANCE OF HARVESTING WITH TWO END-EFFECTORS.

Method	Total number of harvesting peppers	Average picking time(s)
Harvesting method 1	30	23
Harvesting method 2	30	**15**

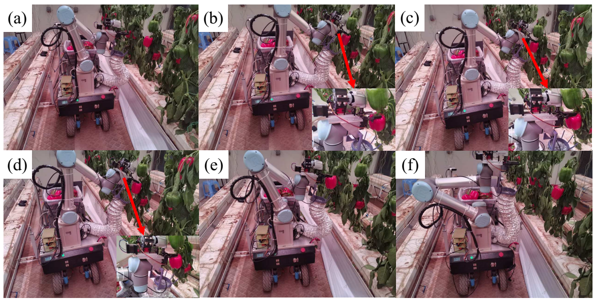

Fig. 12. Sweet pepper harvesting process utilizing harvesting method 2 in a plant factory. (a) Identify fruit peduncle at close range. (b) Move to the picking point. (c) Grasp sweet pepper peduncle. (d) Cut sweet pepper peduncle. (e) Move to the midpoint. (f) Return to the initial position.

per picking process with a fruit recycling device. Fig. 13(a)-(f) represents the harvesting process of sweet pepper without the fruit recovery device. Compared with Fig. 12, after harvesting the sweet pepper, the manipulator needs to place the harvested sweet pepper into the basket. Table I shows the average picking time for picking 30 sweet peppers utilizing the two abovementioned methods. The average picking time of the two methods is 23s and 15s, respectively.

To further verify the sweet pepper harvesting robot, 120 pickable sweet peppers were selected as the experimental e-valuation samples. Table II shows the experiment results. Fig. 14 shows some successfully harvested sweet peppers. The experimental results demonstrate that the harvesting robot is capable of harvesting sweet peppers non-destructively, and the picking success rate is 79.17%. There were also some harvesting failures during the whole harvesting process, as shown in Fig. 15, a case of harvesting failure where the peduncle was not completely cut off. Without considering the motion planning failure of the manipulator, there are several reasons for the picking failure during the harvesting process:

a. Failed to identify and locate the picking point accurately.

b. The end of the robotic arm collided with the sweet pepper plants surrounding the picking point.

c. The end-effector's clamping module slipped while grasping the fruit peduncle.

d. The sweet pepper peduncle is not completely cut off.

e. Harvesting failure due to plant shaking during harvesting.

V. CONCLUSION

This paper developed a sweet pepper harvesting robot and reported its experimental verification. The robot utilizes two cameras to identify the sweet pepper peduncle, performing initial recognition of the sweet pepper from a distance and identifying the ROI of the sweet pepper peduncle at close range, significantly enhancing the accuracy and robustness of peduncle identification. We propose a grasping pose control algorithm of the end-effector of the manipulator by estimating the sweet pepper peduncle pose. The experimental results show that the grasping pose along the peduncle direction and perpendicular to the tangent direction of the picking point can greatly improve the success rate. Finally, the sweet pepper automatic harvesting experiments were conducted in a plant factory. The experimental results show that a single fruit takes approximately 15 seconds to pick, and the picking success rate is 79.17%.

One of the future works is to consider installing multiple sensors to measure grasping success and failure through multi-modal information. In addition, we will consider the obstacle avoidance issue to prevent collision between manipulator and sweet pepper plants.

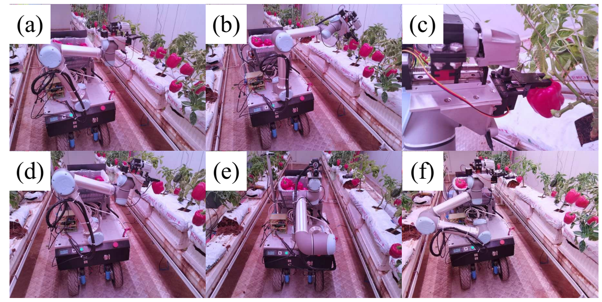

Fig. 13. Sweet pepper harvesting process utilizing harvesting method 1 in a plant factory. (a) Identify fruit peduncle at close range. (b) Move to the picking point. (c) Grasp and cut sweet pepper peduncle. (d) Move to the midpoint. (e) Place the fruit into the collection basket. (f) Return to the initial position.

TABLE II

PERFORMANCE TEST RESULTS OF HARVESTING SWEET PEPPERS.

	Success	Total failure	Failure reasons				
			a	b	c	d	e
Total	95	25	6	4	5	6	4
Success rate	79.17%	20.83%	5%	3.3%	4.2%	5%	3.3%

Fig. 14. A diagram of a portion of sweet pepper successfully picked.

Fig. 15. A case of failure in harvesting sweet peppers.

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