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FRONTIERS OF AGRICULTURAL SCIENCE AND ENGINEERING

Engineering
Transactions of CAE

RESEARCH ARTICLE
2026 / Volume 13 / Issue 2 / 25643

Design and performance evaluation of a rigid-flexible coupling end-effector for tomato picking robots

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KEYWORDS

ADAMS software, compound force, end-effector, rigid-flexible coupling, tomato harvesting robot

HIGHLIGHTS

- Rigid-flexible end-effector with telescopic suction cup and three-finger gripper for non-destructive tomato grasping via adhesion-clamping.
- 180-sample test finds optimal 270° rotation and 8.36 N force, cutting picking time by 40%.
- Integrated suction (3.58 N) and clamping (5.94 N) force analysis framework ensures 88% picking success with 0.5% damage rate.
- Maintains 5.4 s per fruit cycle time under simulated greenhouse conditions (60% RH, 22 °C), achieving 55% efficiency over manual harvesting.
- Proposes YOLOv5 + HSV hybrid model for day-night tomato picking, enhancing night-time recognition accuracy/speed/precision and boosting picking efficiency/success rate.

Received April 18, 2025;
Accepted June 4, 2025.

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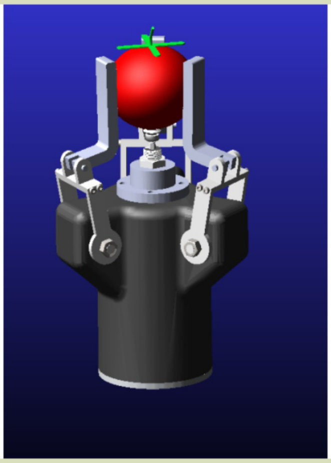
GRAPHICAL ABSTRACT



ABSTRACT

Tomato picking is a time-consuming and laborious work. The use of intelligent equipment of picking instead of manual picking can improve the production efficiency. The end-effector is an important element in direct contact with tomato fruit, and it is the key to realize automatic tomato harvest. This paper introduces a rigid-flexible coupling end-effector with a telescopic pneumatic sucker. The end-effector first extends the vacuum sucker of the adhesion mechanism to hold the target tomato and pull it out for a certain distance, and then grips the tomato with a clamping component. The target tomato picking operation was completed through the movement mode of spiral and pull combination. The physical characteristics of tomato and the mechanical characteristics of fruit stem were investigated, aiming at providing a solid theoretical basis for the design and mechanical analysis of end-effector. Then, the stability of suction and pulling force in the process of holding and pulling tomato were analyzed, so as to clarify the specifications of suction and picking parts. Finally, a composite force analysis of the adhesion mechanism and the holding mechanism was undertaken to achieve the mechanical design goal of the tomato adhesion and picking movement process. The picking performance test of the end-effector showed that the picking time of single fruit was about 5.4s and the success rate of picking could reach 88%. This study provides sufficient theoretical basis for the development of tomato picking robot and the design of end-effector.

1 Introduction

Tomatoes are an important part of the daily diet of people all over the world, with huge demand every year. Harsh picking environment, high picking cost and high labor intensity brings great challenges to fruit picking. The tomato picking environment is poor, the picking cost is high and the labor intensity is great[1–3] In addition, 2–5 tomatoes are generally grown in a bundle and the growing environment is relatively complex. All these challenges make intelligent harvesting machines highly desirable[4–6]. Tomato picking robot has become a research hotspot, and its advantages are that it can realize automatic picking, improve picking efficiency and reduce the labor intensity[7]. Of these, the end-effector is an important actuator in direct contact with the tomato. Standard end-effectors can easily damage tomatoes when grasping them, affecting their market competitiveness[8]. Therefore, research and development of end-effectors for greenhouse tomato harvesting robots will help improve the harvesting efficiency of harvesting robots and achieve lossless harvesting[9].

Xue et al.[10] designed an end actuator for picking the tender tips of tea leaves in a clamping and lifting manner. They used the GUI module of MATLAB software and SolidWorks software to optimize and analyze the structural parameters of the picking end actuator. However, they lacked the analysis of the clamping force and the success rate was not high. Jun et al.[11] developed an end-effector suitable for tomato picking that realized error compensation through suction cup assisted positioning and improved the success rate of cutting fruit stalks. Guo et al.[12] has designed a novel double-finger soft-end actuator with an active palm and two active fingertips. At a pressure of −90 kPa, the end-effector achieves a maximum grasping force of 32 N in the horizontal direction and 28 N in the vertical direction. The working angle of the fingers is 0° to 120°. The size range of objects that can be grasped is from 0 to 200 mm in diameter. However, during the clamping process, the structure of the two fingers is unstable, and it is easy to be disturbed by nearby debris during the picking process. Wang et al.[13] designed a flexible end-effector, which was controlled by different air pressure drives, but caused insufficient clamping force. The end-effector of the tomato grabbing robot designed by Zhou et al.[14] realized the process of separation from the target tomato through the fingertip, but field tests has not been conducted and the success rate of picking cannot be verified.

In the picking process of tomatoes, there is another picking method, the adhesion picking[15–20]. Jo et al.[21] introduced a soft robot gripper based on suction cups for cucumber harvesting, which can adjust its shape and surface parameters to respond to the surface and shape characteristics of cucumbers. However, due to the inconsistent thickness and length of the cucumber stems, the nearby stems and leaves are prone to being sucked up and blocking the suction cups during the adhesion process. Zhao et al.[22] has designed a pressure-stable flexible end-effector for *Agaricus bisporus*, which adopts a low-cost adhesion force adjustment system. However, it cannot accurately identify the target during adhesion, so it is easy to adsorb and simultaneously select nearby *A. bisporus*. Duan et al.[23] designed an adhesion-type end-effector that can take up five tissue culture seedlings at one operation. The fruit is absorbed through the adhesion force of the suction cup and stabilized through the grasping force of the claws, but there is a lack of combined force analysis of adhesion and grasping. Lu et al.[24] designed a straight end-effector to meet the apple picking performance requirements of the new vacuum-based robot harvesting system. The twist-pull fruit picking method was adopted. Through the analysis of multiple performance indicators such as vacuum pressure, overall picking success rate, picking rate of the rotating mechanism and fruit adhesion direction, this end-effector greatly improved the fruit picking performance of the robot.

According to the requirements of controlled environmental agriculture in tomato plantations in southern China, an end-effector with telescopic suction cups was designed for picking tomatoes. To solve the problem of interference from branches and leaves, the vacuum suction cup is first tested, and the positioned tomatoes are sucked up and pulled out a short distance to avoid interference from branches and leaves or other tomatoes. This paper focuses on the design of the adhesion and picking components of the end-effector[25–27], the composite force analysis of the adhesion structure and the clamping structure, and verifies whether the adhesion and picking components meet the design requirements during the picking process. The adhesion and picking components are analyzed and simulated by ADAMS software, and a prototype is made for experimental verification.

2 Materials and methods

2.1 Physical characteristics of facilities tomato

The samples used in this experiment were collected from the Tomato Smart Demonstration Facility located in Caoshe Village, Haizhou District, Lianyungang City, Jiangsu Province, China. The cultivar Pintaro was selected for this study, as it is characterized by its large fruit size, thick skin and disease resistance, making it suitable for mechanical harvesting and transportation. Figure 1 illustrates the geometric parameters of the tomato, indicating the transverse and vertical diameters. The transverse diameter refers to the maximum length between the two profile surfaces of the tomato, while the vertical diameter denotes the longest distance from the base of the peduncle to the bottom of the fruit. A total of 100 tomatoes were randomly selected for measurement, the transverse and vertical diameters were measured using vernier calipers, and the weight of each tomato was recorded using an electronic balance with an accuracy of 0.01 g.

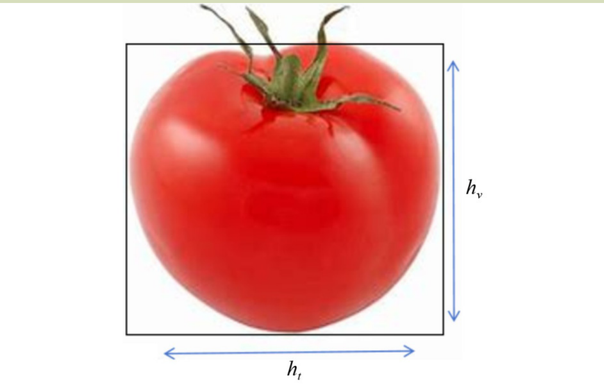


Fig. 1 Tomato geometric parameters (© Qizhi YANG, 2:38 P.M., July 20, 2023).

2.2 Mechanical characteristics of tomato stem

Pintaro tomato is an excellent cultivar with strong plant growth, good fruit hardness, storage resistance and long shelf-life[28]. To study the mechanical characteristics of the fruit pedicel of this cultivar, a tension meter was used on the test platform, as shown in Fig. 2.

To test the breaking force of the tomato pedicel, 20 tomatoes at the firm ripening stage were selected, covering the individual differences in the organism, one end of the thin line was connected to the tomato stem and the other end was connected to the tension meter[8]. The force gauge was hand-held and an

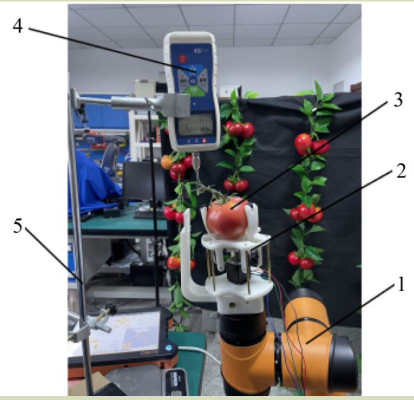


Fig. 2 Experimental platform for mechanical properties of tomato stem. 1, Mechanical arm; 2, end-effector; 3, tomato; 4, tension meter; and 5, hang support racks (© Qizhi YANG, 10:37 A.M., April 12, 2024).

instantaneous tensile force was applied until the fruit stem fractured. The recorded force at the moment of fracture was taken as the breaking strength of the peduncle.

To evaluate the maturity of tomatoes and the optimal harvest time, 20 samples from each of the five stages of green ripening stage, color breaking stage, color changing stage, maturity stage and full ripening stage were selected, totaling 100 fruits at different maturity stages for the torsion test[7]. The motor at the end of the robotic arm is responsible for rotating the end-effector, which interacts with the tomato fruit to record the angle of rotation at which the peduncle fractures at different time intervals.

Sixty mature tomatoes, each with a peduncle, were selected for a combined tensile and torsional testing experiment[26]. A digital dynamometer (Sauter AG, Basel, Switzerland) was employed as the testing instrument. The dynamometer was secured to a suspended support frame, and the peduncle of the tomato was attached to the dynamometer via a thin line. The robotic arm was then maneuvered so that the end-effector grasped the tomato directly below it. Concurrently, the motor at the end of the robotic arm was rotated to facilitate the rotation of the end-effector around the tomato while applying a vertical downward pull until the fruit and peduncle detached, at which point the motion was halted.

2.3 Analysis of tomato holding and pulling force

Tomato fruits typically have an oval spherical shape, and determining the parameters for the gripping force requires investigating the interactions between the suction cup and the fruit, as well as between the pedicel and the plant stem. Through the study of the motion displacement relationship, it is possible to understand the parameters of tomato motion trajectory, velocity and acceleration, so as to provide a theoretical basis for optimizing the holding pull, which is of great significance for optimizing the holding pull control and improving the holding pull efficiency.

2.3.1 Tomato holding pull displacement analysis

Based on the theoretical mechanics principle, the connection between the tomato fruit pedicel and the plant stem is regarded as a fixed-end constraint, which can be simplified into supporting force, normal force and a couple. The supporting force is to keep the connection between the fruit pedicel and the plant stem in a fixed position and the normal force is to prevent the fruit pedicel from rotating around the connection point. This simplified model helps to better understand the force interactions at this connection.

During the gripping and pulling process, the tomato fruit experiences displacement along the gripping direction due to the suction force and pressure from the suction cup. This displacement is generated by the rotation of the fruit around the fixed-end constraint. At the same time, rotation will also make the center of the fruit move from the initial position to the actual position, and will produce a certain displacement in the vertical direction, making it offset from the suction line, as shown in Fig. 3. The displacement relationship between horizontal and vertical directions is:

$$\begin{cases} x = (L+R)(\sin\alpha' - \sin\alpha) \\ y = (L+R)(\cos\alpha - \cos\alpha') \end{cases} \tag{1}$$

where, L is the length of the tomato stem (mm), and R is the radius of the tomato (mm), α' is the tilting angle of the tomato stem during holding and pulling (rad), and α is the initial inclination angle of the tomato stem during the holding and pulling process (rad).

2.3.2 Analysis of the interaction force between tomato and suction cup

When the tomato harvesting robot begins operation, the vacuum system is activated, and the robotic arm guides the end-effector to the pre-harvesting position. The vacuum suction cup extends forward through linear motion of the cylinder to make contact with the fruit, creating a pressure

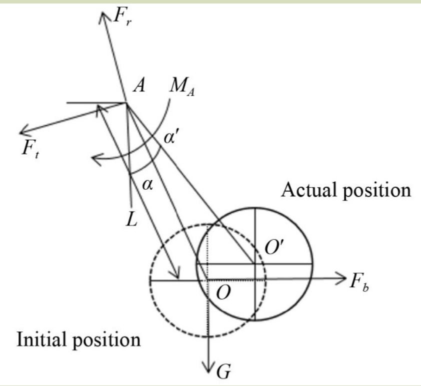


Fig. 3 Analysis of suction and pulling states.

differential that generates suction force and pressure in the area of negative pressure, as shown in Fig. 3. During the process of adhering to the tomato and retracting the suction cup, the mechanical relationship of the vacuum sucker is:

$$F_N + F_b - F_S = ma \tag{2}$$

where F_N is the normal pressure of the sucker on the fruit (N), F_b is the cylinder axial force (N) and, F_S is the adhesion force of vacuum sucker on fruit (N).

Vacuum suction cup and tomato fruit surface pressure F_N is determined by the pressure generated between the fruit surface and the sucker and the sealing area:

$$F_N = p_c(A_2 - A_S) \tag{3}$$

where, p_c is the positive pressure of the suction cup on the tomato fruit (MPa), A_2 is the cross-sectional area of the outer diameter of the sucker (mm^2), $A_2 = \pi\varphi_2{}^2/4$ and φ_2 is the outer diameter of the sucker (mm). A_S is the holding area of the suction cup (mm^2), $A_S = \pi\varphi_S{}^2/4$ and φ_S the diameter of the closed area of the suction cup (mm).

The suction force of vacuum sucker on tomato fruit is F_S.

The schematic diagram of the deformation of the suction cup under force is shown in Fig. 4, when subjected to the cylinder axial tension F_b, the suction cup will gradually restore deformation, the closed space between the suction cup and the tomato will gradually expand, and the holding area A_S will gradually increase, that is, the closed space will gradually increase. The relationship between the compression deformation of the sucker Δz and the diameter of the holding closed area φ_S is:

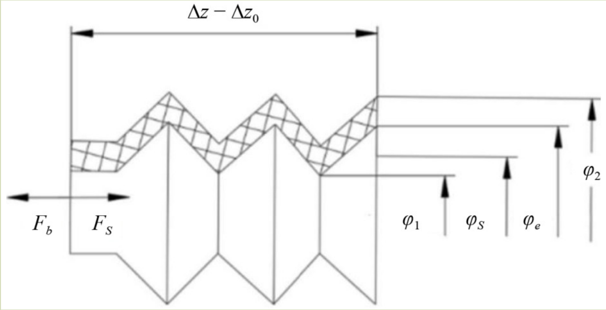


Fig. 4 Deformation of suction cup under force.

$$\varphi_S = \varphi_e - \frac{\Delta z}{\Delta z_0}(\varphi_e - \varphi_1) \tag{4}$$

where, φ_S is the diameter of the vacuum sucker (mm), φ is the effective diameter of the sucker (mm), Δz is the compression deformation of the sucker (mm), and Δz_0 is the maximum deformation of the sucker (mm).

The relationship between the holding force of the suction cup, the vacuum degree and the holding closed area is:

$$F_S = 10^{-3}|\Delta P_u| \cdot A_S \tag{5}$$

where, $|\Delta P_u|$ is the system negative pressure (kPa).

The relationship between the deformation of the sucker under the effective action of different sizes and directions is:

$$10^{-3}|\Delta P_u| \cdot A_S - F_b = k_p\Delta z \tag{6}$$

where k_p is the elastic coefficient of the sucker.

Equations (7) and (8) can be obtained from the above equation

$$F_S = \frac{\pi}{4\times 10^3}|\Delta P_u|\left[\varphi_e - \frac{\Delta z}{\Delta z_0}(\varphi_e - \varphi_1)\right]^2 (0 \ll \Delta z \ll \Delta z_0) \tag{7}$$

$$F_b = \frac{\pi}{4\times 10^3}|\Delta P_u|\left[\varphi_e - \frac{\Delta z}{\Delta z_0}(\varphi_e - \varphi_1)\right]^2 - k_p\Delta z \ (0 \ll \Delta z \ll \Delta z_0) \tag{8}$$

The cylinder axial tension F_b is solved.

Based on the retractable adhesion-picking component design, the cylinder moves in a straight line to provide traction on the tomato fruit to ensure that the axial pull of the cylinder remains constant at a given air pressure:

$$F_b = AP_g = P_g \cdot \frac{\pi}{4}(D-d)^2 \tag{9}$$

where P_g is the pressure in the cavity (MPa), D is the diameter of the cylinder piston rod (mm), and d is the diameter of the cylinder push rod (mm).

2.3.3 Balance analysis of holding and pulling force

In the process of gripping and pulling with the vacuum suction cup, it is essential to consider the gravity of the tomato itself. According to the equations of equilibrium in a planar force system, it can be inferred that:

$$\sum F_x = 0 \rightarrow F_r\sin\alpha + F_t\cos\alpha = F_b + ma \tag{10}$$

$$\sum F_y = 0 \rightarrow F_r\cos\alpha = G + F_t\sin\alpha \tag{11}$$

$$\sum M_A = 0 \rightarrow F_b\left[(L+R)\cos\alpha + y\right] = G(L+R)\sin\alpha + M \tag{12}$$

When the tomato fruit is tilted at a certain angle under the drive of the vacuum sucker, the tomato will be in a static equilibrium state, and Eqs. (13) and 14 are obtained:

$$\begin{cases} F_t = \dfrac{G}{\cos\alpha} \\ F_t = -\dfrac{G\sin\alpha}{\cos^2\alpha} \\ M = -G(L+R)\sin\alpha \end{cases} \tag{13}$$

Combination of the above equation obtains:

$$\alpha = \arcsin\left(\frac{x}{L+R} + \sin\alpha'\right) \tag{14}$$

From the above analysis, it can be seen that in the process of vacuum holding and pulling, the mutual force between the suction cup and the tomato fruit moves in a straight line through the cylinder, and the axial pull force is closely related to the diameter, weight and initial inclination angle of the fruit, which constitutes a multi-factor holding and pulling operation model.

2.4 Parameter calibration of holding system

The design of the end-effector for tomato harvesting relies on a vacuum system to facilitate the attachment and detachment of the harvesting components. During the operation of gripping and pulling, it is crucial to accurately calibrate the pressure parameters to ensure that the vacuum suction cups can effectively complete the harvesting task while avoiding damage to the tomato fruits.

2.4.1 Determination of the diameter of the sucker

According to relevant studies, the irregular curvature of tomato surfaces presents challenges for suction cups with excessively large diameters, which may fail to conform to the surface contours of the tomatoes. This results in an inability to establish a sealed space between the suction cup and the tomato, potentially leading to suction failure. The suction and detachment forces generated by suction cups of different diameters vary significantly. In this study, suction cups of φ20, φ15 and φ10 specifications will be selected, and the suction and pulling force of suction cups of different diameters will be compared through test analysis, so as to determine the final specifications of suction cups selected for the adhesion and picking parts.

For this study, the electronic dynamometer was used to conduct experiments on high-quality Pintaro tomatoes. The electronic force gauge was securely mounted on a support structure, which was anchored to the work surface. One end of the tomato was connected to the force gauge via a thin wire, while the end-effector was adjusted to ensure that the vacuum suction cup, the center of the tomato and the electronic force gauge were aligned on the same horizontal plane.

2.4.2 Negative pressure holding parameter calibration

The negative pressure holding parameter calibration platform was established. Twenty groups of tomato fruits with transverse diameter of 70–80 mm were selected to carry out organ sucker test with diameter of 20 mm. During the experiment, it was ensured that the electronic dynamometer, the center of the tomato and the suction cup were aligned on the same horizontal plane. When the suction cup touches the tomato, the indicator of the negative pressure gauge jumps, and the indicator of the negative pressure gauge before and after holding is recorded. During the holding process of tomato fruit, the electronic dynamometer is pulled at a constant speed until the suction cup is separated from the tomato and the peak value of the electronic dynamometer is recorded.

2.5 Compound force analysis

When the adhesion mechanism and the clamping mechanism act on the tomato at the same time, the tomato is subjected to force analysis, as shown in Fig. 5. The tomato is subjected to the positive pressure N_i at the contact point, the friction force f_i with respect to the lateral clamping of the gripper, and the supporting force N_q exerted by the suction cup on the end-effector sucker.

According to the principle of force balance, the composite analysis of tomato was performed, and the N_q calculation formula of the supporting force of the suction cup was obtained:

$$\sum_{i=1}^{3}(N_{yi} + f_{yi}) = N_q \tag{15}$$

$$N_1 = N_2 = N_3 = N \tag{16}$$

$$\sum F_{yi} = F_{y1}\sin\gamma + F_{y2}\sin\gamma + F_{y3}\sin\gamma \tag{17}$$

$$\sum F_{yi} = N_1\cos\gamma + N_2\cos\gamma + N_3\cos\gamma \tag{18}$$

$$N_q = 3N(\cos\gamma + \mu\sin\gamma) \tag{19}$$

The balance force system in the x direction is shown in Eq. (20). Since the three-claw structure is arranged equally at 120° in space, the component force of the claw force in the horizontal direction x is equal and cancels each other out. In the horizontal direction, the resultant F_x is always 0.

$$\sum_{i=1}^{3}(N_{xi} + f_{xi}) = F_x \tag{20}$$

In the process of pulling the fruit, when the holding mechanism and the adhesion mechanism function at the same time, it needs to meet the following requirements:

$$\begin{cases} 3\times(N\cos\theta + f_p\sin\theta) + mg + F_S \geqslant T \\ N + F_S < F_d \end{cases} \tag{21}$$

where, F_S is the adhesion force of the sucker (N); θ is the inclination angle of the contact surface between the claw and the tomato (°), F_d is the maximum gripping force of tomato (N) and with $f_p = \mu_s N$, $g = 9.8\ \text{N·kg}^{-1}$, $m = 300$ g, $\mu_s = 0.8$. As can be seen from Eq. (21), when the adhesion mechanism acts on the tomato fruit, the positive pressure of the claw on the tomato decreases.

Ten tomatoes at the firm ripening stage were selected from the tomato planting base in Lianyungang City, China, with a transverse diameter of 75–85 mm. The end-effector compound force test was performed to examine the effect of vacuum sucker on the picking force of tomato fruit.

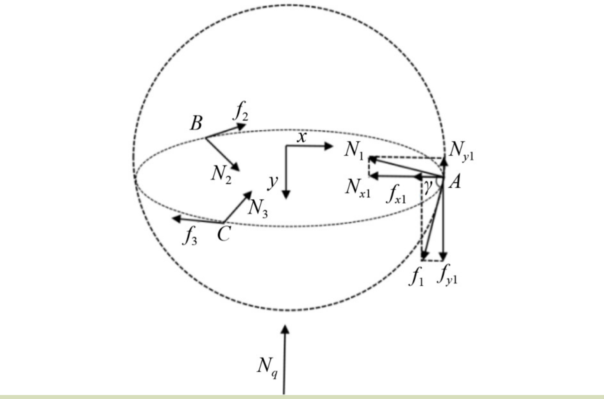


Fig. 5 Horizontal composite analysis of tomatoes.

2.6 Prototype trial production and test scheme

To verify the grasping effect and picking performance of tomato picking end-effector, the test site was selected as the Wisdom Exhibition Facility of Lianyungang Tomato Farm, China, and the cultivar was Pintaro. The experimental setup is illustrated in Fig. 6. The clamp and internal connecting rod mechanism were made by mechanical processing, and aluminum alloy 6061 was selected to ensure the stability of the clamp during the grasping process. The adhesion mechanism used a silicone rubber bellows suction cup, which offers excellent performance and durability, effectively reducing impact forces during both the suction and detachment operations. The cylinder was fixed on the sleeve through the guide shaft support to realize the adhesion function of the end-effector. The experimental scheme was that the end-effector was installed on a six-degrees-of-freedom mechanical arm through the flange. After the vision system recognizes the tomato fruit, the upper computer guides the end-effector to the pre-picking position and picks the target fruit. Ten groups of tomatoes in different positions in the greenhouse of the facility were picked, and various fruit data were recorded to examine the factors affecting the success rate of picking. The picking time was also recorded.

3 Results and discussion

3.1 Physical characteristics of facilities tomato

The geometry and mass of tomato will directly affect the

Fig. 6 Experimental scheme (© Qizhi YANG, 3:53 P.M., April 17, 2024).

dimensional design of tomato picking end-effector. The weight of the tomatoes ranged from 182 to 337 g, the transverse diameter of the tomato was 62–98.3 mm, and the longitudinal diameter of the tomato was 52.4–72.3 mm. The diameter of suction cups can be selected by reference to tomato quality data. Design claw length should not be less than 72.3 mm.

3.2 Mechanical characteristics of tomato stem

In the actual production process, in order to facilitate the storage and transportation of tomatoes, most tomatoes are primarily harvested at the time of firm ripening. Considering that the hand-held tension could not control the angle of inclination between the tomato and the fruit, but there is not significant relationship between the picking angle of the end-effector and the breaking force of the stem[29]. According to the breaking test of the stem, the average breaking force of the stem was 12.5 N and the maximum instantaneous pulling force was 16.3 N.

The experimental results shown that the tomato fruits in the overripe stage fall off when the rotation angle was less than 180°, and the internal cells of such tomato fruits gradually decompose, and the fruit quality declines, nutrients are lost and the taste becomes less appealing. Fully ripe tomatoes detached after being rotated between 180° and 360° followed by pulling. Although these fruits are at their optimal consumption stage, their soft texture renders them unsuitable for long-term storage and transportation, thereby shortening their shelf life. For mature tomatoes, complete harvesting can be achieved with rotations between 360° and 540° followed by pulling. Typically, detachment occurs after a 360° rotation, followed by an additional angle of rotation and pulling. After harvesting, these tomatoes can be stored short-term to maintain their optimal condition. Therefore, it is crucial for the end-effector to ensure that tomatoes are in their ideal harvesting state during the picking process.

A total of 60 mature tomatoes with stems were selected for a combined pulling and twisting experiment. The experimental data are given in Table 1.

According to Table 1, the combined pulling and twisting picking method can achieve tomato harvest with smaller pulling force and fewer rotation angles, thereby reducing picking time and improving picking efficiency. The tested stems primarily detached at the abscission zone, with the maximum breaking force recorded at 15.2 N. It was observed that as the angular degrees of freedom of the end-effector increased, the average breaking force decreased. When the angle of freedom at the end of the mechanical arm reached 360°, it was found that the average pulling force was no longer reduced, and the average time consuming was also not reduced, which may be due to the separation of the fruit handle before the rotation angle of the end motor was in place. Therefore, the rotation angle of the end motor is 270° and the average breaking force is 8.36 N, which is taken as the picking index of the end-effector, that is, the maximum breaking force of the fruit stem is 8.36 N.

3.3 Overall mechanism design and working principle

Based on the picking requirements and combining the advantages of rigid clamping and flexible adhesion, a novel

Table 1 Record of rotational tensile test for tomatoes

Angle	Maximum tension (N)	Minimum tension (N)	Average tension (N)	Proportion of shedding mode (%)		Success rate (%)	Average time spent (s)
				Shedding at the separation layer	Peel off at the pedicle		
45°	15.23	10.82	11.88	80	10	90	2.6
90°	15.68	10.38	11.61	90	10	100	2.2
135°	11.85	9.79	10.45	100	0	100	2.3
180°	10.56	8.32	9.53	100	0	100	1.8
270°	9.73	7.85	8.36	100	0	100	1.7
360°	9.97	8.15	8.65	100	0	100	1.8

end-effector with a retractable suction cup suitable for tomato harvesting has been designed. The total length is 130 mm, the width is 130 mm, and the height is 190 mm. The end-effector is composed of a clamping mechanism, a driving mechanism and an adhesion mechanism. The gripping mechanism comprises three rigid grippers, positioned 120° apart, mimicking the way a human hand grasps a tomato. The finger length of the gripper is 75 mm, and the clamping diameter is 50–110 mm. The surfaces of the grippers are equipped with a layer of silicone rubber cushioning to minimize the damage to the tomatoes during the harvesting process[30,31]. The three grippers are driven by the motor, and the connecting rod and rocker are driven by the linear movement of the screw nut, so as to realize the opening and closing of the gripper. The overall structure of the end-effector is shown in Fig. 7.

For fruits growing in natural environments, there are usually interference factors such as branches and leaves occlusion and fruit overlap. Standard end-effectors[32] tend to inadvertently grasp adjacent branches or injure other tomatoes when attempting to directly grip the tomatoes. In contrast, the end-effector first protruded through the vacuum sucker, sucked and pulled the positioned tomato out, and then clamped it away from the original position to avoid interference from branches and leaves or other tomatoes. The working flow chart is shown in Fig. 8.

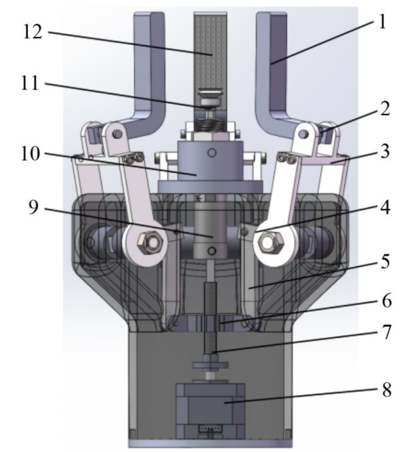


Fig. 7 Overall structure of end-effector. 1, Clamp claw; 2, torsion spring; 3, four-hole connector; 4, connecting rod; 5, rocker; 6, screw nut; 7, ball screw; 8, motor; 9, cylinder; 10, column fixings; 11, vacuum suction cup; and 12, silicone pad.

3.4 Design of the adhesion picking parts

3.4.1 Operating principle of the adhesion mechanism

When adsorbing tomatoes, the air is compressed by a micro air pump and purified by a pneumatic three-in-one unit. The pneumatic three-piece set includes an air filter, a pressure reducing valve and an oil mist lubricator. The air filter is used to filter impurities and particles in the air to ensure its cleanliness. The pressure reducing valve is used to control the air pressure and ensure the safe and stable operation of the air pressure equipment. The oil mist lubricator is used to add lubricating oil, reduce friction and wear, and improve efficiency and service life. At the beginning of adhesion picking, the gas flow is controlled by the solenoid valve. When the suction cup adsorbs the tomato, the solenoid valve opens the fluid pipeline. When the generated air pressure reaches a certain level, the pressure gauge sends a signal to tell the solenoid valve to close the channel to maintain the pressure of the suction cup. When the suction cup detains the tomato, the solenoid valve closes the fluid pipeline and changes the fluid channel, inputting a certain amount of air into the suction cup to make the tomato fall off quickly. The suction cup generates negative pressure through a vacuum generator to achieve the adhesion of tomatoes. The schematic diagram of the adhesion mechanism is shown in Fig. 9.

3.4.2 Analysis of tomato holding and pulling force

The adhesion force of the suction cup is stable adhesion through the pressure difference between the suction cup and the tomato surface which is lower than atmospheric pressure. During the pulling and detaching operation, the fruit experiences relative displacement, requiring the overcoming of the interaction forces between the stem and the plant, as well as the gravitational force acting on the fruit. Once the suction cup is in contact with the tomato fruit, through the telescopic movement of the cylinder, the tomato fruit attached by negative pressure is pulled out.

3.4.3 Parameter calibration of holding system

The design of the end-effector for tomato picking is dependent on a vacuum system. When the end-effector performs the holding and pulling operation, it is essential to accurately calibrate the air pressure parameters to ensure that the vacuum sucker can effectively complete the picking task and avoid damaging the tomato fruit. Suction cups are the actuating elements in direct contact with tomato fruits and the correct

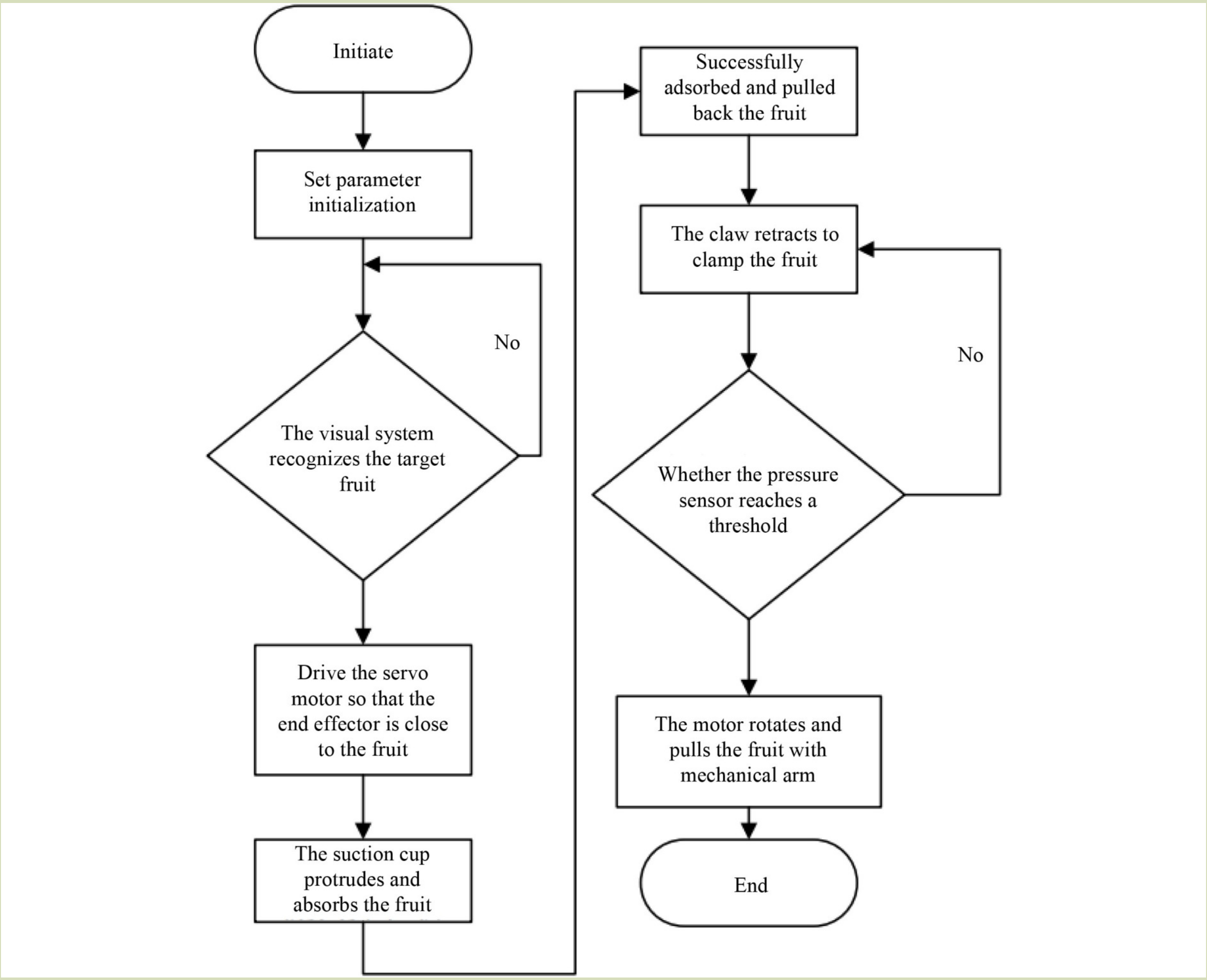


Fig. 8 Workflow diagram.

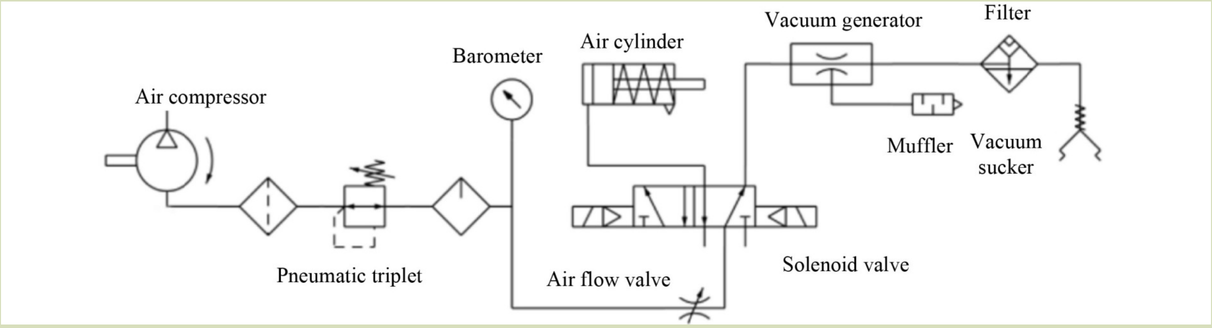


Fig. 9 Principle diagram of adhesion mechanism.

selection is important to achieve non-destructive picking and improve the success rate of picking.

The test results are given in Table 2. The average adhesion forces of the suction cups with diameters of 10, 15, and 25 mm are 0.58, 1.47, 3.58 and 5.28 N, respectively, and the average pulling forces of the suction cups are 0.83, 1.74, 3.36 and 5.64 N. According to the physical properties of the tomato, the adhesion force of the suction cup is too small to support the weight of the tomato. Additionally, considering that the lateral diameter of mature tomatoes is 70–90 mm, the suction cups with a diameter of φ20 mm cover 22%–29% of the tomato surface, providing strong grip stability. However, the suction cups with diameters of φ10 and φ15 mm show local stress concentration, increasing the risk of damaging the tomato fruits. Also, the φ20 mm suction cup provides a 5–8 mm buffer during the working process, avoiding the risk of accidental stem detachment during the test with the φ25 mm suction cup, and the vacuum suction cup with a diameter of 20 mm was finally selected as the adhesion mechanism device.

The holding system needs to detect and adjust the adhesion force of the suction cup to ensure that the air pressure is stable during the adhesion process, and that the vacuum and negative pressure of the vacuum cup reach the required value when holding the tomato fruit, so as to achieve stable adhesion.

The negative pressure holding parameter calibration platform was established. 20 groups of tomato fruits with transverse diameter of 70–80 mm were selected to carry out organ sucker test with diameter of 20 mm. During the experiment, make sure that the electronic dynamometer, the tomato center and the suction cup are at the same level. When the suction cup touches the tomato, the indicator of the negative pressure gauge jumps and the indicator of the negative pressure gauge before and after holding is recorded. During the holding process of tomato fruit, the electronic dynamometer is pulled at a constant speed until the suction cup is separated from the tomato and the peak value of the electronic dynamometer is recorded, as detailed in Table 3.

When the suction cup successfully held the tomato fruit in the test, the average vacuum negative pressure value after holding was −13.6 kPa and the average pulling force was 3.24 N.

$$\text{Vacuum degree} = \frac{\left|\text{Vacuum negative pressure}\right|}{\text{Standard atmosphere}} \times 100\% \quad (22)$$

When the vacuum degree of the vacuum system reaches 13.4% under this vacuum negative pressure, the vacuum sucker can realize the holding and pulling operation. The cylinder works with uniform acceleration motion. Due to the light weight of the cylinder components and the relatively low push force, the acceleration of the pulling force of the suction cup is significantly greater than the working acceleration of the cylinder, indicating that detachment phenomena are unlikely to occur. Therefore, it is feasible to choose a vacuum suction cup with a diameter of 20 mm as the adhesion picking part.

3.5 Visual identification method based on YOLOv5 + HSV fusion algorithm

To solve the problem of recognition of the original YOLOv5 algorithm accuracy is not high, with the improved YOLOv5 + HSV fusion algorithm[33,34] The YOLOv5 is fused with the HSV color space. Through the characteristics of the HSV channel, the red mature tomatoes are extracted from the unripe green tomatoes and the background, which greatly reduces the false recognition rate and missed detection rate of mature tomatoes. Especially in the case of occlusion and light spots, the recognition effect is more obvious, and the recognition accuracy has been greatly improved. The HSV color space segmentation module is specifically designed to segment problems with occlusion and lighting, and HSV has a relatively small impact on lighting. The improved algorithm not only

Table 2 Vacuum suction cup parameters with different diameters

Number of cups folded	Nominal diameter (mm)	Effective diameter (mm)	Maximum stroke compression (mm)	Adhesion force (N)	Pulling force (N)
2.5	10	8	2	0.58	0.83
2.5	15	13	6	1.47	1.74
2.5	20	16	8	3.58	3.36
2.5	25	21	13	5.28	5.64

Table 3 Parameter values of negative pressure suction system

Tomato number	Transverse diameter of tomato (mm)	Longitudinal diameter of tomato (mm)	Mass (g)	Negative pressure before holding (kPa)	Negative pressure after holding (kPa)	Pulling force (N)
1	82.56	76.78	246.12	−2.8	−13.8	3.32
2	78.62	71.55	221.56	−2.6	−13.4	3.24
3	79.95	74.62	231.45	−2.7	−13.6	3.29
4	78.16	74.82	229.42	−2.6	−13.4	3.26
5	84.42	78.12	251.34	−2.8	−13.9	3.55
6	76.21	74.68	227.56	−2.6	−13.6	3.06
7	77.16	68.63	218.93	−2.6	−13.4	2.93
8	80.34	78.73	238.32	−2.6	−13.5	3.27
9	79.65	70.88	226.11	−2.6	−13.5	3.11
10	85.37	82.63	257.42	−2.9	−14.1	3.68
11	76.82	69.13	231.78	−2.6	−13.5	3.05
12	82.74	72.82	239.94	−2.8	−13.7	3.37
13	83.19	71.54	241.56	−2.8	−13.8	3.28
14	80.53	73.28	243.93	−2.7	−13.6	3.24
15	78.61	72.32	236.52	−2.6	−13.5	3.21
16	79.39	73.80	239.56	−2.7	−13.5	3.29
17	80.73	75.12	241.64	−2.7	−13.5	3.34
18	84.67	71.96	238.43	−2.8	−13.8	3.36
19	78.12	74.56	236.27	−2.6	−13.4	3.05
20	77.25	71.83	226.43	−2.6	−13.4	2.96

retains the original feature of fast recognition speed, but also improves the recognition accuracy of tomatoes.

3.6 Compound force analysis

Based on the SolidWorks model of the end-effector, take θ = 78° and when the claw holds the tomato, $\Delta\theta < 10°$. Using the experimental data, the average adhesion force of the 20 mm sucker is 3.58 N, which can be obtained by adding the formula, $2.07 < N < 6.22$. It can be concluded that when the adhesion mechanism acts on the tomato, the clamping force of the clamping mechanism on the tomato fruit can be reduced, and the tomato can be picked with a smaller clamping force and the damage of the tomato can be reduced.

To investigate the effect of end-effector adhesion on tomato fruit picking force, ADAMS 2020 software was used to simulate end-effector motion grabbing. The end-effector and tomato model were imported into the software in x–t format. The material properties[35–37] are detailed in Table 4. The sleeve was fixed on the earth and the corresponding rotational and translational pairs were set for each connecting rod and slider. The opening and closing of the gripper were realized by the

Table 4 Material properties of each component

Material property	Elastic modulus (MPa)	Poisson’s ratio	Stress intensity (MPa)	Density ($kg \cdot m^{-3}$)
Tomato	0.762	0.45	0.122	1.07×10^{-6}
Aluminum alloy	6.9×10^{4}	0.30	370	2.73×10^{-3}

torque of the lead screw and the process of adhesion force was simulated by applying contact force to the sucker to simplify.

The parameter settings of the end effector are shown in Fig. 10, as indicated by the simulation results, when the vacuum sucker is in the range of 0–1.8 s, due to the contact with the tomato, the adhesion force increases continuously, reaching a peak of 4 N. When the claw contacts the tomato, the tomato experiences an upward movement, at this time the tomato is out of the contact with the sucker, the adhesion force drops to 0. When the tomato falls, the adhesion force continues to rise. The adhesion force will fluctuate, and when the clamping is stable, the adhesion force is stable at about 3.8 N. When the suction cup adsorbs the tomato, the gripper begins to clamp the tomato and when the gripper contacts the tomato, there will be an impact, at this time the instant impact force is 15 N, and it rapidly decreases within 1 s. When the gripper is stabilized, the gripper force is stable at about 6 N. Consequently, when both the adhesion mechanism and the clamping mechanism act on the tomato simultaneously, the design effectively protects the fruit from damage while meeting the required specifications.

Ten tomatoes at the firm ripening stage were selected from the tomato planting base in Lianyungang City, China, with transverse diameters of 75–85 mm. The end-effector compound force test was performed to investigate the effect of vacuum sucker on the picking force of tomato fruit.

As shown in Fig. 11, the average adhesion force of the suction cup is measured at 3.50 N, and the average gripping force of the claw is 5.94 N. When both the adhesion force of the suction cup and the gripping force of the claw act on the surface of the tomato simultaneously, the damage threshold of the tomato skin is determined to be 9.8 N. When the pulling force decreases, the gripping force of tomato increases, indicating that the gripping force of the claw can be effectively reduced when the adhesion mechanism is engaged with the surface of the tomato. In other words, the tomato fruit can be picked with a small gripping force, proving that the telescopic adhesion picking part is both feasible and effective.

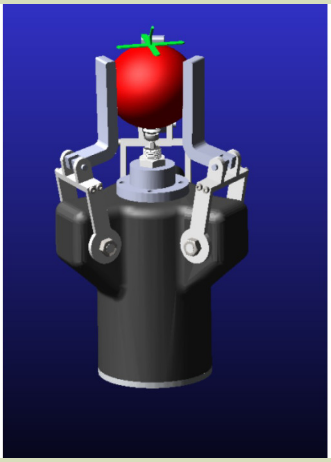


Fig. 10 End-effector parameter settings.

3.7 Test results and analysis

All prototype tests were performed under controlled environmental conditions in the Lianyungang Tomato Smart Demonstration Facility. The environmental parameters that may affect the results throughout the entire experiment are: temperature at 22 °C, relative humidity at 60% and light intensity at 1 kilolux (klx). Ten groups of tomato plants with different positions were picked in the environment of the greenhouse and the success rate of picking the end-effector of the tomato-picking robot was tested in all directions. According to the negative pressure holding test, the stable adhesion pressure is measured at −13.6 kPa. Comprehensive statistics on the successfully picked tomatoes were compiled, as given in Table 5. The success rate of end-effector picking is primarily divided into two components: the success rate of adhesion of target fruit by vacuum sucker and the success rate of picking fruit by end-effector.

A total of 113 tomatoes were picked from plants in different positions across 10 groups, with 99 successfully adhered, resulting in a successful adhesion rate of 88%. Additionally, 99 tomatoes were successfully picked, yielding a picking success rate of 88%. When the telescopic adhesion mechanism successfully absorbs the tomato fruit, the clamping mechanism can successfully complete the picking operation. Among the 12 failure cases, the most common problem was that the valve stem tilt angle was too large, resulting in the contact area of the suction cup exceeding the effective sealing area. In addition, environmental factors such as uneven fruit surfaces, dust and humidity can also lead to the failure of adhesion. In this study, tomatoes were categorized into three fruit classes according to diameter: < 70 mm, small; 70–90 mm, medium; and > 90 mm, large. To verify the relationship between the size and the success rate, a significance test was conducted as given in Table 6.

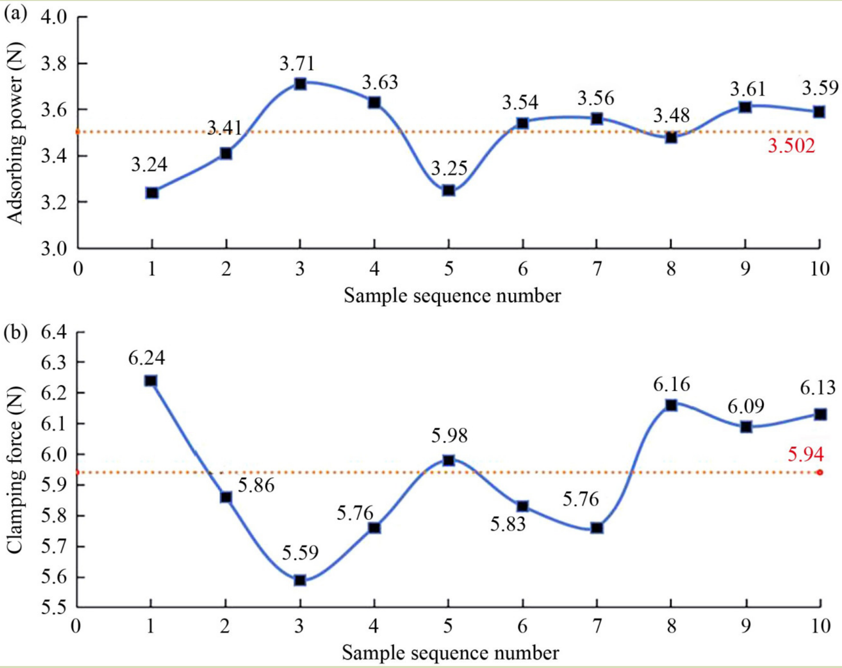


Fig. 11 The force situation during the picking process. (a) Absorption force, (b) clamping gripper.

Table 5 Success rate of end-effector harvesting

Serial number	Quantity	Adhesion success quantity	Harvest success
1	14	12	12
2	8	8	8
3	13	12	12
4	12	10	10
5	7	6	6
6	18	15	15
7	10	10	10
8	13	9	9
9	7	7	7
10	11	10	10

Table 6 Success rate of picking fruits of different sizes

Fruit type	Number of pick	Number of successe	Success rate (%)	Adjusted residual	*p*-value (vs. medium)
Large fruit	15	11	73.3	−2.1	0.0071**
Medium fruit	86	79	91.8	Reference	—
Small fruit	12	9	75.0	−1.4	0.041

Table 7 Performance comparison of end-effectors and other types of picking method end-effectors

Adhesion mode	Total time (s)	Success rate (%)	Damage rate (%)
Manual practices	12.1	95	0.6
Pure adhesion end-effector	6.5	84	1.4
Pure clamping end-effector	7.2	81	7.7
Rigid-flexible coupling end-effector	5.4	88	0.8

Adjusted residual, standardized residuals (|residual| > 2 indicates significant deviation from expected counts. The end-effector has a higher success rate of picking medium-sized fruits.

Small tomatoes exhibit reduced surface curvature and a smaller contact area between the suction cup and the fruit, leading to an uneven distribution of the adhesion force, which results in the suction cup easily detaching after adhesion. Conversely, as the diameter of larger fruits increases, their weight also correspondingly rises, causing the adhesion capacity of the vacuum suction cup to become insufficient, which results in the fruit falling after adhesion. Therefore, the end-effector is determined to be more effective for tomatoes with a diameter of 70–90 mm.

According to the performance analysis (Table 7) of pure adhesion end-effectors, pure clamping end-effectors and manual picking in the reference literature, the success rate of pure adhesion end-effectors is not high due to their easy adhesion to adjacent leaves. Pure clamping leads to an excessively high damage rate due to uneven clamping force, and it has a high requirement for stem strength. Compared with the manual picking method, the average time for the end-effector designed in this study to complete the picking operation is 5.4 s, and it has high picking efficiency and low damage rate, meeting the requirements of practical applications.

4 Conclusions

In response to the actual requirements for efficient and non-destructive picking of facility tomatoes, a three-claw end-effector of a facility tomato-picking robot equipped with a telescopic suction cup was comprehensively designed.

The physical and mechanical characteristics of tomato powder taro were analyzed, and the mechanical characteristics of tomato stem were tested. The results showed that the rotation angle of the end motor was 270° and the maximum breaking force of the stem was 8.36 N.

Through a detailed analysis of the suction and pulling force of tomatoes, it was determined that the suction force magnitude, suction cup diameter and system vacuum degree were all key factors affecting the operation of the adhesion and picking components. The precise calibration of the adhesion and picking component system was completed. It was determined that when the suction cup diameter was 20 mm and the vacuum degree reached 13.4%, the suction and pulling operation could be successfully accomplished.

By means of kinematic analysis of the end-effector, the size structure and kinematic parameters of the adhesion and picking component of the end-effector were successfully obtained. Through the combined force analysis of the adhesion mechanism and the clamping mechanism of the end-effector and verified by simulation, the feasibility and effectiveness of the telescopic adhesion and picking component were strongly confirmed.

The test results showed that under the conditions of a temperature of 22 °C, a relative humidity of 60%, a light intensity of 1 klx, and an adhesion air pressure of −13.6 kPa, the success rate of tomato picking using this end-effector could reach 88%, and the average duration of the overall picking was 5.4 s, which could effectively achieve the mechanized picking of facility tomatoes.

Acknowledgements

This work was financially supported by the 2023 Open Project of Key Laboratory of Modern Agricultural Equipment and Technology (Jiangsu University), Ministry of Education and High-tech Key Laboratory of Agricultural Equipment and Intelligence of Jiangsu Province of China (MAET202319 and MAET 202327) and the Key Agricultural Science and Technological Independent Innovation Fund of Jiangsu Province of China (CX(24)3032 and CX(21)1007).

Compliance with ethics guidelines

Qizhi Yang, Guangyi Qu, Xia Zhong, Xinyu Yang, Lei Liu, Xu Hu, and Min M. Addy declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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