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Structural Forms and Crop Adaptation Mechanisms of End-Effectors for Fruit and Vegetable Harvesting

Kangdi Feng

School of Mechanical Engineering, Dalian University of Technology, Dalian, 116000, Liaoning, China

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Abstract: With the rapid development of agricultural automation, the design of harvesting robot end-effectors has become increasingly important for improving harvesting efficiency and reducing fruit damage. This paper reviews the development of fruit and vegetable harvesting end-effectors and discusses how different end-effector structures are suited to different crop characteristics. Existing end-effectors can generally be divided into three types: mechanical gripping, vacuum adsorption, and flexible compliant. The paper focuses on analyzing the effects of drive modes, contact mechanisms, and structural parameters on harvesting performance. Existing studies show that rigid structures are efficient but can easily damage fruit surfaces; flexible structures exhibit excellent non-damaging performance yet still have limitations in load capacity and response speed; and vacuum adsorption is limited by the surface morphology of the fruit. Crop hardness, shape, and fruit stem attachment method largely influence the choice of end-effector design, and no single end-effector is suitable for all harvesting conditions. Future research is likely to focus on rigid-flexible coupled variable stiffness design, modular rapid reconfiguration, and the integration of sensing and actuation systems, in order to achieve efficient and low-damage harvesting in unstructured environments.

1. Introduction

Global population growth and the aging of rural labor forces have intensified labor shortages in agriculture. The labor cost of the harvesting process already accounts for 50%–70% of the total cost of fruit and vegetable production. As a result, agricultural robots have attracted increasing attention as a potential solution [1]. However, the overall success rate of existing harvesting robots is only about 66%, with a fruit damage rate of approximately 5%, which which remains insufficient for large-scale commercial use [2]. As the core component that directly interacts physically with crops, the performance of the end-effector plays an important role in harvesting efficiency and fruit protection [3].

The unstructured characteristics of orchard environments and the significant differences in crop traits make it difficult for a single end-effector to be universally applicable. Recent studies have gradually shifted from rigid mechanical grippers to flexible and hybrid end-effectors, while gradually integrating visual and force-sensing technologies to enhance adaptability [3]. For example, flexible and vacuum-adsorption end-effectors have shown good performance in reducing fruit damage in apple harvesting. Although relevant studies have made certain progress, end-effectors still face challenges such as poor universality, high cost, and insufficient robustness in complex environments. Therefore, designing end-effectors capable of adapting to unstructured environments and achieving efficient, non-destructive harvesting remains a core issue in current research.

This paper systematically reviews the structural classification, key technologies, and crop adaptation strategies of fruit and vegetable harvesting end-effectors, compares the advantages and disadvantages of different technical approaches, and analyzes development trends. It aims to provide theoretical foundations and technical references for the design and selection of end-effector systems in harvesting robots, and provide reference for future end-effector design in agricultural harvesting robots.

2. Key Technologies and Design of End-Effectors (EE)

2.1 Mechanical Gripping End-Effectors

Mechanical gripping end-effectors are among the most widely used actuators in fruit and vegetable harvesting robots. Their core principle lies in achieving stable grasping of fruits through direct contact and force application by mechanical fingers. This type of end-effector typically offers advantages such as simple structure, convenient control, and strong load-bearing capacity. It is particularly suitable for fruits with hard skins and regular shapes, such as spherical or near-spherical fruits like citrus and apples [4-5].

In terms of finger configuration, the three-finger structure is widely adopted due to its self-centering capability and good adaptability to irregular surfaces. Xiao et al. designed a three-finger gripping end-effector based on the action principles of manual citrus harvesting. The design achieves stable enveloping by having the inner sides of the fingers conform to the fruit surface, while integrating a blade to cut the fruit stem [4]. Field test data showed that, without a vision system, this end-effector achieved a 93.33% harvesting success rate for citrus fruits with an average longitudinal diameter of 50.24 mm. The average harvesting time per fruit was 4.05 s, and the fruit damage rate was only 1.11% [4]. Mechanical analysis indicated a safe gripping force range of 6–8 N, which remains below the reported biological yield threshold of 11.03 N for citrus fruits. This suggests that the proposed structure can achieve non-destructive grasping under the tested conditions [4].

To better accommodate fruits of varying sizes and shapes, Xu et al. proposed a mechanical gripper based on a three-finger and rotatable mechanism, in which two fingers can rotate around a fixed finger via synchronous gears to increase the contact area with the fruit [5]. The gripper uses a ball screw to drive the slider and controls the opening and closing of the fingers through a linkage mechanism [5]. Through kinematic analysis and structural parameter optimization, the end-effector demonstrated optimal force control and response stability at a driving speed of 5 mm/s [5]. Crop adaptation experiments showed that the gripper could successfully grasp spherical and cylindrical fruits and vegetables weighing 8–300 g with diameters ranging from 9–122 mm, covering a variety of crops such as cherries, loquats, tomatoes, yellow peaches, apples, and zucchini. It also maintained stable grasping under moving and shaking conditions [5].

In the aspect of force sensing and closed-loop control, some end-effectors integrate force sensors inside the fingers to achieve precise gripping force feedback. Xu arranged thin-film resistive force sensors on the rotatable fingers to detect force distribution in real time, thereby judging the contact state between the fingers and the fruit. This information is used to control the rotation direction of the fingers and ensure sufficient contact area [5]. The sensor measurement error was less than 5%, providing a hardware foundation for dynamically adjusting gripping force and avoiding local stress concentration [5].

The design of mechanical gripping end-effectors therefore relies on careful coordination between geometric parameters and control strategies, which must be adapted to the target crop's size distribution, mass, and epidermal mechanical properties. The three-finger configuration has shown strong versatility in harvesting spherical fruits, while the addition of rotatable fingers further improves adaptability to more irregular geometries.

2.2 Flexible Compliant End-Effectors

Flexible compliant end-effectors, also known as soft end-effectors, are fabricated from hyperelastic materials such as silicone and elastomers. They utilize the deformation of the material itself to adapt to the irregular geometric shapes of crops and achieve non-destructive grasping by distributing contact stress [6]. Compared with traditional rigid structures, flexible end-effectors offer superior compliance in unstructured environments and can grasp soft or delicate agricultural products without requiring complex control strategies [6]. Current research mainly focuses on pneumatic actuation and structures based on the Fin Ray Effect (FRE).

2.2.1 Pneumatically Actuated Flexible End-Effectors

Pneumatically actuated flexible end-effectors achieve bending deformation by regulating the internal chamber pressure. Zhou et al. designed a multi-chamber flexible finger. Before grasping, the finger is driven by negative pressure to bend backward, increasing the opening diameter at the tip and improving visual positioning tolerance. During grasping, positive pressure is applied to inflate the finger, causing it to bend inward from the base to complete the grasp [7]. Simulation results indicated that finger displacement increases with inflation pressure in both horizontal and vertical directions. However, when the inflation pressure exceeds 35 kPa, the horizontal displacement curve of the six-chamber finger tends to flatten, indicating that it has approached the horizontal extension limit [7].

In terms of crop adaptability, Zhou et al. measured the physical properties of tomatoes through experiments: transverse diameters ranged from 63.8–89.7 mm, mass from 131.7–364.8 g, the static friction coefficient between the tomato peel and Dragon Skin 30 silicone was 1.41, and the safe gripping force threshold was 11.13 N [7]. Based on these parameters, the study employed a genetic algorithm to optimize the number of chambers, number of fingers, and inflation pressure. The optimal solution obtained was a 3-finger, 4-chamber configuration with an optimal inflation pressure of 28.293 kPa [7]. In experimental validation, static grasping tests showed that the optimized end-effector could stably grasp tomatoes at inflation pressures below 28.293 kPa, with no damage observed after the fruits were stored for more than 9 days [7]. In dynamic grasping tests, the success rate reached 97% at an inflation pressure of 29 kPa, with no fruit damage [7].

Overall, pneumatically actuated flexible end-effectors achieve adaptive bending through regulation of chamber pressure. After optimization using finite element simulation and genetic algorithms, they are capable of achieving efficient and relatively non-destructive grasping with low damage rates. They are particularly suitable for harvesting soft fruits and vegetables such as tomatoes.

2.2.2 Flexible Structures Based on the Fin Ray Effect (FRE)

The Fin Ray Effect (FRE) structure is inspired by the passive deformation behavior of fish fins. When force is applied to one side of the structure, it bends toward the loading direction and gradually conforms to the object's surface, enabling compliant wrapping. The geometric parameters of FRE fingers significantly influence their compliance and mechanical response: the number of crossbeams and filling density determine bending continuity and stiffness; smaller beam thickness results in greater flexibility and lower local stress; and inclined beams produce larger deflection and better compliance compared to parallel beams [8].

Guo et al. designed a flexible three-finger end-effector based on the FRE principle. Each finger has a triangular structure composed of inclined fin plates on both sides and uniformly distributed internal ribs [9]. To fully utilize the layer jamming effect, the study designed five rib distribution schemes: parallel sparse, parallel thickened, parallel dense, inclined sparse, and inclined dense [9]. Finite element analysis results showed that fingers with sparsely distributed ribs exhibited the best extensibility, with total deformation of approximately 16 mm and 13.7 mm under a 5 N load. However, structural breakage occurred under a 10 N load. Fingers with densely distributed ribs did not break under a 10 N load but showed reduced deformation due to the layer jamming effect [9]. The parallel thickened rib scheme provided excellent extensibility while maintaining load-bearing capacity. In terms of crop adaptability, Guo et al.'s grasping load tests indicated that the end-effector could withstand pulling forces exceeding 16 N, which is more than 3.44 times its own weight. Enveloping rate tests showed a 23.4% enveloping rate for apples with a diameter of approximately 103 mm, and a 78.4% enveloping rate for small tomatoes with a diameter of approximately 29 mm [9]. Grasping experiments on fruits of different shapes and sizes, including citrus, apples, pears, small tomatoes, and strawberries, achieved a 100% effective grasping rate, with no damage to the fruit peel after release [9].

Chen et al. developed a soft gripper based on the FRE structure for apple harvesting. After optimization through finite element analysis, the front and rear beams of the fingers had a thickness of 3.5 mm, a width of 16 mm, and 9 crossbeams [10]. The force feedback system in this study achieved constant-pressure grasping using the servo motor's own torque feedback, eliminating the need for external force sensors and simplifying the end-effector structure [10]. Slip detection was realized by integrating an ultrasonic distance sensor to monitor the relative position between the fruit and the fingers in real time. When the sliding distance exceeded a preset threshold, the servo torque was dynamically adjusted to prevent damage [10]. In crop adaptability experiments, under the force feedback enabled condition, the soft finger damage rate was 0% across 10 apple samples. In the disabled state, the slight damage rate was 10% and the severe damage rate was 10% [10]. In comparative experiments, rigid fingers achieved a 100% harvesting success rate but a 16% damage rate. Without slip detection, the soft fingers achieved a 96% success rate with an 8% damage rate. With slip detection enabled, the soft fingers achieved an 80% success rate with a 0% damage rate [10].

Overall, FRE-based flexible end-effectors rely on passive structural deformation to achieve adaptive enveloping. They combine high load-bearing capacity with excellent non-destructive grasping performance across multiple crops. They can also effectively integrate force and slip sensing functions, minimizing fruit damage rates while ensuring high harvesting success rates.

2.3 Vacuum Adsorption End-Effectors

Vacuum adsorption end-effectors rely on negative pressure to form a sealed interface between the suction cup and the fruit surface, thereby generating adsorption force for grasping and detachment. Compared with mechanical gripping systems, vacuum-based end-effectors generally have simpler structures, typically consisting of suction cups, vacuum lines, pumps, and control valves. They feature non-contact or soft-contact characteristics, which can effectively reduce mechanical damage to the fruit surface, making them especially suitable for harvesting fruits and vegetables with soft or delicate skins [10]. However, traditional conical suction cups often suffer from poor sealing when dealing with non-spherical, high-curvature, or irregular surfaces, leading to adsorption failure or fruit damage. Therefore, structural optimization and adaptability analysis tailored to specific crop characteristics have become the core focus of research in this field [11]. The morphological features and physical properties of different crops impose differentiated requirements on the structural design of vacuum adsorption end-effectors. Through typical studies on strawberries, apples, and cucumbers, the adaptation patterns between crops and end-effector structures, as well as directions for structural innovation, can be clearly identified.

Cucumbers are cylindrical crops with large curvature, featuring uneven surfaces and irregular protrusions. Traditional conical suction cups achieved a 0% adsorption success rate on cucumbers [11]. Jo et al. proposed a soft suction cup based on an origami-inspired structure, optimizing it from both shape and surface dimensions [11]. The suction cup adopts a hyperbolic paraboloid geometry instead of traditional planar or spherical designs to maximize the effective adsorption radius, with an ideal effective radius of 12.51 mm [11]. The inner lip of the suction cup incorporates a micro-etched origami structure as a deformation guide, which restricts disordered deformation of the silicone material on uneven surfaces, enabling active conformation rather than random wrinkling, thereby improving airtightness [11]. Experimental validation showed that the shape-optimized suction cup alone achieved a measured effective radius of 6.21 mm, while the dual-optimized (shape + surface) suction cup reached 10.66 mm. Its torsional deformation resistance increased from 37.68 N·mm to 71.26 N·mm [11]. Finite element analysis further indicated that the suction cup with the origami structure exhibited 1.326–1.30 times greater deformation than the non-structured suction cup within 0.2–1.0 s, demonstrating stronger compliance to irregular surfaces [11]. Field trials across three different cucumber planting bases achieved a comprehensive harvesting success rate of 86.2%. Failure cases were primarily attributed to excessively thick or short fruit stems causing incomplete cutting, rather than adsorption failure, indirectly validating the effectiveness of the suction cup design [11].

Strawberries are soft berries with irregular surfaces and fragile tissues that are prone to necrosis. Kurpaska conducted a systematic study on the effects of suction cup geometric parameters and adsorption position on adsorption force and fruit damage [12]. The experiment used three silicone suction cups and performed adsorption tests on three regions of the fruit: the top, the middle, and the stem area. Suction cups No. 1 and No. 3, both with a cavity depth of 15 mm, achieved average adsorption forces of 2.38 N and 2.26 N respectively, belonging to the same statistical homogeneous group. In contrast, the flatter No. 2 suction cup with a 10 mm cavity depth had an average adsorption force of only 1.86 N, significantly lower than the former two [12]. This indicates that increasing the cavity depth of the suction cup helps enhance sealing performance, allowing the flexible material to better adapt to surface deformation of soft fruits. Suction cup No. 3, having the smallest end-face area, produced the highest average stress on the fruit at 0.0300 MPa. Suction cups No. 1 and No. 2, with similar end-face areas, produced stresses of 0.0092 MPa and 0.0074 MPa respectively [12]. Stress was highest when adsorbing at the middle region, but it was still only 20%–31% of the destructive stress of strawberry pulp [12]. Therefore, for soft small fruits such as strawberries, suction cups need sufficient cavity depth and material flexibility. The adsorption strategy should preferentially select regions with gentler curvature in the middle of the fruit to minimize tissue damage while ensuring adequate adsorption force.

Hua et al. developed a vacuum end-effector for fresh apple harvesting and compared the performance of two suction cup diameters: 33 mm and 43 mm [13]. The study found that the 33 mm suction cup achieved significantly higher adsorption success rates than the 43 mm suction cup across various inclination angles and fruit size grades. For small fruits at large inclination angles, the 43 mm suction cup achieved only a 40% success rate, while the 33 mm suction cup reached 80% [13]. This result indicates that the suction cup diameter must match the surface curvature of the fruit; an excessively large diameter tends to lose sealing due to edge lifting during curved surface contact [13]. Regarding adsorption position on the fruit surface, statistical analysis of the distance deviation between four theoretical points (image center, minimum circumscribed circle center, centroid, and equatorial circle center) and the actual adsorption point revealed that the equatorial circle center had the smallest average deviation and the lowest variance, making it the optimal theoretical adsorption point [13]. For detachment method, given the high stem strength of apples, integrating a rotary mechanism into the structure is key to achieving non-destructive detachment. The combined rotary-pulling motion achieved a harvesting success rate of 83.3%, significantly higher than the 60.0% of the pure pulling mode, while maintaining an 83.1% fruit stem integrity rate [13]. Vacuum pressure experiments further showed that −65 kPa is the critical value. Success rate increased significantly from 44.4% at −55 kPa to 82.2% at −65 kPa. Further increasing the pressure to −75 kPa only slightly improved the success rate to 83.3%, with no damage observed to the fruit pulp after 48 hours [13].

The design of vacuum-based end-effectors therefore needs to consider the coupling between suction cup geometry, surface microstructures, and detachment mechanisms, as well as the morphological and mechanical properties of the target crop.

3. Discussion

3.1 Limitations and Challenges of Current Technology Applications

At present, the application scope of fruit and vegetable harvesting end-effectors is still relatively limited. Most studies focus on dedicated designs targeting specific crops. Although high success rates can be achieved under specific conditions, most existing systems are still based on a single dominant approach—rigid gripping, vacuum adsorption, or flexible grasping—which limits their adaptability across different crop types [1]. For instance, rigid gripping end-effectors are well suited to hard fruits, but may easily cause damage when applied to softer crops. By contrast, flexible compliant end-effectors generally achieve better non-destructive performance, although their load-bearing capacity and actuation speed remain limited [7, 9]. In addition, many existing end-effectors still show limited robustness when operating in complex and unstructured environments. For example, vacuum-based systems are highly sensitive to surface conditions such as cleanliness, whereas soft materials may degrade or lose performance over prolonged operation [11, 14]. These limitations suggest that a single structural paradigm is unlikely to fully satisfy the requirements of multi-crop and high-efficiency agricultural operations.

To facilitate comparison of the technical characteristics and application boundaries of the three types of end-effectors, Table 1 and Table 2 summarize their performance across multiple dimensions, including crop adaptability and typical operational performance.

Table 1. Comparison of Adaptability and Performance Parameters of the Three Types of End-Effectors

Comparison Dimension	Mechanical Gripping Type	Vacuum Adsorption Type	Flexible Compliant Type
Suitable Crops	Hard spherical fruits such as apples and citrus	Apples, pears (smooth surfaces); cucumbers (requires hyperbolic paraboloid suction cups); strawberries (small suction cups with low pressure)	Soft and irregular fruits such as tomatoes, strawberries, and clustered fruits
Unsuitable Crops	Soft fruits such as strawberries and tomatoes (damage threshold 2–4 N)	Kiwifruit, pineapples, and other hairy or rough-surfaced fruits	Heavy fruits such as watermelons and pumpkins
Typical Performance	Success rate 80–95% [4][5]; Damage rate 1.1–16% [4][5]; Cycle time 1.8–6 s/fruit [4][5]	Success rate 80–96% [11][13]; Damage rate <5% [11][13]; Cycle time 2–4 s/fruit [13]	Success rate 86–100% [7][9];Damage rate 0–8% [7][10];Cycle time 6–10 s/fruit [7]

Table 2. Comparison of Advantages and Disadvantages of the Three Types of End-Effectors

Technical Route	Advantages	Disadvantages
Mechanical Gripping	Strong load capacity, high efficiency, simple control	Prone to causing mechanical damage, poor adaptability
Flexible Compliant	Strong shape adaptability, best non-destructive performance, high fault tolerance	Weak load capacity, slow response speed, prone to aging
Vacuum Adsorption	Non-contact/soft contact, simple structure, good non-destructive performance	Highly dependent on fruit surface morphology, high energy consumption, difficult to seal on non-spherical fruits

3.2 Variable Stiffness Structure Design

To overcome the limitations of single materials, rigid-flexible coupling and variable stiffness design have become the core pathway to resolve the contradiction between non-destructive performance and load-bearing capacity. In the field of variable stiffness technology, Ye et al. reviewed passive variable stiffness mechanisms such as granular jamming and layer jamming. Granular jamming increases structural stiffness by applying vacuum pressure to a flexible cavity filled with loose particles, which causes particle compaction and interlocking [6]. End-effectors based on this principle can achieve significant stiffness enhancement (reported up to 235%) and are capable of maintaining a grasping state without continuous energy input [6]. Gao et al. [8] further pointed out that by optimizing the beam inclination angle and filling density of FRE fingers, the layer jamming effect can be triggered during deformation, dynamically increasing contact force and stiffness as deformation grows [8]. This combination of passive adaptability and active stiffness modulation provides a useful strategy for improving grasp stability in complex environments.

3.3 Integrated Fusion of Perception and Actuation

Most current end-effectors still function primarily as passive actuators with limited environmental sensing capability. Future developments are expected to focus on tighter integration between sensing and actuation. End-effectors should incorporate force and tactile sensors. Chen et al. exploited built-in servo torque feedback and estimated finger gripping force through a statics-based model, enabling constant-force control without external sensors [10]. Hua et al. integrated a vacuum pressure sensor into the vacuum adsorption end-effector to determine successful adsorption by detecting negative pressure changes inside the suction cup, thereby triggering subsequent rotary separation actions [14]. In terms of multi-modal perception, Ye et al. noted that embedding strain sensors, temperature sensors, humidity sensors, and even chemical sensors into soft end-effectors can simultaneously obtain information such as contact force, surface texture, ripeness, and pesticide residues of the fruit [6].

4. Conclusion

This study reviews three major categories of fruit and vegetable harvesting end-effectors, namely mechanical gripping, vacuum adsorption, and flexible compliant systems, and discusses their underlying design principles, actuation mechanisms, and crop adaptation strategies. It further examines their performance across representative crops such as strawberries, apples, cucumbers, tomatoes, and citrus, and compares the respective strengths and limitations of different technical approaches. On this basis, potential future research directions are outlined, including structural optimization of variable-stiffness mechanisms and the tighter integration of multi-modal perception (e.g., force and tactile sensing) with actuation systems. Rather than claiming to fully address existing research gaps, this review aims to provide a structured synthesis of current crop-adaptive strategies in harvesting end-effectors, thereby offering a reference framework that may assist researchers in understanding the technological landscape and identifying promising directions for further investigation.

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