

Article

Design and Evaluation of a Novel Actuated End Effector for Selective Broccoli Harvesting in Dense Planting Conditions

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Abstract

The commercialization of selective broccoli harvesters, a critical response to agricultural labor shortages, is hampered by end effectors with large operational envelopes and poor adaptability to complex field conditions. To address these limitations, this study developed and evaluated a novel end-effector with an integrated transverse cutting mechanism and a foldable grasping cavity. Unlike conventional fixed cylindrical cavities, our design utilizes actuated grasping arms and a mechanical linkage system to significantly reduce the operational footprint and enhance maneuverability. Key design parameters were optimized based on broccoli morphological data and experimental measurements of the maximum stem cutting force. Furthermore, dynamic simulations were employed to validate the operational trajectory and ensure interference-free motion. Field tests demonstrated an operational success rate of 93.33% and a cutting success rate of 92.86%. The end effector successfully operated in dense planting environments, effectively avoiding interference with adjacent broccoli heads. This research provides a robust and promising solution that advances the automation of broccoli harvesting, paving the way for the commercial adoption of robotic harvesting technologies.

Keywords: broccoli harvesting; end effector; agricultural robotics; selective harvesting; grasp-and-cut



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1. Introduction

Broccoli (*Brassica oleracea* var. *italica*), a high-economic-value cruciferous vegetable, has seen continuous expansion in global cultivation. According to FAO (Food and Agriculture Organization of the United Nations) statistics, China's broccoli planting area reached 490,000 hectares with a yield exceeding 9.71 million tons in 2023 [1]. However, its harvesting remains highly reliant on manual labor, facing dual pressures of labor shortages and rising costs [2]. With the exacerbation of population aging, labor supply issues have become increasingly severe. Developing selective harvesting machinery for broccoli has thus become an urgent need for industrial sustainability.

While mechanized harvesting research for vegetables has advanced, such as for white radish [3] and chili peppers [4], and cabbage harvesting technologies are relatively mature [5], most existing equipment employs one-time non-selective harvesting modes [6,7], which are incompatible with broccoli's staggered maturity, requiring batch-wise selective harvesting. Selective harvesters typically integrate three core modules—visual detection,

positioning systems, and end effectors—to enable picking based on crop maturity and size. Although selective end effectors have been widely studied [8–10], such as tomatoes [11], sweet peppers [12], grapes [13,14], button mushrooms [15], and apples [16], direct application to broccoli is challenging due to its thick stem (requiring high cutting force) and bulky head (posing unique gripping challenges).

Roboveg designed a multi-DOF manipulator-based end effector using cavity sleeving and single-blade transverse cutting, but its large cavity structure is prone to field interference [17]. Sami AGTech industry proposed a flexible gripping system combined with high-pressure waterjet cutting, which is effective but bulky, costly, and water-intensive—unsuitable for China’s agricultural context [18]. Japan’s Mycom prototype removes leaves before stem clamping, but it only adapts to single-row planting, conflicting with China’s mainstream double/multi-row agronomy [19]. Xu et al. [20] developed an under-actuated dual-blade cutter with self-adaptive gripping rods, which achieved an 84% picking success rate in laboratory tests. Their experiments used leafless broccoli heads in simplified conditions without field validation. Its picking reliability needs to be further verified in field tests. Zhao et al. [21] improved cutting success using Delta robot-based dual-ring blades but produced uneven cut surfaces. Kang et al. [22] achieved 90% success for heads <15 cm in diameter with a humanoid pinching cutter, but success rates dropped to 63.63% for larger heads (>15 cm) or thick stems (>50 mm). Song et al. [23] proposed a centering cutter with five-blade opposing cuts (0.6 s/cycle), but its extreme positioning precision requirement and post-harvest detachment issues limit field applicability.

Existing fruit/vegetable harvesting end effectors are ill-suited for broccoli, and current broccoli-specific designs have significant limitations: large cavity cutters prone to interference; under-actuated grippers with unreliable grasping; waterjet systems with high resource consumption; humanoid pinchers with poor size adaptability; and centering cutters with strict positioning demands. This study presents an innovative multi-cylinder coordinated end effector based on a Cartesian manipulator. Building on cavity and transverse cutting principles, key improvements include the following:

- Dual-blade coordinated cutting to enhance efficiency/reliability while reducing single-side profile via bilateral stroke distribution, minimizing field interference.
- Integrated grasp-cut structure with multi-rod dynamic wrapping cavities (replacing rigid cylinders) to further reduce operational envelope.
- Optimized cylinder actuation timing to minimize maximum profile and improve success rates via trajectory optimization.

Regarding manipulator architectures, while Cartesian coordinate manipulators have been tested for selective harvesting, their adoption is constrained by challenges in complex field environments. Notably, broccoli heads grow upright, with larger heads being more exposed, leading to relatively regular spatial poses. Cartesian coordinate manipulators, with their simple structure, deterministic trajectories, low cost, and easy maintenance, show potential for broccoli harvesting compared with high-cost, complex multi-DOF manipulators. Cartesian architectures are theoretically suitable for broccoli’s growth characteristics.

Field tests demonstrated stable performance of the developed mechanism, marking a critical step toward industrializing selective broccoli harvesting technology.

2. Structure and Working Principle of End Effector

2.1. Structure of End Effector

The main structure of the end effector adopts a front-back and left-right symmetrical design, as shown in Figure 1. The mechanical principle of the end effector is illustrated in Figure 1a, with the overall structure of the end effector presented in Figure 1b. It is primarily composed of air cylinders, push rods, connecting rods, cutting blades, and a

sheet metal frame for installation. The end effector is driven by seven air cylinders, which are divided into two functional groups:

- **Posture Control Group** (three air cylinders): This group includes two position adjustment cylinders (labeled as 1 in Figure 1) and one push rod cylinder (labeled as 1 in Figure 1). These three cylinders work in coordination to regulate the spatial posture of the blades (loading action). Each posture control cylinder can be independently controlled and maintain its state.
- **Cutting Execution Group** (four air cylinders): This group comprises four blade cylinders of the same model (labeled as 1 in Figure 1), which directly provide driving force for the cutting blades. Every two-blade cylinder jointly drives a rectangular cutting blade to achieve synchronous extension (cutting) or retraction (reset) of the blades.

The piston rod of the push rod cylinder (labeled as 1 in Figure 1) is connected to the push rod (labeled as 1 in Figure 1) through a hinge. The push rod (labeled as 1 in Figure 1) is hinged to the connecting rod (labeled as 1 in Figure 1), which is in turn hinged to the frame and can rotate around the hinge point. The telescopic movement of the push rod cylinder (labeled as 1 in Figure 1) is converted into rotational motion of the connecting rod (labeled as 1 in Figure 1) via the push rod (labeled as 1 in Figure 1).

The mounting plane of the blade cylinder (labeled as 1 in Figure 1) is hinged to the connecting rod (labeled as 1 in Figure 1), allowing it to rotate around this point. The front end of the piston rod of the position adjustment cylinder (labeled as 1 in Figure 1) is hinged to the mounting plane of the blade cylinder (labeled as 1 in Figure 1), while the tail end of its cylinder body is hinged to the connecting rod (labeled as 1 in Figure 1).

The telescopic movement of the position adjustment cylinder (labeled as 1 in Figure 1) drives the mounting plane of the blade cylinder (labeled as 1 in Figure 1) to rotate around its hinge point with the connecting rod (labeled as 1 in Figure 1), achieving two key functions:

- Adjusting the cutting blade to the required transverse cutting posture.
- Changing the overall width of the end effector to expand or contract its clamping area.

The four-blade cylinders (labeled as 1 in Figure 1) extend simultaneously to drive their connected blades for transverse cutting and retract to withdraw the blades.

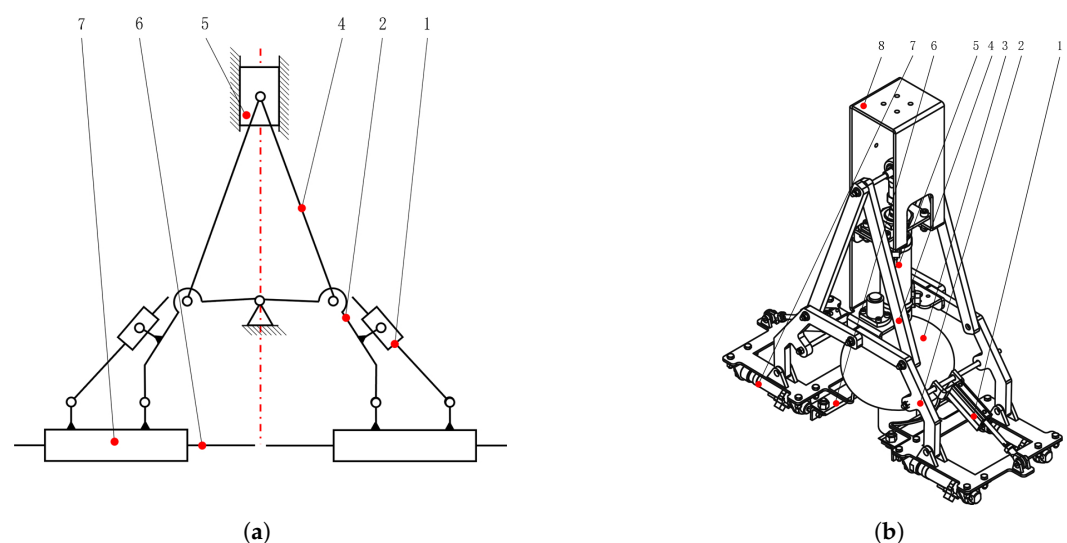


Figure 1. Schematic diagram of mechanical structure: (a) Schematic diagram of mechanical principle; (b) Overview diagram of end effector structure: 1. Position adjustment cylinder; 2. Connecting rod; 3. Broccoli; 4. Push rod; 5. Push rod cylinder; 6. Cutting blade; 7. Blade cylinder; 8. Frame. (The numerical labeling in (b) is also valid for (a)).

2.2. Working Principle of End Effector

Prior to harvesting, the push rod cylinder (labeled as 1 in Figure 1) extends, driving the connecting rod (labeled as 1 in Figure 1) to rotate via the push rod (labeled as 1 in Figure 1). This action causes the blade cylinders (labeled as 1 in Figure 1) and cutting blades (labeled as 1 in Figure 1) to expand to the position shown in Figure 2a, in which the red arrows indicate the actions to be taken in the next step (the same labeling convention applies to the other three figures, where red arrows consistently denote subsequent operations). After the linear module completes positioning, the central axis of the end effector aligns with the central axis of the broccoli head, assuming the configuration depicted in Figure 2a.

Subsequently, the push rod cylinder (labeled as 1 in Figure 1) retracts, leading to the state shown in Figure 2b. Following this, all position adjustment cylinders (labeled as 1 in Figure 1) extend, resulting in the configuration presented in Figure 2c. At this stage, the cutting blades (labeled as 1 in Figure 1) on both sides are horizontally aligned, and the broccoli head is positioned within the “cavity” formed by the mechanical structure.

Finally, all blade cylinders (labeled as 1 in Figure 1) extend simultaneously to execute the cutting of the broccoli stem, as illustrated in Figure 2d. Upon completion of the cutting process, the end effector reverts to the state shown in Figure 2a by retracting each cylinder in reverse sequence, thereby releasing the harvested broccoli head.

To summarize, the end-effector performs three sets of cylinder actions from the start of grasping to the completion of cutting. By controlling the timing sequence of two position adjustment cylinders, different operation trajectories can be generated through the combination of action timings.

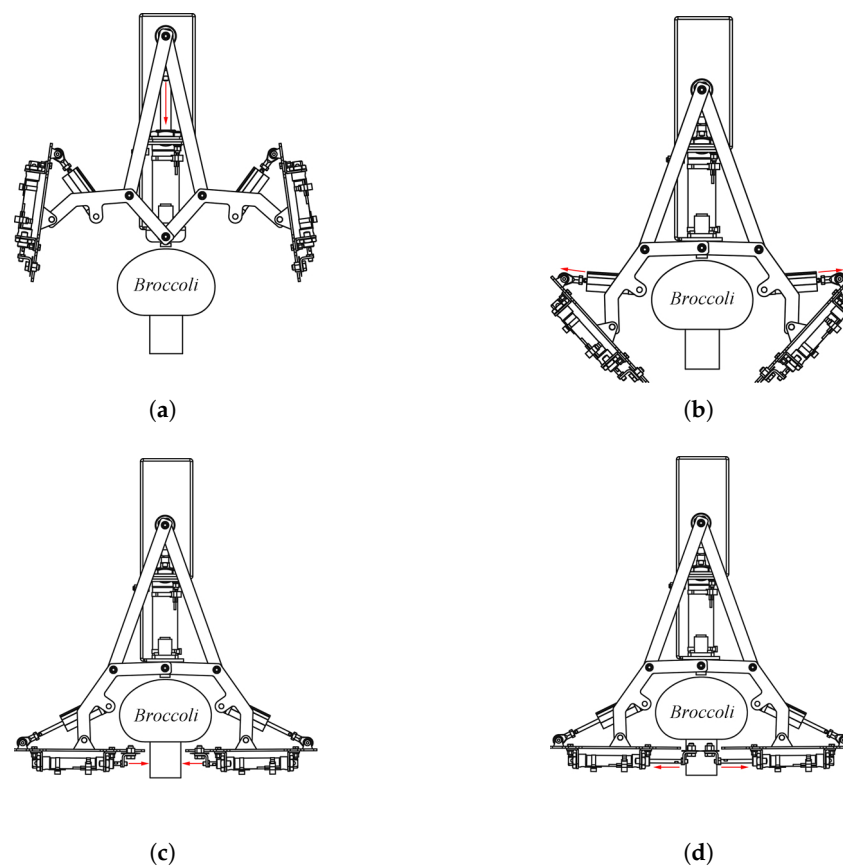


Figure 2. Action sequence diagram of end effector: (a) Immediately before the push rod cylinder retraction; (b) Immediately before two-position adjustment cylinder extension; (c) Immediately before four-blade cylinder extension; (d) Upon completion of four-blade cylinder extension.

2.3. The Reason for Selecting This Kind of Structure

The end effector employs a driving scheme with seven independently controlled cylinders. While this design increases the complexity of the system's gas circuit and manufacturing costs, it serves as a critical technical guarantee for realizing its core functionalities, including the reducibility of the outer contour trajectory, high stability during the cutting process, and adjustability of the grasping cavity. The dynamic adjustment function of the grasping cavity is achieved through independently controlling the push rod cylinder (labeled as 1 in Figure 1). The reducible characteristic of the end-effector's outer contour trajectory is enabled by two independently controlled position adjustment cylinders (labeled as 1 in Figure 1). Moreover, these two cylinders, together with the mounting plane of the blade cylinders (labeled as 1 in Figure 1), form a triangular stable structure, which is conducive to enhancing the overall rigidity and stability of the system during cutting.

In particular, the blade drive adopts a layout of coordinated driving by double cylinders on one side (with a total of four cylinders on both sides working in coordination). Compared with the alternative scheme of a single cylinder on one side (arranged in the center), this design offers multiple advantages. Firstly, the double-cylinder configuration on one side provides necessary redundancy for the cutting force. Secondly, the use of cylinders with smaller cylinder diameters can meet the driving force requirements, effectively reducing the vertical dimension of the end effector. Thirdly, under the premise of using a 160 mm long blade to ensure a wide cutting surface, the double cylinders provide direct driving at both ends along the length of the blade, offering reliable support for the lateral linear cutting trajectory of the blade and eliminating the need for additional guide rails. Finally, the double-cylinder drive on one side creates an unobstructed space in the middle of the long blade along the movement direction of the piston rod, effectively avoiding structural interference between the blade and the broccoli stem when the blade penetrates into the stem.

In contrast, the scheme of a single cylinder on one side (centrally arranged) has obvious drawbacks: it lacks driving redundancy; requires cylinders with larger cylinder diameters; must rely on additional guide rails to ensure the stability of the blade trajectory; and to avoid interference between the piston rod and the stem after the blade cuts into the stem, the blade installation width (l_2 in Equation (3)) needs to be significantly increased to 30 mm~40 mm, whereas the double-cylinder scheme on one side only requires an installation width of approximately 15 mm to effectively avoid this problem.

In summary, although the multi-cylinder driving scheme may increase costs, it has irreplaceable value in significantly improving cutting stability, minimizing the operating width of the outer contour, and ensuring high reliability of the system operation. It is the core design choice for this end effector to achieve efficient and reliable operations.

3. Mechanical Analysis of Broccoli Stems and Structural Optimization of End-Effector

The design of the end effector is grounded in the agronomic parameters of broccoli cultivation, as summarized in Table 1. These parameters encompass critical factors such as plant spacing, row spacing, maximum diameter of broccoli heads, and stem physical properties, which serve as the foundational guidelines for optimizing the structural dimensions of the end effector and its operational performance.

Table 1. Parameters of broccoli cultivation environment.

Parameters	Variable Symbol	Unit	Range of Values
Cultivar	—	—	Youxiu
Plant spacing	S_{plant}	mm	450~500
Row spacing	S_{row}	mm	450~650
Crown width	W_c	mm	600~760
Head diameter	D	mm	130~160
Stem diameter	d	mm	40~60
Head height	h_4	mm	90~130

3.1. Maximum Cutting Force Experiment

3.1.1. Introduction to the Maximum Cutting Force Test Rig

For the purpose of testing the maximum cutting force of broccoli stems, a high-precision cutting test device was independently developed in this study, as shown in Figure 3. The rig integrates dual-sensor data acquisition functionality. Through a combination of a servo motor (labeled as 1 in Figure 3) and a synchronous belt linear module (labeled as 4 in Figure 3), precise speed regulation of the blade within the range of 0 mm/s~2000 mm/s is achieved. A specially designed carbon steel blade (with a wedge angle of 20°) is installed at the front end of the guide rail. The sliding cutting angle parameters can be adjusted by changing the installation position of the blade, and the rig also supports the replacement of blades with different shapes. The definitions of the two blades' wedge angles and sliding cutting angle are shown in Figure 4a–c.

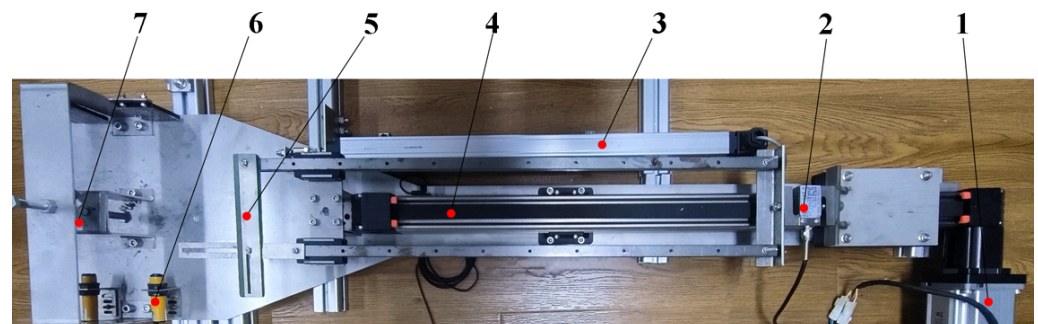


Figure 3. Physical diagram of the maximum cutting force test rig: 1. Servo motor; 2. Force measurement sensor; 3. Displacement sensor; 4. Linear motion module; 5. Cutting blade; 6. Photoelectric switch for velocity measurement sensor; 7. Broccoli stem clamping station.

Additionally, the rig is equipped with a multi-dimensional sensing system: a force sensor (labeled as 2 in Figure 3) with a measuring range of 0 N~200 N is used to monitor the reaction force along the movement direction of the slider in real time; a displacement sensor (labeled as 3 in Figure 3) is connected to the blade through a floating joint to record the cutting displacement; and a photoelectric speed-measuring sensor (labeled as 6 in Figure 3) is employed for speed verification. Data from each sensor are synchronously collected by a host computer, and the original electrical signals are stored in '.csv' format.

During the test, each of the broccoli stem samples is fixed in the broccoli stem clamping station (labeled as 7 in Figure 3) to ensure that the distance from the cutting surface to the bottom of the sample stem is constantly 10 mm. In the operation process, the servo motor drives the blade to perform linear cutting according to preset parameters, and the sensors collect force-displacement data synchronously. With its modular design and precise control, this rig provides a reliable experimental platform for the study of the cutting mechanical properties of broccoli.

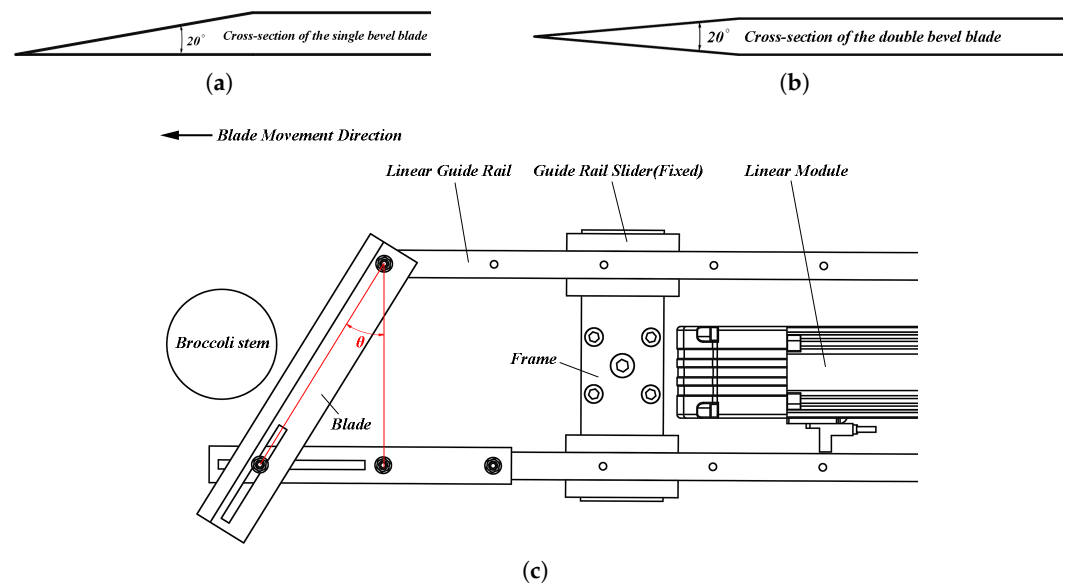


Figure 4. Schematic diagrams of blade with a wedge angle of 20° and sliding cutting angle (θ): (a) Cross-section of the single-bevel blade with a wedge angle of 20°; (b) Cross-section of the double-bevel blade with a wedge angle of 20°; (c) Schematic diagram of the sliding cutting angle (θ).

3.1.2. Results and Analysis of the Maximum Cutting Force Experiment

Samples were commercially procured from local markets, with 10 cm~15 cm intact stems (leafless). They were transported under frozen preservation with crushed ice and thawed at room temperature for 2 h prior to testing, maintaining a moisture content to ensure biomechanical validity.

This study systematically investigated the cutting mechanical properties of broccoli stems through a full-factorial experimental design. Based on the experimental factor level table (Table 2), 54 full-factorial test groups were constructed. Analysis of variance (ANOVA) results (Table 3, based on Table 4) showed that blade type ($p < 0.001$), blade thickness ($p < 0.001$), and sliding cutting angle ($p = 0.002$) had significant effects on maximum cutting force, while cutting speed ($p = 0.647$) did not reach statistical significance. Among them, blade type and thickness exhibited the most prominent main effects, requiring priority in design parameter optimization. The sliding cutting angle had a relatively secondary influence, allowing performance matching through local adjustments. Two-factor interaction analysis revealed no significant second-order factor interactions ($p > 0.05$).

Analysis of the main effect on maximum cutting force (Figure 5) reveals the following influences of individual factors. With respect to cutting speed (shown in Figure 5a), a non-linear relationship with the maximum cutting force is observed within the range of 0~1000 mm/s, exhibiting distinct variation trends. For blade type (shown in Figure 5b), the double-bevel blade type results in a lower maximum cutting force compared with the single-bevel blade type. Regarding blade thickness (shown in Figure 5c), within the range of 1~3 mm, the maximum cutting force increases with increasing thickness, with the 1 mm thickness yielding the smallest maximum cutting force, thus representing an optimal parameter choice for design optimization. As for the sliding cutting angle (shown in Figure 5d), a negative correlation with the maximum cutting force is evident in the range of 0~40°—specifically, the maximum cutting force decreases as the sliding cutting angle increases. Combining trend analysis from the main effect diagram of maximum cutting force (Figure 5), a preliminary optimization combination was proposed as a blade thickness of 1 mm, a double-bevel blade type, and a sliding cutting angle of 0°.

Table 2. Experimental factor level table for multi-factor mixed-level test for maximum cutting force.

Cutting Speed (m/s)	Blade Type	Blade Thickness (mm)	Angle of Sliding Cutting (°)
0.1	Single-bevel blade with wedge angle	1.0	0
0.5	Double-bevel blade with wedge angle	2.0	20
1.0		3.0	40

Table 3. ANOVA results for multi-factor mixed-level test for maximum cutting force.

Coded Factor	F-Value	p-Value
Model	4.760	0.000
A	0.420	0.662
B	19.610	0.000 *
C	33.440	0.000 *
D	6.710	0.004 *
AB	0.030	0.968
AC	0.970	0.438
AD	1.920	0.135
BC	1.280	0.293
BD	1.160	0.329
CD	0.430	0.787

Notes: ‘*’ denotes significance at the $p < 0.01$ level; ‘A’ represents the cutting speed factor (unit: m/s); ‘B’ represents the blade type factor; ‘C’ represents the blade thickness (unit: mm); ‘D’ represents the sliding cutting angle factor (unit: °).

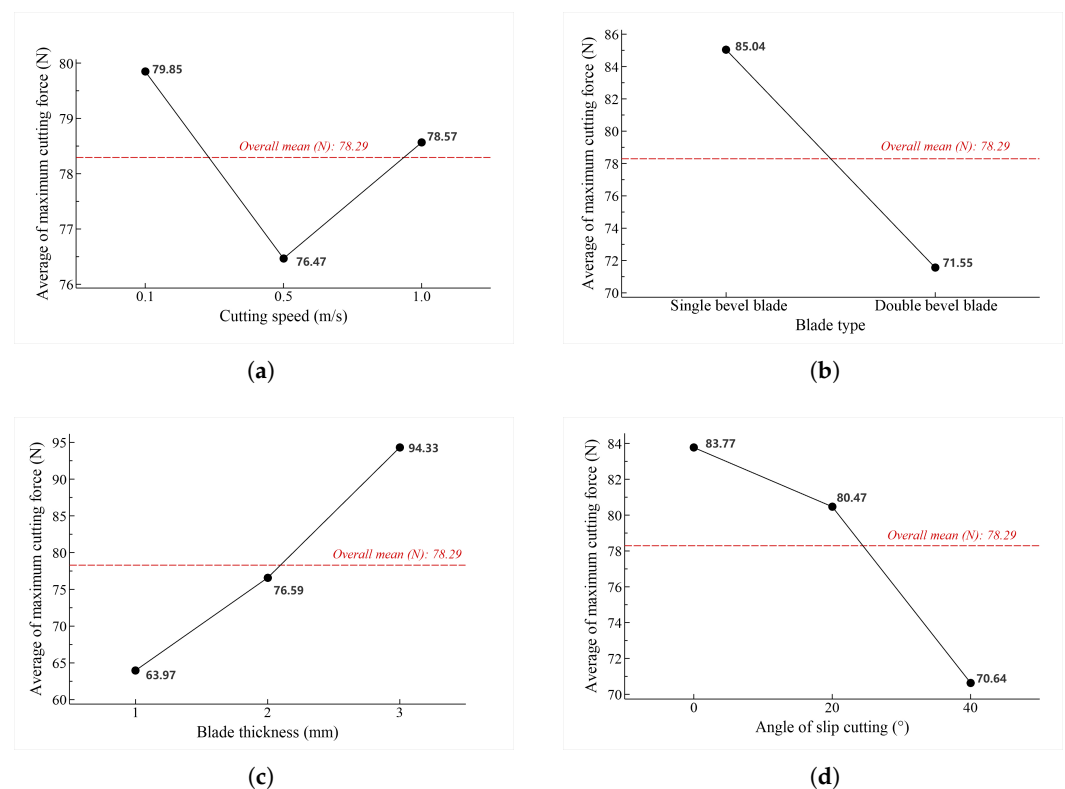


Figure 5. Diagram of main effects on maximum cutting force: (a) Main effect of cutting speed on maximum cutting force; (b) Main effect of blade type on maximum cutting force; (c) Main effect of blade thickness on maximum cutting force; (d) Main effect of angle of sliding cutting on maximum cutting force.

Table 4. Results of 54 full factorial test groups.

Test Code	Cutting Speed (m/s)	Blade Type	Blade Thickness (mm)	Angle of Sliding Cutting (°)	Maximum Cutting Force (N)
1	0.1	Single-bevel blade	1	20	72.78
2	1.0	Double-bevel blade	2	40	72.93
3	0.5	Double-bevel blade	1	40	52.47
4	0.1	Single-bevel blade	2	0	115.31
5	0.1	Single-bevel blade	3	20	82.27
6	0.5	Double-bevel blade	1	20	51.91
7	0.5	Double-bevel blade	3	40	81.21
8	0.5	Single-bevel blade	2	20	78.22
9	0.1	Single-bevel blade	1	0	83.72
10	0.5	Single-bevel blade	3	40	75.35
11	0.5	Single-bevel blade	2	40	70.36
12	0.5	Single-bevel blade	1	0	70.70
13	0.5	Single-bevel blade	3	0	86.97
14	1.0	Double-bevel blade	3	20	103.65
15	0.5	Single-bevel blade	2	0	82.75
16	0.1	Double-bevel blade	1	0	67.15
17	0.1	Double-bevel blade	2	40	59.27
18	1.0	Double-bevel blade	3	0	82.80
19	1.0	Single-bevel blade	3	40	107.38
20	0.1	Single-bevel blade	1	40	60.41
21	1.0	Single-bevel blade	2	20	95.35
22	1.0	Single-bevel blade	3	0	111.51
23	0.1	Double-bevel blade	2	20	83.79
24	0.1	Double-bevel blade	1	20	51.32
25	0.5	Double-bevel blade	2	40	61.70
26	0.5	Single-bevel blade	3	20	112.87
27	0.1	Single-bevel blade	3	0	123.02
28	0.1	Double-bevel blade	3	40	94.42
29	1.0	Double-bevel blade	2	0	74.22
30	1.0	Double-bevel blade	3	40	80.24
31	1.0	Double-bevel blade	1	0	46.41
32	1.0	Single-bevel blade	2	0	98.92
33	0.5	Double-bevel blade	2	0	69.37
34	0.5	Double-bevel blade	3	0	95.04
35	1.0	Single-bevel blade	2	40	58.25
36	1.0	Double-bevel blade	2	20	72.22
37	0.1	Single-bevel blade	3	40	87.94
38	0.1	Double-bevel blade	3	20	80.39
39	0.1	Double-bevel blade	3	0	101.83
40	1.0	Double-bevel blade	1	40	45.66
41	1.0	Double-bevel blade	1	20	72.37
42	1.0	Single-bevel blade	1	40	60.40
43	0.5	Double-bevel blade	2	20	58.83
44	1.0	Single-bevel blade	1	0	70.70
45	0.1	Double-bevel blade	1	40	46.60
46	0.1	Single-bevel blade	2	20	84.85
47	0.5	Single-bevel blade	1	20	87.98
48	1.0	Single-bevel blade	1	20	68.66
49	0.5	Double-bevel blade	3	20	98.53
50	0.1	Single-bevel blade	2	40	73.43
51	1.0	Single-bevel blade	3	20	92.52
52	0.5	Single-bevel blade	1	40	83.42
53	0.5	Double-bevel blade	1	0	58.74
54	0.1	Double-bevel blade	2	0	68.78

To further validate key parameters and provide a mechanical basis for structural design, ten parallel experimental groups on cutting positions were conducted under the

conditions of 1 mm blade thickness, double-bevel blade of blade type, and 0° sliding cutting angle. During the experimental procedure, the stems of each broccoli plant were sectioned into 190 three samples according to the zoning criteria depicted in Figure 6a,b and Table 5, corresponding to the Z_1 , Z_2 , and Z_3 zones, respectively. Subsequently, a maximum cutting force test was performed on these samples, and the experimental results are presented in Table 6.

The “ Z_1 ” zone extended from 0 mm to 30 mm from the bottom of the lowermost floret stem, the “ Z_2 ” zone covered the range of 31 mm to 60 mm, and the “ Z_3 ” zone corresponded to the depth of 61 mm to 90 mm. The detailed delineation criteria for each zone are illustrated in Table 5.

ANOVA confirms that cutting position has a highly significant statistical effect on maximum cutting force ($p < 0.001$). As shown in Table 6, ten groups of parallel experiments on cutting positions show that under the specific conditions of 1 mm blade thickness, double-bevel blade of blade type, and 0° sliding cutting angle, cutting experiments on broccoli stems yielded maximum force values ranging from 30 N to 130 N. Spatial analysis of individual plants revealed a non-linear increase in maximum cutting force with distance from the bottom of the head (The coordinate origin for stem zoning). However, maximum cutting forces are below 100 N within Zones Z_1 and Z_2 . This spatial force distribution directly informs the design of the end-effector, as the agronomically required 30 mm~40 mm stem retention aligns with Zone Z_2 , where forces remain safely below the 100 N threshold.

The critical finding—that cutting forces are constrained within 100 N for positions 0 mm~60 mm below the bottom of the flower head—establishes a foundational design parameter: end-effectors must be engineered to sustain loads of at least 100 N within this interval. This quantitative guideline ensures both efficient harvesting and mechanical durability in robotic systems.

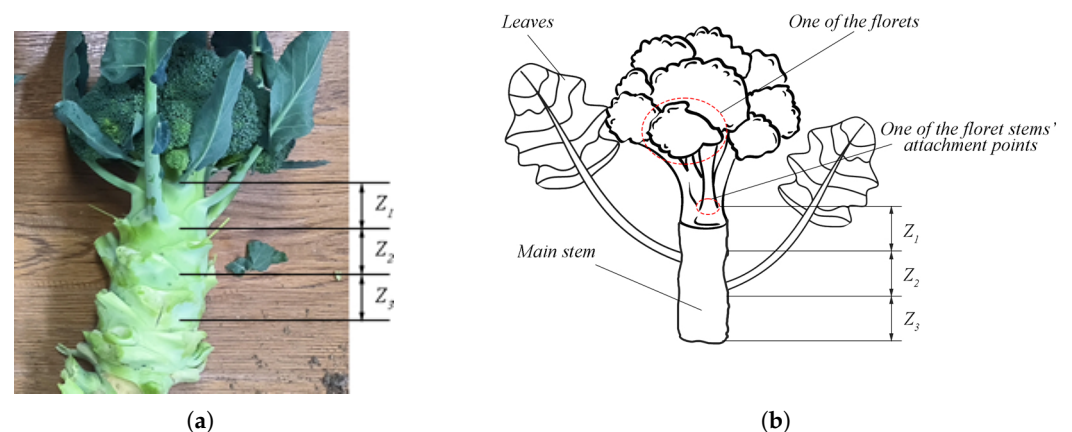


Figure 6. Schematic diagram of cutting position zoning for broccoli stem: (a) Physical diagram; (b) Simulation diagram (adapted and referenced from Song et al. [23]).

Table 5. Cutting position zoning table.

Zone Code	Zone Name	Coordinate Interval	Unit
Z_1	Starting zone	00 ¹ ~30	mm
Z_2	Middle zone	31~60	mm
Z_3	End zone	61~90	mm

¹ The coordinate origin for stem zoning is defined as the attachment point of the lowermost floret stem to the main stem, which is the farthest from the apex of the broccoli head, as shown in Figure 6b.

Table 6. Maximum cutting force results for different cutting positions on broccoli stems.

Experimental Group	Cutting Position Zone Code	Maximum Cutting Force (N)
MCFP-1	Z ₁	68.28
	Z ₂	92.67
	Z ₃	123.34
MCFP-2	Z ₁	58.55
	Z ₂	66.03
	Z ₃	78.34
MCFP-3	Z ₁	76.08
	Z ₂	77.42
	Z ₃	100.42
MCFP-4	Z ₁	41.04
	Z ₂	71.97
	Z ₃	79.09
MCFP-5	Z ₁	50.01
	Z ₂	67.32
	Z ₃	91.24
MCFP-6	Z ₁	31.50
	Z ₂	56.54
	Z ₃	86.37
MCFP-7	Z ₁	43.28
	Z ₂	70.20
	Z ₃	95.99
MCFP-8	Z ₁	67.45
	Z ₂	93.78
	Z ₃	96.8
MCFP-9	Z ₁	44.97
	Z ₂	88.67
	Z ₃	127.90
MCFP-10	Z ₁	56.05
	Z ₂	81.41
	Z ₃	103.09

Synthesizing the experimental results, this study established a tool design parameter system for broccoli harvesting end effectors: 1 mm blade thickness, double-bevel blade of blade type, 0° sliding cutting angle, combined with an optimized cutting position 0 mm~60 mm below the bottom of flower heads. Under these conditions, the maximum cutting force did not exceed 100 N. These conclusions provide critical technical parameters for the mechanical structure design and power system matching of end effectors. Specifically, morphological data (including stem diameter, flower head diameters, and head height, as shown in Table 1) were first used to define the range of feasible design parameters, ensuring the end-effector could adapt to the morphological characteristics of broccoli. Based on the conclusions drawn from the aforementioned experiments regarding cutting forces—using a 1 mm thick double-bevel blade with a 0° sliding cutting angle and an optimal cutting position 0 to 60 mm below the base of the flower head, under which the maximum cutting force remains within 100 N—the selection of the blade cylinders (labeled as 1 in Figure 1) and its arrangement have been determined.

3.2. Width Design of End Effector at the Pre-Extension Stage of Four-Blade Cylinders

The maximum cutting force test experiments determined the optimized design parameter combination for the end effector as follows: blade thickness of 1 mm, blade width of 30 mm, double-bevel blade of blade type, sliding cutting angle of 0°, with a required cutting force of at least 100 N.

The width of the end effector at the pre-extension stage of four-blade cylinders directly affects its adaptation in field environments. Based on the range of plant spacing, row spacing, and head diameter summarized in Table 1, the width of the end effector must be

restricted to 580 mm (290 mm per side). As shown in Figure 7, its width B is composed of five components. The calculation formula for B is given by Equation (1):

$$B = 2(l_0 + l_1 + l_2 + l_3 + r) \quad (1)$$

where the following is true:

B : Width of the end effector, mm;

l_0 : Other installation width, mm;

l_1 : Cylinder installation width, mm;

l_2 : Blade installation width, mm;

l_3 : Tolerance gap, mm;

r : Stem radius of broccoli, mm.

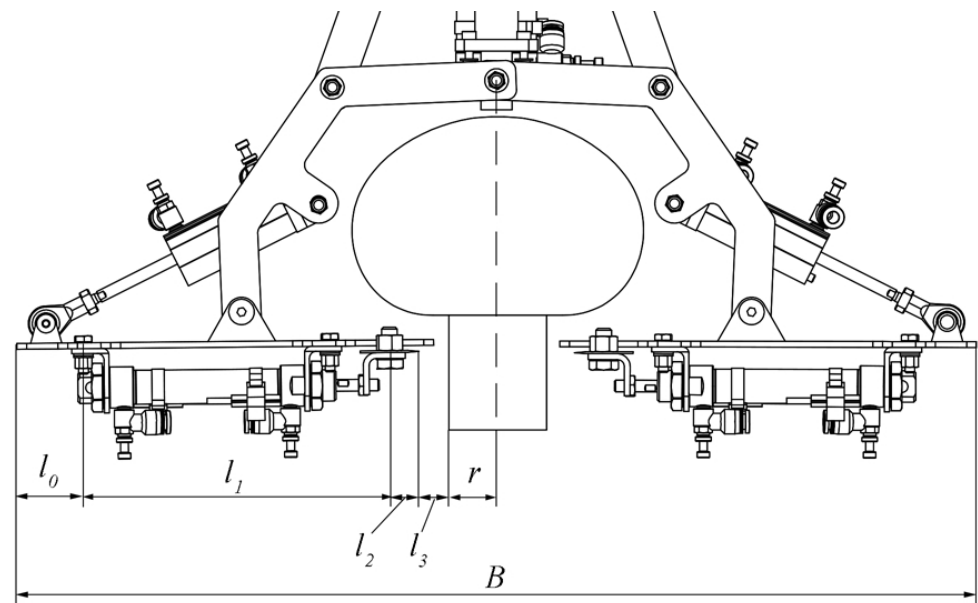


Figure 7. Schematic diagram of end effector width composition.

l_0 is a constant (value: 36 mm) determined by the installation method of the position adjustment cylinders (labeled as 1 in Figure 1). l_1 is the installation width of the blade cylinders (labeled as 1 in Figure 1), determined by the cylinder model and installation method. l_2 is the blade installation width—since rectangular blades are used, this value is 15 mm. l_3 is the tolerance gap, referring to the distance between the blade and the surface of the broccoli stem. When the end effector assumes the posture depicted in Figure 2c, generally set to 10 mm, r is the stem radius of the broccoli. According to the broccoli stem diameter range of 40 mm~60 mm specified in Table 1, r is taken as 30 mm based on the maximum stem diameter. The stem radius of 30 mm (corresponding to 60 mm diameter) was selected based on measurement. This choice not only covers the maximum operational scenario but also creates a 5 mm~10 mm tolerance gap for smaller stems. Among them, the sum of l_3 and r is called the cutting stroke B_0 , which is equal to the effective stroke of the blade cylinder (labeled as 1 in Figure 1), as shown in Equation (2).

$$B_0 = l_3 + r \quad (2)$$

Thus, the cutting stroke B_0 is determined to be 40 mm, and the formula for calculating the end effector width B is given by Equation (3).

$$B = 2(l_0 + l_1 + l_2 + B_0) \quad (3)$$

In Equation (3), l_0 and B_0 are both constant values, while the end effector width B is determined by l_1 and l_2 . Based on the conditions of a cutting stroke of 40 mm and a maximum cutting force of not less than 100 N, the model and installation method for the blade cylinders were selected, leading to l_1 being specified as 157 mm.

In summary, with l_0 set at 36 mm, l_1 at 157 mm, l_2 at 15 mm, and B_0 at 40 mm, B is calculated as 496 mm (248 mm per side), which meets the requirement: the total width of the end effector must be restricted to 580 mm (290 mm per side).

3.3. Key Dimensional Parameter Design of Connecting Rod

Experiments revealed a highly significant correlation between the cutting position and the maximum cutting force. Within the range of 0 mm~60 mm below the broccoli head, the maximum cutting force remained consistently below 100 N. In this section, we analyze the composition of cutting positions based on the morphological characteristic range of broccoli heads and the obtained conclusions, thereby designing the key dimensional parameters of the connecting rod (labeled as 1 in Figure 1). The calculation method for the cutting position is given in Equation (4).

$$h_1 + h_2 = h_3 + h_4 + h_5 \quad (4)$$

where the following is true:

h_1 : Key dimensional parameter of the connecting rod, mm;

h_2 : Necessary blade installation distance, determined by mounting configuration, mm;

h_3 : Top clearance between the broccoli head and end effector, mm;

h_4 : Height of the broccoli head, mm;

h_5 : Distance from the cutting position to the base of the broccoli head, mm.

The cutting position analysis diagram takes the fixed hinge point of the connecting rod as the coordinate origin. h_1 is defined as the vertical distance from the fixed hinge point to the connecting hinge point of the blade mounting plane. In Equation (4), h_2 is a constant (value: 17 mm) determined by the mounting dimensions of other components. Thus, h_1 directly determines the blade's cutting position, as illustrated in Figure 8. As an adjustable parameter, h_3 is tentatively set to 15 mm to ensure a safety clearance of at least 5 mm from the broccoli head apex. The parameter h_3 was designed by integrating mechanical structural constraints and dynamic adjustment logic, with its value determined by the connecting rod width (10 mm from the center to the edge) and a 5 mm safety margin, designed to avoid rigid collision between the broccoli top and the connecting rod edge. It is not a fixed threshold but can be dynamically adjusted through the Z-axis depth control of the Cartesian manipulators, enabling the safety margin to adaptively change within 5 mm~10 mm for different flower head heights, ensuring both cutting safety and operational flexibility. Statistical analysis of 54 broccoli heads (diameter range: 130 mm~160 mm) showed that 90% exhibited heights between 90 mm~130 mm, with 62.96% falling within 110 mm~130 mm. Given the desired cutting position range (0 mm~60 mm below the head):

For heads 120 mm~130 mm tall, a cutting position at 140 mm corresponds to 0 mm~10 mm below the head. For heads 90 mm~100 mm tall, this position translates to 30 mm~40 mm below the head. Both scenarios satisfy the experimental criteria. Therefore, h_4 was set to 130 mm and h_5 to 0 mm~30 mm. The optimal cutting position was determined to be 160 mm (ranging from 145 mm to 175 mm). When h_2 is set to 17 mm, the corresponding h_1 should be 143 mm.

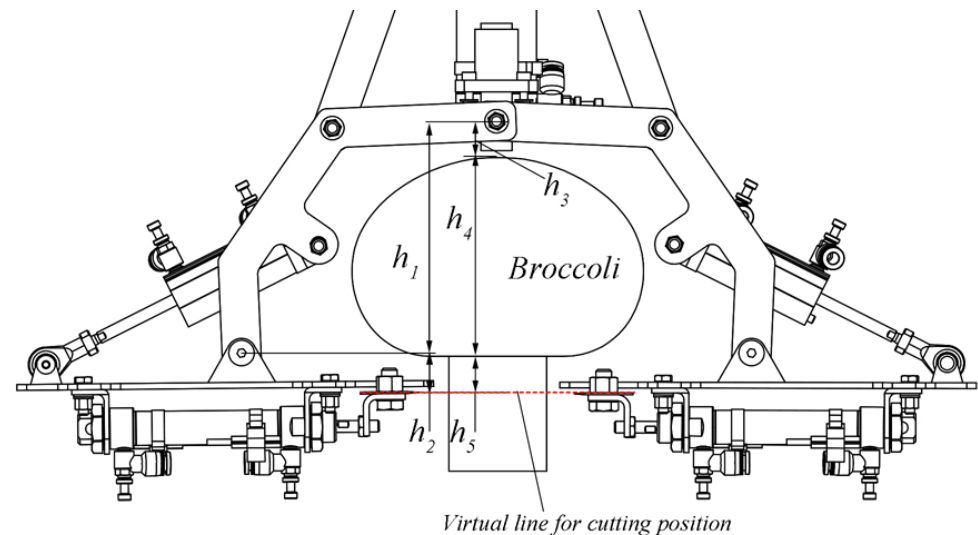


Figure 8. Schematic diagram for cutting position analysis.

3.4. Trajectory Simulation and Optimization

We employed SolidWorks 2023 as the core tool to conduct operational simulations of the end effector's motion and perform interference checks on the operating range of the Cartesian manipulators. The specific methods and their advantages are as follows:

(1) Trajectory analysis: SolidWorks Motion 2023 was used for trajectory simulation of the end effector. By setting the motion parameters and timing of each cylinder, the trajectory changes were accurately simulated. The software can output parameters such as the running trajectory and coordinates of the characteristic points of the end effector model in real time, which can be processed with Origin 2024 to generate trajectory comparison graphs (such as Figure 9) after being output as table files. The running animation intuitively displays the operation process, assisting in trajectory optimization.

(2) Interference checking: Considering the vertical trajectory characteristics of the Cartesian manipulators, we defined the motion boundaries of each axis of the manipulator (e.g., maximum stroke range) using the “Mate” function in the SolidWorks 2023 assembly environment. Then, we determined the range where the manipulator can move freely without interfering with other parts (such as the chassis) by setting the coordinates of each axis of the manipulator, thus completing the interference check.

SolidWorks Motion is highly integrated with the 3D modeling module, enabling the entire process from model construction to simulation analysis without data conversion, which significantly improves design efficiency; its visual interface facilitates quick parameter adjustment and scheme verification. Through feedback from simulation results, design parameters (such as cylinder installation methods) can be quickly iterated, eliminating interference issues in the design stage and reducing the cost and time of physical prototype debugging.

As shown in Figures 9 and 10a,b, the integrated multi-cylinder end effector can exhibit various operational trajectories depending on the extension timing of the position adjustment cylinders (labeled as 1 in Figure 1). In operation Mode 1, the position adjustment cylinders (labeled as 1 in Figure 1) are first extended, and once they reach full extension, the push rod cylinder (labeled as 1 in Figure 1) is retracted. In operation Mode 2, the push rod cylinder (labeled as 1 in Figure 1) is retracted first, and after achieving full retraction, the position adjustment cylinders (labeled as 1 in Figure 1) are extended. In operation Mode 3, the retraction of the push rod cylinder (labeled as 1 in Figure 1) is initiated first, and during this retraction process, the extension of the position adjustment cylinders (labeled as 1 in Figure 1) is activated. The activation timing of the position adjustment

cylinders (labeled as 1 in Figure 1) relative to the push rod cylinder's (labeled as 1 in Figure 1) retraction stroke determines distinct operational trajectories.

As shown in Figure 9, in operation Mode 1, the outer contour operation trajectory of the end effector is DC (D'C'), and the operation trajectory of the blade is EFG (E'F'G'). In operation Mode 2, the outer contour operation trajectory of the end effector is ABC (A'B'C'), and the operation trajectory of the blade is EHG (E'H'G'). When harvesting in Mode 1, the operational width of the outer contour operation trajectory is larger, prone to damaging the surrounding environment. When harvesting in Mode 2, the operational width of the outer contour operation trajectory is smaller, showing better adaptability to field environments, but in the final stage (H to G segment), it is easily blocked by the leaves of the broccoli, causing the cutting blades to fail to reach the position. Therefore, it is necessary to adjust the extension timing of the position adjustment cylinders (labeled as 1 in Figure 1) according to field conditions to change the operational trajectory of the end effector.

Measured results show that the extension action of the position adjustment cylinders (labeled as 1 in Figure 1) takes approximately 0.36 s, and the retraction of the push rod cylinder (labeled as 1 in Figure 1) takes approximately 0.85 s. The position adjustment cylinder (labeled as 1 in Figure 1) starts to operate when the blade edge is below the bottom of the flower head, generating the operational trajectory curve of the end effector as shown in Figure 9, where the green contour drawn based on the broccoli head diameter, stem diameter, and broccoli head height in Table 1 represents the possible area of broccoli plants.

In operation Mode 3, the operational trajectory curve of the end effector is generated when the position adjustment cylinders (labeled as 1 in Figure 1) start to operate 0.40 s after the retraction action of the push rod cylinder (labeled as 1 in Figure 1) is initiated.

Simulation of the end effector's operation trajectory shows that the end effector operating in Mode 3 can adapt to broccoli heads with a diameter of 200 mm, with the maximum unilateral width of the outer contour operation trajectory reduced by approximately 25 mm compared with operating in Mode 1, and compared with operating in Mode 2, the end effector operating in Mode 3 is less likely to be blocked by plant stems and leaves. Consequently, Mode 3 is selected as the operational mode for field harvesting trials due to its adaptability to complex environmental conditions.

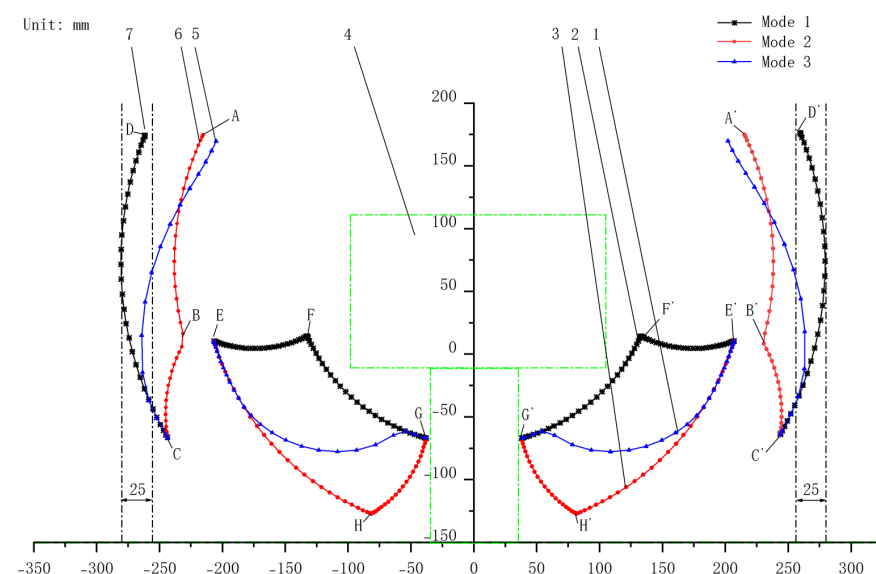


Figure 9. Trajectory analysis diagram of the end effector: 1, 2, and 3 represent the blade's operational trajectories in three modes (blue for Mode 3, red for Mode 2, and black for Mode 1); 4 designates the region of broccoli heads and stems; and 5, 6, and 7 denote the outer contour operational trajectories under three modes (blue for Mode 3, red for Mode 2, and black for Mode 1).

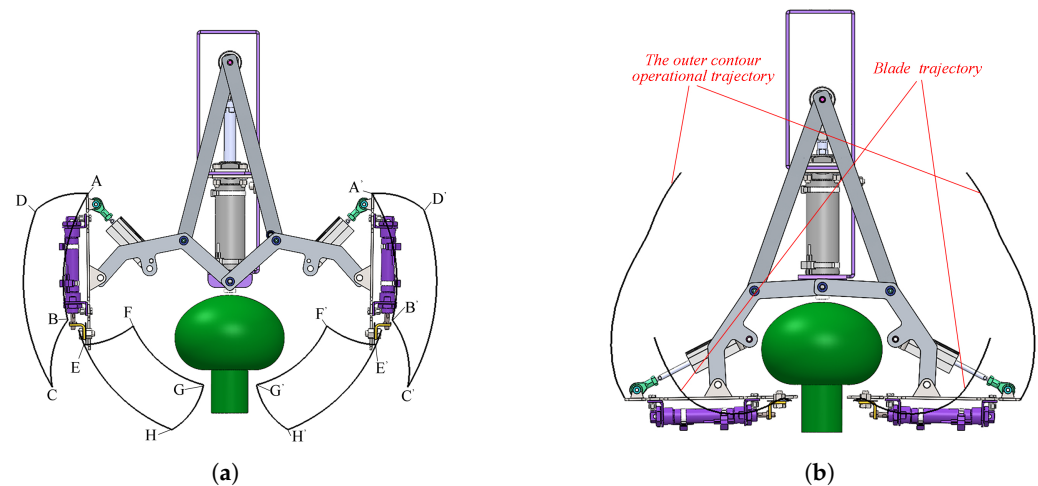


Figure 10. Simulation diagram of end effector operational trajectories: (a) Outer contour and blade trajectory in operation Mode 1 and Mode 2; (b) Outer contour and blade trajectory in operation Mode 3.

4. Bench-Scale Performance Testing of the End Effector

4.1. Experimental Methodology

The end-effector was mounted at the end of the Z-axis linear module of the Cartesian coordinate manipulator. For this test, broccoli samples with flower head diameters ranging from 130 mm to 180 mm were used, secured by a custom-designed holder (Figure 11). During the test, only vertical (Z-axis) movements of the Cartesian coordinate manipulator were performed. The execution depth was manually adjusted to position the harvesting origin of the end-effector at the top of the target flower head. The end-effector was manually controlled to carry out cutting operations on 50 whole broccoli plants with stems and leaves. The operational success rate was calculated based on these trials.



Figure 11. Diagram of the custom-designed holder for a broccoli sample.

4.2. Test Results

A total of 50 broccoli plants with stems and leaves were harvested, and under the assumption of accurate positioning, the end effector achieved a cutting success rate of 96% (48/50) and an operational success rate of 100%. The results are shown in Table 7. The average duration per cutting operation was 2.6 s, meeting the expected cutting performance. The single failed cutting case was primarily attributed to interference between the top of the tool cylinder's piston rod and the broccoli's stems or leaves. This issue can be addressed by extending the length of the end effector's blade, which would increase the spacing between the blade cylinders and thereby reduce the likelihood of such interference.

First, the Z-axis is at the origin, with the end-effector in an open configuration, as shown in Figure 12a. Secondly, the Z-axis has moved to the target position, positioning

the end-effector at the top of the flower head, as shown in Figure 12b. Then, following successful actuation, the end-effector fully encloses the broccoli head, reaching a state ready for immediate harvesting. Thirdly, post-cutting, the Z-axis initiates its return movement, lifting the end-effector upward; concurrently, the severed broccoli head is elevated as the Z-axis retracts, as shown in Figure 12c. Finally, once the Z-axis returns to the origin, the end-effector begins to open, allowing the broccoli head to fall under gravity, as shown in Figure 12d. A single test cycle is completed upon full opening of the end-effector.

Table 7. Results of bench-scale performance testing for the end effector.

Test Code	Head Diameter (mm)	End Effector Operation (Y/N) *	End Effector Cutting (Y/N)
BST-1	183.1	Y	Y
BST-2	155.3	Y	Y
BST-3	168.5	Y	Y
BST-4	155.6	Y	Y
BST-5	141.1	Y	Y
BST-6	141.6	Y	Y
BST-7	141.5	Y	Y
BST-8	128.0	Y	Y
BST-9	154.2	Y	Y
BST-10	140.9	Y	Y
BST-11	144.5	Y	Y
BST-12	130.5	Y	Y
BST-13	176.5	Y	Y
BST-14	163.3	Y	Y
BST-15	135.7	Y	Y
BST-16	145.2	Y	Y
BST-17	175.8	Y	N ¹
BST-18	140.8	Y	Y
BST-19	144.6	Y	Y
BST-20	140.5	Y	Y
BST-21	163.6	Y	Y
BST-22	129.1	Y	Y
BST-23	163.1	Y	Y
BST-24	154.2	Y	Y
BST-25	150.6	Y	Y
BST-26	143.4	Y	Y
BST-27	139.8	Y	Y
BST-28	142.7	Y	Y
BST-29	163.0	Y	N ²
BST-30	142.7	Y	Y
BST-31	168.3	Y	Y
BST-32	135.9	Y	Y
BST-33	176.1	Y	Y
BST-34	150.4	Y	Y
BST-35	130.2	Y	Y
BST-36	161.8	Y	Y
BST-37	147.5	Y	Y
BST-38	159.6	Y	Y
BST-39	172.9	Y	Y
BST-40	138.4	Y	Y
BST-41	156.3	Y	Y
BST-42	144.1	Y	Y
BST-43	165.7	Y	Y
BST-44	132.8	Y	Y
BST-45	179.5	Y	Y
BST-46	153.2	Y	Y
BST-47	149.0	Y	Y
BST-48	163.4	Y	Y
BST-49	158.9	Y	Y
BST-50	155.5	Y	Y

* Y denotes success, and N denotes failure. ¹ Overly thick stem diameters led to adhesion of the stem epidermis post-cutting, resulting in operational failure. ² Minimal obstruction from stems or leaves at the tip of the piston rod caused cylinder extension failure, thereby inducing cutting failure.

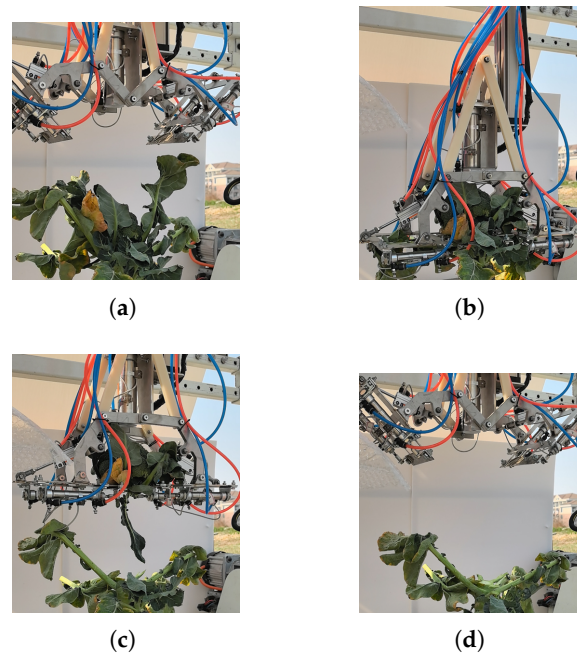


Figure 12. Diagram of the cutting process of the end-effector during bench testing: (a) Z-axis at origin with end-effector in initial state; (b) Z-axis positioned and end-effector operated successfully; (c) Successful cutting with Z-axis returned to origin; (d) End-effector in the process of opening.

5. Field Validation Test of the End Effector

5.1. Experimental Site and Equipment

The experimental equipment employed in this study is a self-developed selective broccoli harvester, which integrates a visual recognition system and an actuation system.

A vernier perimeter ruler with a diameter measurement range of 20 mm~300 mm and a precision of 0.1 mm was utilized to measure the diameter of broccoli heads, as illustrated in Figure 13.

The experimental subjects were randomly selected broccoli heads with diameters ranging from 100 mm to 200 mm, planted at standard spacing (45 cm to 50 cm within rows and between rows) using the cultivar ‘Yanxiu’. The trial was conducted in a farmland located in Touzao Town, Jiangsu Province, as shown in Figure 14.

To facilitate performance testing of the end effector, a broccoli selective harvester equipped with a Cartesian coordinate manipulator and a depth vision camera was developed in this study, as shown in Figure 14a,b. The depth vision camera was mounted at the front of the vehicle, comprising an analytical approach previously developed by Zuo, Z. in agronomy [24].



Figure 13. Schematic diagram of broccoli head diameter measurement using a vernier perimeter ruler.

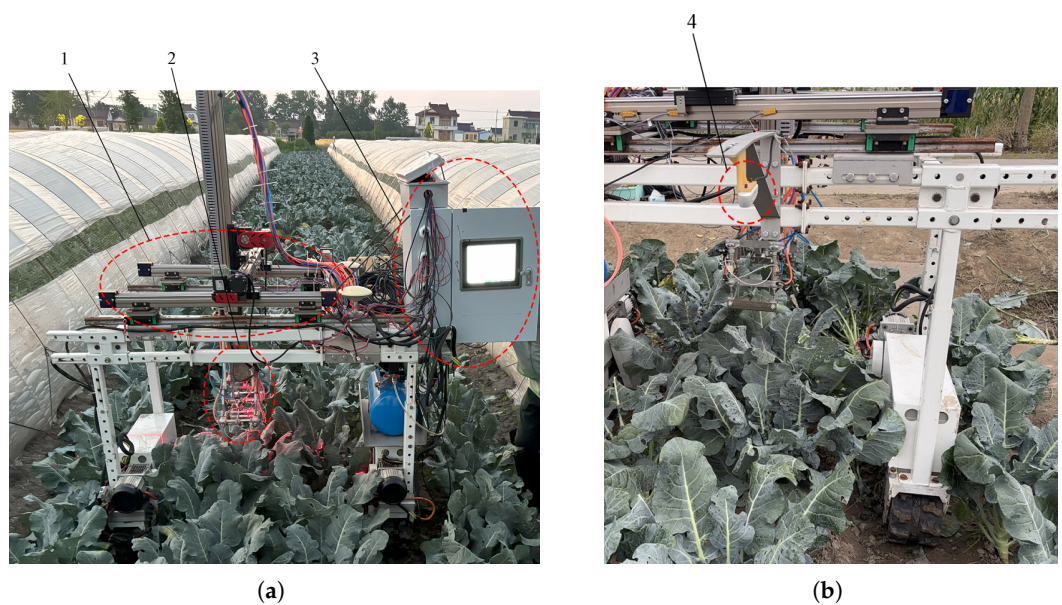


Figure 14. Diagram of experimental site and equipment: (a) Captured from the rear of the vehicle: 1. Cartesian coordinate manipulator, 2. End effector, 3. Control box; (b) Captured from the front of the vehicle: 4. Depth vision camera.

5.2. Experimental Methodology and Evaluation Criteria

During harvesting, the depth vision camera first captures the absolute geographic coordinates of broccoli heads, which are then transmitted to an industrial computer to calculate the positioning coordinates for the Cartesian coordinate manipulator. The Cartesian coordinate manipulator then drives the end effector to the position above the apex of the target broccoli head. Upon reaching the designated location, the end effector executes the harvesting operation. Finally, the Cartesian coordinate manipulator navigates the end effector back to the initial position, where the end effector releases the harvested broccoli upon arrival. The harvesting procedure was executed via dedicated picking software.

The end effector is considered to have operated successfully if it reached the target position and completed the cutting action. The operation success rate is calculated using Equation (5).

$$p_{succ} = \frac{n_m}{N_m} \quad (5)$$

In Equation (5), p_{succ} represents the operation success rate, where n_m denotes the number of successfully operated samples and N_m is the total number of samples.

5.3. Experimental Results

In this test, the end effector was positioned using the broccoli selective harvester and operated in Mode 3. Thirty broccoli heads were randomly selected in the field, with their diameters measured. Field test results are presented in Table 8 and Figure 15. Figure 15a shows the cross-section of the stem of a single broccoli specimen, and Figure 15b shows the harvested broccoli specimens after cutting.



Figure 15. Photos about the cutting quality in the field test: (a) Cross-section of the stem of a single broccoli specimen; (b) Harvested broccoli specimens after cutting by the end effector.

The operational process of the end effector and the Cartesian coordinate manipulator in the field is shown in Figure 16.

Figure 16a depicts the initial state of the end effector (consistent with the end effector posture shown in Figure 2a): the three axes of the Cartesian coordinate manipulator are

at the origin position with coordinate parameters $(x, y, z) = (0, 0, 0)$, ready to initiate the harvesting cycle.

Figure 16b shows the positioning result of the end effector: driven by the Cartesian coordinate manipulator, the x and y axes first move to position above the broccoli head, followed by the downward movement of the z axis. The end effector, in an open state, is suspended above the target head, with the coordinate parameters assumed to be (x_0, y_0, z_0) at this stage. Subsequently, the end effector enters the operational procedure, where the push rod cylinder (labeled as 1 in Figure 1) and position adjustment cylinders (labeled as 1 in Figure 1) are activated according to the preset timing sequence.

Figure 16c presents the ready state of the end effector before cutting (consistent with the state shown in Figure 2c): the bilateral cutting blade assemblies remain parallel-aligned (without executing the cutting action), and the broccoli head is fully enclosed within the cavity formed by connecting rods (labeled as 1 in Figure 1) and other components.

Figure 16d records the state after the completion of cutting: after the bilateral blade cylinders (labeled as 1 in Figure 1) drive the blades to sever the stem and retract to their original positions, the z-axis first ascends, and the end effector moves upward accordingly, lifting the harvested broccoli head away from the stem. At this point, the Cartesian manipulator coordinate transitions from (x_0, y_0, z_0) to $(x_0, y_0, 0)$.

In Figure 16e, the end effector retracts to the highest position, corresponding to the Cartesian manipulator coordinate $(x_0, y_0, 0)$ —this configuration serves as a safety measure to effectively prevent collisions with surrounding vegetation or soil during transfer.

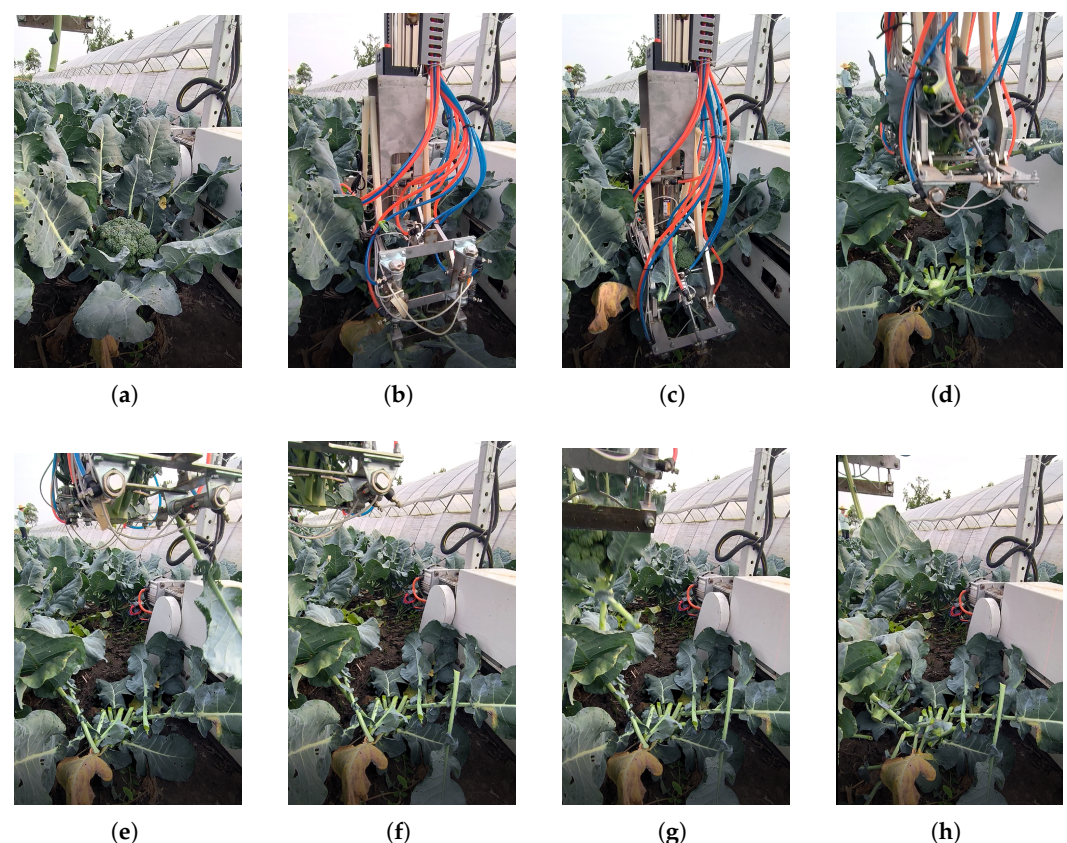


Figure 16. Operational sequence diagram of the end effector during harvesting: (a) End effector at origin in initial state; (b) End effector positioned above the top of the broccoli head; (c) End effector reaching the target operation position; (d) End effector completing cutting and initiating return movement; (e) End effector retracting to the highest elevation; (f) End effector returning to the origin position; (g) End effector opening mechanism activated; (h) End effector fully opened—broccoli head released.

Figure 16f shows the Cartesian manipulator fully returning to the origin position with coordinates reset to (0, 0, 0). During this process, the gripped broccoli head remains stable without detachment. Subsequently, the push rod cylinder and positioning adjustment cylinders of the end effector enter the preparation phase for the release action.

Figure 16g captures the moment when the end effector initiates the release procedure: the push rod cylinder and positioning adjustment cylinders start resetting, the end effector begins to open, and the broccoli head gradually detaches from the cavity as the end effector opens.

Figure 16h presents the state after the end effector is fully opened: the broccoli head is successfully released, and both the end effector and the Cartesian manipulator are reset to their initial configurations (consistent with the state in Figure 16a), preparing for the initiation of the next harvesting cycle.

Field testing demonstrated that the end effector of the broccoli selective harvester achieved an operational success rate of approximately 93.33% (28/30), indicating stable performance in agricultural environments and meeting operational requirements. Samples with failed end effector operation could not undergo cutting; excluding these, the cutting success rate was calculated as 92.86% (26/28) based on the reduced sample size (28 valid operations). This result confirms the reliable functionality of the cutting mechanism.

Table 8. Table of end effector field test results.

Test Code	Head Diameter (mm)	End Effector Operation (Y/N) *	End Effector Cutting (Y/N)
FT-1	164.0	Y	N ³
FT-2	169.1	Y	Y
FT-3	165.5	Y	Y
FT-4	176.2	Y	Y
FT-5	143.3	Y	Y
FT-6	179.1	Y	Y
FT-7	174.1	Y	Y
FT-8	165.2	Y	Y
FT-9	148.0	Y	Y
FT-10	172.4	Y	Y
FT-11	121.2	Y	Y
FT-12	119.6	Y	Y
FT-13	168.2	Y	Y
FT-14	163.5	Y	Y
FT-15	166.0	Y	Y
FT-16	126.2	Y	Y
FT-17	154.6	Y	Y
FT-18	135.7	Y	Y
FT-19	153.5	Y	Y
FT-20	159.2	Y	Y
FT-21	158.9	Y	N ³
FT-22	157.5	Y	Y
FT-23	148.0	N ¹	-
FT-24	178.6	Y	Y
FT-25	102.7	Y	Y
FT-26	108.4	Y	Y
FT-27	144.0	Y	Y
FT-28	142.5	Y	Y
FT-29	161.6	Y	Y
FT-30	179.5	N ²	-

* Y denotes success, and N denotes failure. ¹ Inadequate inter-head spacing: Insufficient distance between adjacent broccoli heads, falling below the design tolerance, impeded the end effector's access to the target position, resulting in operational failure. ² Combined effect of head diameter variability and positioning error: Deviations in flower head diameter exceeding design specifications (130 mm~160 mm, shown in Table 1), compounded by positional inaccuracies beyond acceptable tolerances, synergistically precluded the cutting tool from reaching the designated cutting position, thereby causing system malfunction. ³ Cutting failure due to incomplete stem severance.

In the performance test, the average operational cycle for single-plant broccoli harvesting by the harvester was stabilized at approximately 7.0 s. This data demonstrates that the robotic arm configuration based on the Cartesian coordinate manipulator exhibits remarkable

engineering applicability in broccoli harvesting scenarios, with its operational efficiency showing promise to meet the fundamental requirements of large-scale production.

6. Discussion

To address the challenges of broccoli selective harvesters, this study presents an integrated grasp-cut end effector, integrating transverse cutting and a foldable grasping cavity.

This study determined the key design parameters of the end effector through maximum cutting force tests: when the blade thickness is 1 mm, a double-bevel structure is adopted, the sliding cutting angle is 0° , and the cutting position is in the range of 0 mm~60 mm below the bottom of the flower heads, the maximum cutting force can be controlled within 100 N. This design criterion ensures the cutting success rate of the end effector and can be directly applied by researchers. It is noteworthy that ANOVA of the multi-factor mixed-level test of maximum cutting force (shown in Table 3) and the main effect plot of the sliding angle (shown in Figure 5d) suggested 40° as the theoretically optimal parameter. However, during the structural design of the end-effector, we found that a 40° sliding angle would require an excessive width of the end-effector B beyond the allowable operational range. To address this, we tried a 0° sliding angle in the cutting position test and obtained the corresponding maximum cutting force data. The results showed that the measured forces fully met the load requirements for blade cylinder (labeled as 1 in Figure 1) selection, validating the 0° sliding angle as the engineering-feasible solution. This compromise between theoretical optimization and practical constraints ensures both performance and operational viability. Testing on 50 broccoli plants yielded a 96% cutting success rate and a 100% operational success rate. When combined with data from 30 field-tested plants, the overall practical operational success rate reached 97.5% (78 out of 80). A post-hoc power analysis was conducted using G*Power 3.1.9.7 software with the following parameters: one-tailed test, effect size (g) of 0.09 (derived from the difference between the observed success rate of 96% and the benchmark value of 87%), significance level (α) of 0.05, total sample size (n) of 80, and a constant proportion set at 86.96% (comprehensive cutting success rate from Kang et al. [22]). The analysis results showed a lower critical success count of 75, meaning statistical significance could be confirmed when the number of successful cases was 75 or more. The actual test power reached 0.8988 (approximately 90%), indicating that the sample size had nearly a 90% probability of detecting a true effect. The actual α value was 0.0426, which is below the preset 0.05, further controlling the risk of false positives. Given the test results (total successful cases > 75, success rate > 93.75%), the cutting success rate of the end-effector is significantly higher than the 87% benchmark, demonstrating high statistical reliability and robustness.

Regarding the relevance between the force data in Table 4 and the design parameter—stem diameter—we would like to clarify as follows: The stem diameter range of 40 mm~60 mm in Table 1 is not a variable in the cutting experiments but rather the design input conditions for the end-effector. The core objective of this study is to obtain the maximum cutting force under optimal working conditions (such as blade thickness and blade type) within this diameter range to meet the cutting requirements of all samples to the greatest extent. Specifically, through preliminary statistics, it was found that the stem diameters of common broccoli in the market are distributed within 40 mm~60 mm, which is significantly representative. Based on the maximum cutting force test of stems with diameters ranging from 40 mm to 60 mm under certain conditions (1 mm blade thickness, double-bevel blade, 0° sliding cutting angle, combined with an optimized cutting position 0 mm to 60 mm below the bottom of flower heads, where the maximum cutting force did not exceed 100 N), a blade cylinder with a bore diameter of 16 mm and an air pressure of 0.5 MPa (with a theoretical driving force of approximately 80 N) was selected, and a single-

side dual-cylinder drive was adopted to form a 50% cutting force redundancy (design threshold of approximately 160 N). Despite the lack of control over stem diameter variables in the cutting experiments, the rationality of this design has been verified in the following ways: In field trials ($n = 28$), the cutting success rate reached 92.86 %, and no failure due to insufficient cutting force occurred during 2 h of continuous operation; in a large number of stem cutting tests ($n = 84$), the measured maximum cutting force was always lower than 160 N, indicating that the 50% redundancy can meet actual needs. There are indeed certain empirical limitations in the current setting of the redundancy value. In future research, we will improve the accuracy by introducing the response surface method to optimize the cutting force redundancy parameters and establish a prediction model combining multiple variables such as stem diameter and hardness.

A performance comparison between the results of this study and those from other relevant studies is provided in Table 9 to help readers gain a clearer understanding of this research. In the field performance testing of the end effector, both the operation and cutting success rates have exceeded 90%, verifying the feasibility and effectiveness of the overall design scheme. Compared with the conventional combination of a fixed cavity and a single-blade transverse cutting end effector [17], the design featuring a mobile cavity with bilateral cutting demonstrates remarkable superiority in spatial utilization. With a substantial reduction in unilateral working space occupation, this configuration effectively mitigates interference risks during operation. In terms of grasping performance, the mobile cavity employs an encirclement-based principle to grasp broccoli florets, offering a more reliable and stable gripping effect compared with under-actuated grippers [20]. From a cost-control perspective, the cutting approach utilizing mechanical blades driven by pneumatic cylinders exhibits greater economic efficiency than waterjet cutting technology [18], which is resource-intensive, and complex flexible finger grasping solutions. The application of long-blade transverse cutting technology in the cutting structure design ensures that the cutting surface completely covers the bottom of the florets. This design significantly enhances the adaptability of the device to broccoli of various shapes, reducing the system's reliance on high-precision positioning compared with anthropomorphic pinching–cutting structures [22].

In terms of the precise positioning of the blade, the three posture control cylinders (push rod cylinder and position adjustment cylinders) achieve precise blade positioning through coordinated movements with precise timing. Specifically, first, the push rod cylinder's piston rod extends, and the position adjustment cylinders' piston rods fully retract, placing the end effector in an open state to lay the foundation for subsequent actions. After the Cartesian manipulators complete positioning (aligning the central axis of the end effector with that of the broccoli head), the push rod cylinder's piston rod retracts, driving the connecting rod to rotate downward via the push rod. The position adjustment cylinders extend a few milliseconds later (preset in the program). Once all three cylinders are fully in place, the blades on both sides of the end effector are positioned on the same plane, and the end effector is in a fully grasping state, with the broccoli head enclosed in the "cavity" formed by the connecting rods, blade mounting planes, and the frame. It is worth noting that the hinge joints of the end effector use plastic sliding bearings from Igus, which can precisely control the relative positions of the hinges, ensuring smooth and gap-free movement—a key detail for achieving high-precision blade positioning.

Regarding robotic arm selection, Cartesian coordinate manipulators, owing to their structural characteristics, have significant advantages over multi-DOF robotic arms in terms of operational efficiency and cost control. The Cartesian manipulators used in this study, with 3 degrees of freedom (X, Y, and Z axes), consist of standardized components such as linear guides and synchronous belt modules, with fewer parts (about 1/3 to 1/2 of

multi-DOF robotic arms), reducing manufacturing costs. In contrast, multi-DOF robotic arms (e.g., 6-DOF articulated arms) require high-precision harmonic drives, multi-axis controllers, and complex sensing systems, resulting in higher initial costs and more customized components. In structured planting environments (e.g., fixed row and plant spacing for broccoli), Cartesian harvesters are more efficient. Their trajectories are straight or fixed paths (e.g., “positioning-descending-cutting-ascending”), with simple path planning (no complex obstacle avoidance algorithms). In our field tests, the average harvest cycle per plant is approximately 7.0 s, which can be further optimized. Multi-DOF robotic arms, while adaptable to unstructured environments, require real-time obstacle avoidance and posture adjustment, leading to longer average harvest times (around 12.00 s as per related studies: Kang et al. [22]). Cartesian manipulators are more convenient to maintain. Their core components (guides, motors) are less exposed, have modular structures, and clear failure points (e.g., insufficient guide lubrication, motor overheating), allowing field maintenance with simple tools. Multi-DOF robotic arms have highly integrated joints, sensors, and cables, making fault diagnosis complex (e.g., harmonic drive wear, multi-axis synchronization errors) and requiring professional technicians for maintenance, with faster component aging in dusty and humid field environments, leading to more frequent maintenance. In summary, Cartesian coordinate manipulators are better suited to the working requirements of the broccoli selective harvesting end effector, providing a technical guarantee for achieving efficient and cost-effective broccoli cutting operations.

However, the end effector still revealed multi-dimensional problems in the test process that need to be solved urgently. Significant variability exists in the retained length of the broccoli stem, showing a notable deviation from standardized market specifications. The surface quality of the stem section has not achieved the desired smoothness and flatness. Further resources should be invested in exploring optimal cutting parameters or integrating with other processes (such as conveying) for improvement. It is also worth noting that when the spacing between broccoli plants was excessively small (e.g., less than 300 mm), the end effector often encountered obstacles from surrounding stems, leaves, or other plants during the grasping process, leading to a reduction in operational success rates. Terrain undulations and weather conditions (such as varying light intensity) affected the recognition performance of the vision system, which in turn caused inaccuracies in the coordinate positioning of the Cartesian manipulator. This resulted in positioning deviations of the end effector beyond the allowable tolerance range, further influencing the success rates.

Table 9. Performance comparison of selective broccoli harvesters in existing studies.

Item	This Paper	Song et al. [23]	Xu et al. [20]	Kang et al. [22]
Test site	Field	Laboratory	Laboratory	Field
Presence of leaves in samples	Yes	No	No	Yes
Manipulator	Cartesian coordinate robot	Ball screw slide	Multi-DOF robot	Multi-DOF robot
End effector type	Collapsible gripping chamber	Centering cutting type	Under-actuated type	Humanoid pinching-cutting type
Average harvesting time per plant (s)	about 7.0	Not reported	about 11.37	about 11.99
Cutting success rate (%)	94.87 (n = 78)	100 (n = 20)	84 (n = 50)	86.96 (n = 95)

7. Conclusions

This study successfully designed, fabricated, and validated a novel, compact end effector for the selective harvesting of broccoli, directly addressing the critical challenge of large operational footprints in existing systems. Through systematic analysis of broccoli's biomechanical properties and morphological characteristics, an integrated grasp-cut mechanism was optimized. The design features a transverse cutter and a foldable grasping cavity, whose operational trajectories were verified via trajectory simulations. Rigorous field trials confirmed the design's efficacy: the end effector achieved an overall cutting success rate of 94.87% and demonstrated its ability to harvest in dense planting conditions without interfering with adjacent plants. When mounted on a Cartesian coordinate manipulator, the system completed a full harvesting cycle in an average of 7.0 s, proving its operational efficiency. Collectively, these findings present a robust and viable solution for automated broccoli harvesting in complex, unstructured environments. The research validates a new technical pathway that significantly enhances the potential for commercial-scale robotic harvesting. Future work should focus on long-term durability testing, integration with an AI-based vision system for fully autonomous targeting, and adapting the design for a wider range of broccoli cultivars and variable field conditions. This work lays a critical foundation for the development of the next generation of intelligent and commercially viable robotic harvesters for specialty crops.

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