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A Novel Soft Gripper Design Integrating a Unilateral Fingernail-like Mechanism for Grasping Flat Objects

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***Abstract*— The grasping capabilities of robotic arms have been extensively studied by researchers in terms of accuracy, flexibility, and versatility, enabling robots to perform various tasks in domestic, industrial, and medical scenarios. However, grasping flat objects has remained a significant challenge and is often overlooked as a limiting case in robotic manipulation. To address this highly difficult task, this paper proposes a novel gripper design that combines a pneumatic soft gripper with a unilateral fingernail structure. We evaluate two grasping strategies and corresponding target generation methods tailored for this design. The proposed system significantly improves the success rate of stably grasping flat objects that lie flush on tables. Moreover, its soft interaction with the table surface reduces the need for highly precise object-table height detection, thereby saving computational time and cost. Finally, we conduct experimental tests on various common flat objects, validating the effectiveness of both the gripper design and the grasping strategies.**

I. INTRODUCTION

Grasping has long been a central research topic in robotics, as it represents one of the most fundamental manipulation capabilities. To enable robots to handle objects of diverse shapes and physical properties in domestic, industrial, and medical scenarios, researchers have proposed novel gripper designs and general methods for generating grasp points. Amid these mainstream research efforts, flat objects have often been overlooked as a particularly challenging limiting case. This oversight stems primarily from the limitations of existing gripper mechanisms and sensing methods when dealing with such objects.

Grasping flat objects poses several distinct challenges. First, commonly used perception techniques struggle to accurately and efficiently detect the height difference between the object and the table surface. For instance, real-time point cloud data often becomes unreliable below 5 mm accuracy. Multi-view point cloud registration is computationally expensive and offers limited improvement in precision, while high-accuracy lidar systems capable of millimeter-level real-time sensing are prohibitively expensive. Second, most conventional grippers are ill-suited for this task. Traditional two-finger rigid grippers require a sufficient gap between the object and the table to avoid collisions. Electromagnetic grippers are restricted to metallic objects. Pneumatic suction cups can handle items with flat surfaces such as paper or cards but fail on very thin objects. Other specialized grippers, such as those based on jamming or multi-fingered hands, are also ineffective. Finally, even when successfully lifted, flat objects are prone to drop due to a limited contact area (low friction) and minimal tolerance in grip positioning. Wider items may also experience torque under gripper pressure, leading to premature release.

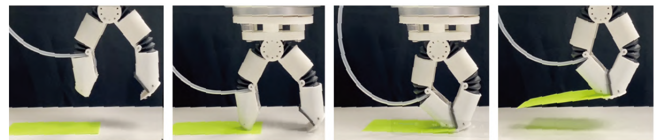

Fig. 1. Challenge the gripper to pick up a piece of paper.

To address these challenges, several studies have developed specialized grippers and grasping strategies for manipulating small, flat objects on planar surfaces [1]. Inspired by human dexterity, Sarantopoulos et al. [2] proposed a bio-inspired grasp strategy in which one finger slides the object toward the edge of the table, allowing the other finger to close and secure it. Odhner et al. [3], [4] introduced a "flip-and-pinch" method, where the hand flips thin objects off the surface to facilitate easier gripping. Babin et al. [5] and Lévesque et al. [6] equipped a gripper finger with a sharp-tip structure and developed a scooping strategy: one finger blocks the object on one side while the other slides beneath it from the opposite side. Other approaches leverage adaptive materials and structures for compliance. Toyoda's jamming gripper incorporates a stretchable membrane that acts like a suction cup upon contact, enabling secure attachment to flat objects [7]. Similarly, Liu et al. [8] engineered an annular microwedge adhesion membrane that generates a centripetal loading force when stretched. Wang et al. [9] designed an origami-inspired bending actuator equipped with octopus-like suction cups, capable of handling a variety of objects ranging from small irregular shapes to large flat items. Although suction represents a common principle, some designs integrate additional actuation mechanisms. For example, Guo et al. [10] enhanced a traditional soft gripper with two active fingertips driven by motors, enabling a rolling motion that aids in grasping thin objects such as credit cards and sheets

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of paper. However, these approaches are often limited by object type, size, or material properties.

The fingernail mechanism has been widely adopted by researchers to enhance the grasping capabilities of robotic grippers, particularly for flat and thin objects. For instance, Jain et al. [11] designed a retractable vertical nail mechanism that operates without complex path planning. Yoshimi et al. [12] employed a two-fingered parallel soft gripper equipped with a unilateral soft nail and introduced sliding and raising motions to pick up items such as paper sheets or plastic cards. Similarly, Nishimura et al. [13] demonstrated a pinching mode capable of scooping small or thin objects from a table. Beyond parallel-grip configurations, some designs utilize environmental interactions for dexterous manipulation. Watanabe et al. [14] proposed fingers that can turn over upon contact with a flat surface: one finger lifts the object while the other secures it from above to prevent slippage. Hashanjana et al. [15] further developed a gripper system with a retractable spatula plate designed to grip very thin and highly delicate food materials. Inspired by these advances, this work seeks to extend the boundaries of robotic grasping through innovations in both mechanical design and grasp strategy.

The main contributions of this work are as follows:

1) We propose a novel gripper design that integrates a soft pneumatic actuator with a unilateral fingernail-like structure. This design enables effective and stable lifting of flat objects flush on table surfaces. The compliant interaction between the gripper and the table allows safe soft contact, eliminating the need for high-precision object-table height detection, and thereby reducing computational cost and time.
2) We introduce two grasping strategies—Grip and Sweep—along with corresponding target generation methods to handle a wide variety of flat object shapes and material properties.
3) We conducted extensive experiments using common flat objects from the household, industrial, and medical contexts. The results demonstrate the effectiveness, real-time performance, and generalizability of both the proposed gripper design and the grasping strategies.

This paper is organized into several sections, beginning with the mechanism (Section II), the proposed grasp strategy (Section III), and finally its experimental evaluation (Section IV). In Section V, conclusions are drawn.

II. MECHANISM

The proposed gripper design integrates a soft pneumatic actuator with a unilateral fingernail-shaped structure to address the challenges of grasping flat objects. The overall architecture consists of two fingers, where one finger incorporates a rigid fingernail extension, and both fingers are driven by pneumatic actuators. This hybrid approach combines the adaptability and safe interaction of soft robotics with the precision of a bio-inspired fingernail mechanism.

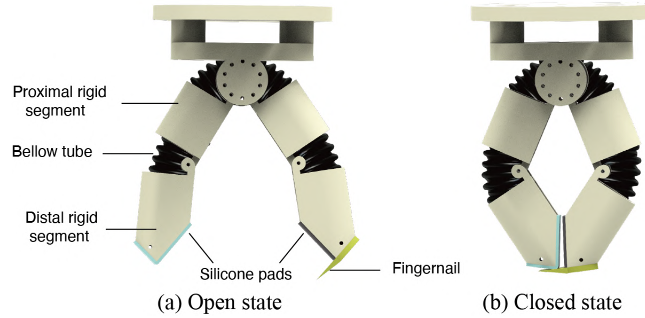


Fig. 2. The schematic diagram of the gripper in (a) Open state and (b) Closed state.

A. Design Overview

Fig. 2, Schematic of the proposed gripper design, showing the pneumatic soft actuators, the unilateral fingernail structure and key dimensions. The gripper is mounted on a standard robotic arm (e.g., UR5) and features a base frame housing the pneumatic control system and binocular camera. The two fingers are symmetrically placed in the open state, with a maximum opening width of 60 mm to accommodate various objects. The "nailed" finger includes a unilateral extension —a rigid, wedge-shaped 3D-printed plate, extending 10 mm beyond the fingertip. This extension is angled at 10 degrees to facilitate inserting under flat objects without requiring a gap.

B. Pneumatic Soft Actuator

Each finger is actuated by a bellows-style pneumatic soft actuator made by PE, inspired by prior soft grippers. The actuators are inflated/deflated via proportional valves connected to a compressed air source (pressure range: 0-0.2 MPa). Its inflation causes the two segments of the finger to rotate around the joints; therefore, the fingers curl inward for grasping. The soft actuator allows deformation upon contact, preventing damage to delicate objects or the table. This compliance reduces the need for millimeter-level height detection, as the gripper can "forgive" minor positioning errors by deforming. In addition, silicone is pasted on the contact surface of the finger to increase friction and provide a better griping.

C. Unilateral Fingernail Structure

The fingernail is attached to one finger's tip, providing a rigid "scoop" for Sweep mode. During operation, the fingernail acts as a passive wedge: in Grip mode, it aids in enveloping; in Sweep, it serves as a stationary barrier for object sliding. This unilateral design minimizes complexity (no need for symmetric nails) while enabling asymmetric strategies for thin objects.

D. Integration and Operation

The actuators and fingernail are integrated via a modular frame, allowing easy swapping for maintenance. Control is achieved through a simple state machine: open (deflate),

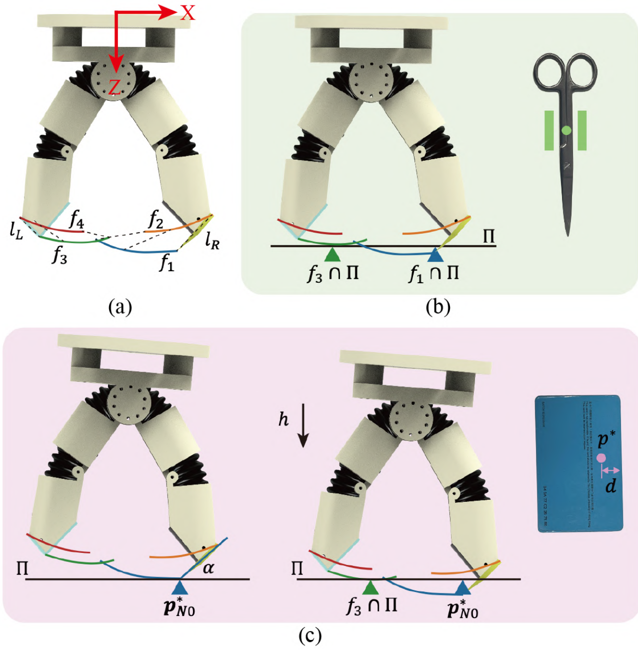


Fig. 3. Grasping strategies and target generation. (a) Definitions of key concepts, (b) Grip mode, (c) Sweep mode.

close (inflate to target pressure), and hold (maintain pressure). Force feedback is optional via magnetic pad based on hall-effect, but the design relies on open-loop control for real-time performance (less than 1 second per grasp). Fabrication cost is low (1 using 3D printed components), making it accessible for research and deployment. This mechanism directly mitigates the Introduction's challenges: the soft structure enables safe table contact without precise sensing, while the fingernail ensures stable lifting of flush objects. It forms the foundation for the grasping strategies detailed in Section III.

III. GRASPING STRATEGIES AND TARGET GENERATION METHODS

Based on the proposed mechanism, we introduce two adapted grasping strategies: Grip and Sweep.

First of all, we introduce the necessary definitions and concepts. Our gripper follows an arc trajectory at its lowest point when opening or closing without external force. Therefore, to accurately determine the contact point between the gripper and the table surface (defined as Π) for grasp pose generation, we conducted a characterization analysis on two specific points located on the rigid section of each finger (results are provided in the Experimental section). This analysis yielded four distinct curves $f_1(t)$, $f_2(t)$, $f_3(t)$, and $f_4(t)$ and the two reference points on each finger should follow the constraints of distance, that is, $\|f_1(t) - f_2(t)\| = l_N$ and $\|f_3(t) - f_4(t)\| = l$, as illustrated in Fig. 3 (a).

A. Grip Mode

In Grip mode (shown in Fig. 3 (b)), the gripper aligns with the target grasp point (such as the green dot and lines on the scissors in Fig. 3 (b)), resembling the operation of a traditional two-finger rigid gripper. For flat objects, the gripper axis should be perpendicular to the table. This mode can also be applied to non-flat objects, enhancing the general utility of our gripper. During closure, both fingers move symmetrically, eventually fully enveloping the object between them. Note that, in this mode, we should garuentee the lowest trajectories intersect Π, that is, $f_1 \cap \Pi \neq \emptyset$ and $f_3 \cap \Pi \neq \emptyset$. This condition is neccessary to gain more grasping space, otherwise the gripper tips will miss the thin object.

B. Sweep Mode

Sweep mode (shown in Fig. 3 (c)) is designed for handling very thin objects (e.g., a sheet of paper). Hence, we assume the highest suface of the object is the same with Π. In this mode, it is intuitively to find a target contact point on the object for the finger without nail since this finger will sweet the object. This contact point is defined as $\mathbf{p}^*$ whose distance to the object edge is d. Given this target, the geometric relationship between two finger tips without any external force and other constraints such as the angle between the fingernail and Π (defined as α) and the height of the gripper (defined as h), we can obtain the target contact point $\mathbf{p}^*_{N0}$ of the fingernail.

After the fingernail is placed at it target position $\mathbf{p}^*_{N0}$, we adjust α and h to garuentee $f_3 \cap \Pi = \mathbf{p}^*$. During closure, the non-nailed finger pushes the object, leveraging friction to slide it toward the nailed side. The object is eventually secured between the inner surface of the nail and the tip of the opposing finger.

Note that, our Sweep mode requires the fingernail to contact the table before the other finger because of special thin objects with hard properties and sharp edges, such as credit card and coins. Otherwise, if the non-nailed finger contacts the object first (named as scoop strategy in some papers), when we lower the gripper allowing the trajectory of the fingernail to insect Π, the pressure from the non-nailed finger to the object hinders the fingernail from inserting under the objects. Our Sweep mode can effectively address this confilct showning the strength of our strategy to regular scoop mode.

IV. EXPERIMENTS AND RESULTS

To validate the proposed gripper design—which integrates a pneumatic soft actuator with a unilateral fingernail structure—along with the two grasping strategies, we conduct extensive grasping experiments on more than ten types of objects. Each object is grasped ten times to calculate the success rate. A grasp is considered successful if the object remains securely held without dropping for 10 seconds while suspended in the air, during which the gripper's orientation is randomly altered.

A. Characterization of Grasping Force

In this subsection, we characterize the grasping force generated by the pneumatic soft actuators to understand the gripper's force capabilities across its operational pressure

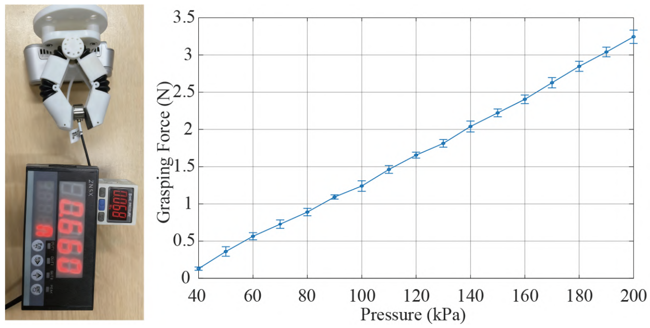


Fig. 4. The experimental setup and the relationship between Grasping Force and Pressure for the proposed gripper.

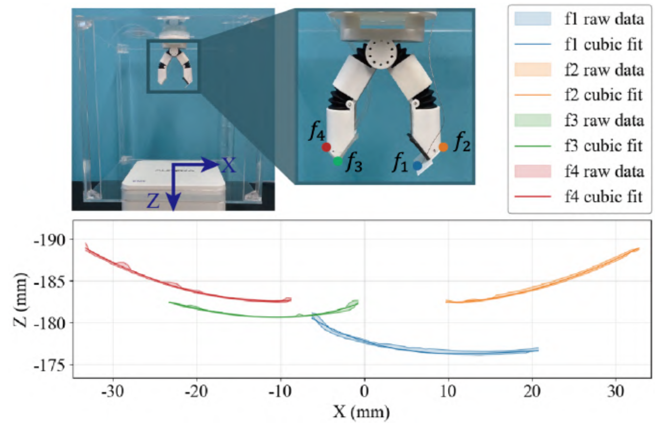


Fig. 5. Gripper setup with labelled points f_1-f_4 and raw trajectory data and cubic fits for f_1 (blue), f_2 (orange), f_3 (green), and f_4 (red) in the X-Z plane.

range. As shown in Fig. 4, the gripper was tested in a controlled environment to measure grasping force. A mini air pump (KMDP-U3, KAIMENG, Shenzhen, China) and proportional valve (ITV0010, Tokyo, Japan) were used to inflate the bellows-style pneumatic actuators. Pressure was incrementally adjusted from 0 to 0.2 MPa (0-200 kPa) in 10 kPa steps. Grasping force was measured using a clamping force sensor (ZNLBM-IX, Bengbu, China) attached between the fingers simulate object contact. Each pressure level was tested five times to account for variability due to material deformation, and average forces were recorded with error bars representing standard deviation.

The results, shown in Fig. 4(b), demonstrate a linear relationship between applied pressure and average grasping force, increasing from 0.1 N at 40 kPa to approximately 3.2 N at 200 kPa. Error bars indicate low variability (standard deviation <0.07 N), confirming the actuators' consistent performance. This force range is sufficient for handling lightweight flat objects while maintaining compliance to avoid damage.

B. Characterization of Finger Trajectories

To determine the accurate contact points between the gripper and the table surface for grasp pose generation, we characterized the trajectories of four specific points on the rigid sections of the fingers during opening and closing without external forces. As shown in Fig. 5, the gripper was mounted inside a transparent enclosure for unobstructed tracking, with the base frame secured to simulate operational conditions. These points (f_1, f_2, f_3, and f_4 in Fig. 3 and Fig. 5) represent two reference points per finger, with f_1 and f_2 on the non-nailed finger and f_3 and f_4 on the nailed finger, as illustrated in the gripper schematic. Trajectories were recorded using the NDI Aurora electromagnetic tracking system (NDI, Waterloo, Canada), which provides high-precision 6-DoF position data with sub-millimetre accuracy. Sensors were attached to the four points on the fingertips and rigid segments. The gripper was actuated through a full open-close cycle with no objects or external contacts. Data was collected at 40 Hz over 10 trials per point to account for variability in actuator deformation. Raw position data (X-Z plane, as Y is negligible in symmetric motion) was processed and fitted using cubic polynomials to model the arc trajectories, ensuring the fits satisfied distance constraints between paired points.

The trajectories exhibit smooth, arc-like paths in the X-Z plane, with Z decreasing from approximately -175 mm to -195 mm as X varies from -30 mm to 30 mm, confirming the gripper's curling motion. Cubic fits closely matched the raw data, with low root-mean-square errors (RMSE $<$ 0.5 mm across all points), indicating reliable modelling for pose generation. For instance, the nailed finger's points (f_1 and f_2) show a slight asymmetry due to the fingernail extension, enabling the wedge insertion in Sweep mode, while the non-nailed finger (f_3 and f_4) follows a more symmetric curve for enveloping. These characterizations ensure that the lowest trajectories intersect Π (e.g., $f_1 \cap \Pi \neq \emptyset$ and $f_3 \cap \Pi \neq \emptyset$ in Grip mode), providing the necessary grasping space for thin objects and validating the design's adaptability.

We adopt cubic polynomial fit to obtain the trajectories and use the coefficient of multiple determination, R^2, which measures the strength of the statistical association between independent and dependent variables, to evaluate the goodness of fit. $R^2 \in [0, 1]$ with higher values indicating a better fit. The cubic polynomial fit results and the corresponding R^2 are as follows.

$$
\begin{aligned}
f_1(t) &= 3.635 \times 10^{-4} t^3 - 0.020 t^2 + 0.305 t - 177.752 \\
&\quad t \in [-6.25, 20.75], R^2 = 0.9810 \\
f_2(t) &= 9.230 \times 10^{-5} t^3 - 0.016 t^2 + 0.279 x - 183.660 \\
&\quad t \in [9.75, 32.75], R^2 = 0.9990 \\
f_3(t) &= -3.068 \times 10^{-4} x^3 - 0.024 x^2 - 0.406 x - 182.523 \\
&\quad t \in [-23.25, -0.75], R^2 = 0.9777 \\
f_4(t) &= -6.998 \times 10^{-6} x^3 - 0.013 x^2 - 0.280 x - 184.099 \\
&\quad t \in [-33.25, -8.75], R^2 = 0.9949
\end{aligned}
$$

The extremely small coefficients of cubic term and high R^2 values show that the trajectories are more like a quadratic curve and the adopted cubic polynomial fit method is sufficiently accurate to conpute the target grasping points.

No.	Object	Illustration	Thickness (mm)	Weight (g)
1	Paper clip		1.02	< 0.1
2	Ejection Pin		0.61	< 0.1
3	Coin		1.85	4.9
4	Flosser (w/ package)		2.07	0.8
5	Paper sheet		0.12	0.6
6	Access card		0.81	5.3
7	Rubber band		1.94	< 0.1
8	Comb		4.55	8.5
9	Flosser (w/o package)		1.97	0.3
10	File		2.08	7.5
11	Scalpel handle		2.74	20.0
12	Surgical scissors		4.64	40.0
13	Mathieu needle holder		4.72	24.2
14	Snack (w/ package)		-- (deformation)	56.2
15	Tank		52.81 (diameter)	169.1

Fig. 6. The objects used in the experiments, along with their dimensions and weights.

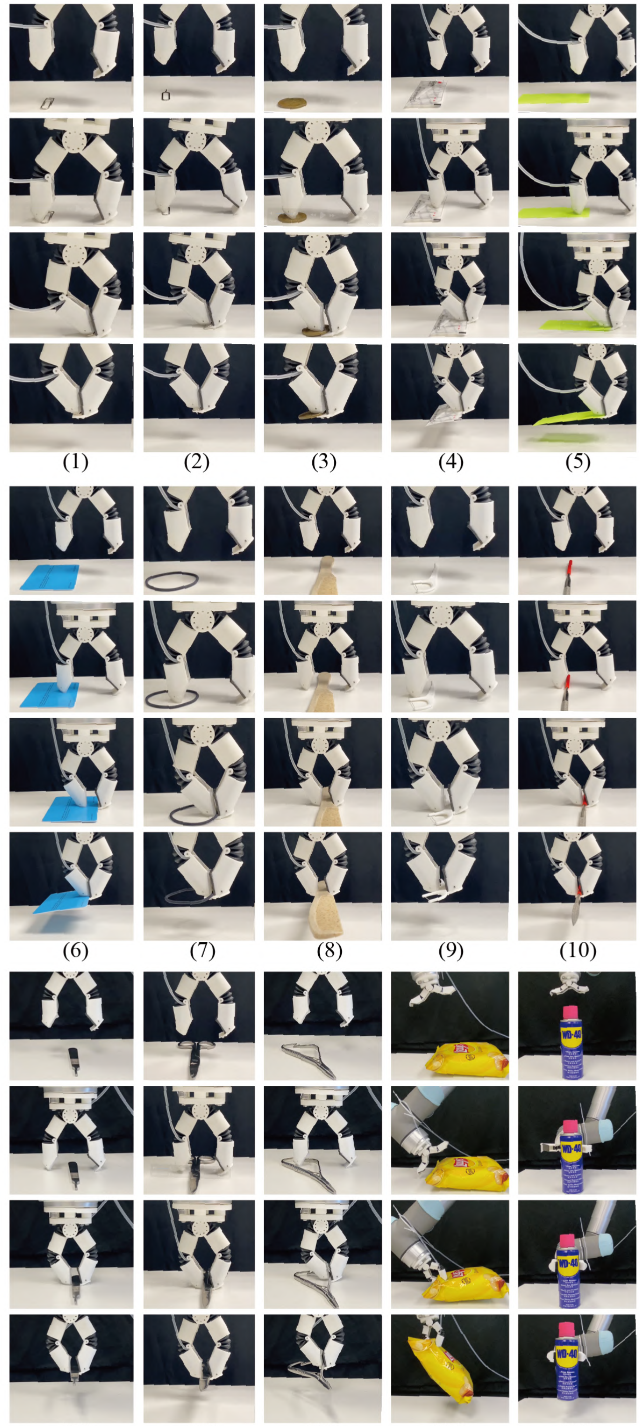


Fig. 7. The experimental snapshots of grasping with the proposed gripper. Sweep mode: (1)-(7), Grip mode: (8)-(15).

C. Grasping Demonstration

Building on the characterized grasping force, which provides insight into the gripper's operational capabilities, we evaluated its practical performance through grasping experiments on 15 common objects (13 of which are very thin and flat) from household, industrial, and medical contexts. The same mini air pump and proportional valve were employed to control actuator inflation during these trials. The gripper was mounted on an UR5 robotic arm, with a calibrated Intel RealSense D435 camera to detect the table height. The objects tested, along with their dimensions and weights, are detailed in Fig. 6 and include items such as paper clips (household), file (industrial), and scalpel handles (medical). As shown in Fig. 7, each object was grasped to calculate the success rate, defined as the object remaining securely held without dropping for 10 seconds while suspended, with the gripper's orientation randomly altered.

D. Ablation Experiments

To further validate the advantages of our soft gripper design, we conducted an ablation study comparing it against a commercial rigid gripper, specifically the OnRobot RG6, which is a two-fingered parallel rigid gripper commonly used in industrial settings. The ablation experiments mirrored the grasping demonstration setup, using the same UR5 robotic arm and Intel RealSense D435 camera. Since the trajectories of RG6 finger tips are arc-like that is, the height of finger tips changes along with the distance between them, we carfully computed the height of the finger tip corresponding to the distance between fingers when the gripper grasps the object to gain more grasping space for RG6 gripper. Grasp poses were generated using our proposed target generation methods (Grip and Sweep), but adapted to the rigid mechanism's limitations—no fingernail structure was available, so Sweep mode relied on friction alone without a scooping wedge. The same 15 flat objects (as detailed in Fig. 6) were tested with partially detailed in Fig. 8, with each grasped ten times under identical conditions: random orientation changes while suspended for 10 seconds. As shown in Table I, the RG6

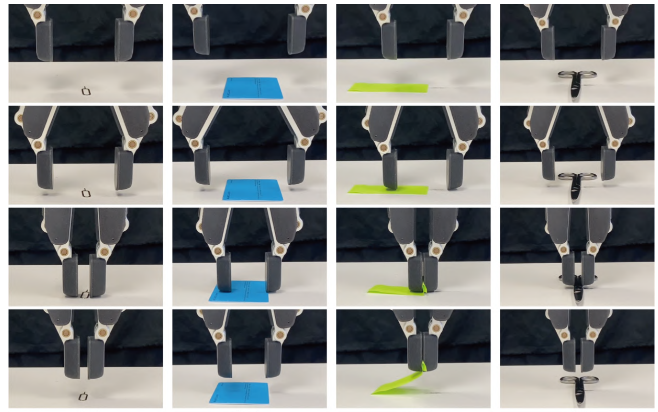
TABLE I
SUCCESS RATE (PER 10 ATTEMPTS)

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RG6	1	0	2	4	2	4	1	5	4	6	2	5	6	10	10
Ours	10	10	8	10	10	6	10	10	10	10	8	10	10	10	7

achieved an average success rate of approximately 41% (62 successful grasps out of 150 attempts), significantly lower than our soft gripper's 92.7% (139/150). Breakdown by object type revealed stark differences: for thin items like paper sheets and credit cards (e.g., Objects 1-5), the RG6 averaged only 18% success, while our soft gripper reached 96% success. For wider medical tools like scalpel handles (e.g., Objects 13-15), the RG6 performed better at 73% but still lagged behind our design's 89%.

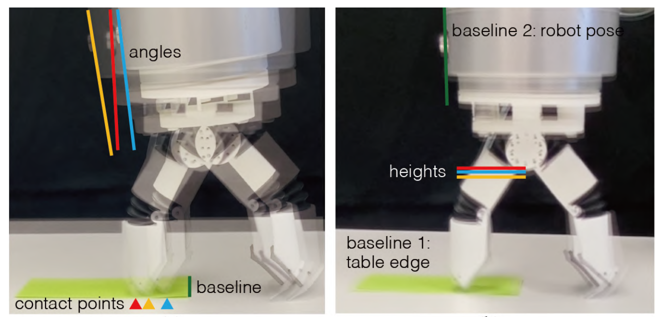
These results highlight the role of compliance and the unilateral fingernail structure in handling flat objects flush with surfaces, where rigid grippers often struggle due to the need for precise height detection and the risk of collisions. For instance, the RG6's lower success on thin items stemmed from slippage and inability to insert under flush objects without damaging the table or object (as shown in Fig. 8), whereas our soft gripper's compliance allowed inaccurate sensory feedback and deformation upon contact, enabling successful graspings (as shown in Fig. 9). Force data from the characterization further confirmed the actuator's compliance, with the 3.2 N maximum force sufficient for stable lifting without precise height detection. This comparison underscores the limitations of rigid grippers in scenarios requiring adaptability, such as grasping flat objects without gaps.

Similar ablation studies in robotics literature have shown that soft grippers outperform rigid ones in compliant interactions with delicate or irregularly positioned objects, particularly for thin materials. For instance, rigid grippers require reliable point cloud data for safe grasping heights, which becomes unreliable below 5 mm accuracy (the accuracy of real-time point clouds), leading to frequent failures in real-world scenarios. Though there are many methods to register point clouds to generate more accurate targets, the enomouse computional time sacrafies the efficiency of real-time manipulation, which is a primary abality in real applications. The ablation confirms that the integration of pneumatic softness with the unilateral fingernail is critical for the observed improvements in success rate, stability, and efficiency, aligning with findings that soft grippers provide superior multi-dimensional compliance for flexible materials.



(a) (b) (c) (d)

Fig. 8. The experimental snapshots of grasping with OnRobot RG6. Graspings fail due to (a) hitting the table (the height is too low), (b) missing the target (the height is too high), (c) wrinkling the paper sheet, (d) the slippery round edges of the scissors.



(a) (b)

Fig. 9. Our gripper has more grasping space duo to its soft compliance. (a) This figure depicts our gripper contacting the paper sheet under three scenarios (using the sheet's right edge as the baseline). It highlights that although real-time point clouds cause variations in the computed approach angles and contact points, our gripper remains effective despite these positional inaccuracies. (b) Thisfigure depicts our gripper contacting the paper sheet under three scenarios (using the table edge and robot pose as the baseline). When the orientation maintains, our gripper has a larger grasping space than rigid grippers due to its soft contact with the table.

V. CONCLUSIONS AND DISCUSSIONS

This paper presents a novel gripper design that integrates a pneumatic soft structure with a unilateral fingernail-like mechanism. This design enables effective and stable lifting of flat objects placed flush on table surfaces, while allowing compliant and safe interaction with the table. It eliminates the need for high-precision object-table height detection, thereby reducing computational cost and time. Furthermore, two grasping strategies—Grip and Sweep—along with corresponding target generation methods are proposed to handle a wide variety of flat object shapes and material properties. Extensive experiments involving common flat objects from household, industrial, and medical scenarios demonstrate the effectiveness, real-time performance, and generalizability of both the gripper design and the grasping strategies.

We found two main limitations of our gripper's gripping force during the study compared to traditional rigid grippers, suction cups, or electromagnetic grippers. In future works, we are going to address the identified limitations by exploring several enhancements to the gripper design and its capabilities. First, to strengthen the gripping force while preserving the soft compliance, we plan to integrate hybrid actuation mechanisms, such as embedding shape-memory alloys (SMAs) or variable-stiffness materials into the pneumatic actuators. This could enable tunable force output, potentially increasing the maximum grasping force from the current 3.2 N to over 10 N without compromising adaptability, allowing the gripper to handle heavier flat objects like metal sheets or medical trays. Second, we intend to develop a modular, controllable detachable nail system using pneumatic attachments at the fingertip. This would permit quick swapping or adjustment of nail angles via remote control, thereby adapting to a broader range of object types, including irregularly shaped items like fabrics, electronics components, or delicate biological samples. Furthermore, we aim to incorporate advanced sensing, such as embedded tactile sensors or AI-driven vision algorithms, for real-time feedback on grasp stability and automatic mode selection between Grip and Sweep. Finally, we will conduct field trials in real-world environments, such as cluttered industrial assembly lines or surgical settings, to evaluate long-term durability and integrate the gripper with autonomous robotic platforms for end-to-end manipulation tasks. These advancements will enhance the versatility and robustness of the system, paving the way for broader adoption in robotics applications.

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