Enhancing Grasping Diversity With a Pinch-Suction and Soft-Rigid Hybrid Multimodal Gripper

Yuwen Zhao, Jiaqi Zhu, Jie Zhang, Siyuan Zhang, Maosen Shao, Zhiping Chai, Yimu Liu, Jianing Wu, Zhigang Wu, and Jinxiu Zhang

***Abstract*—Multimodal grasping has emerged as a promising strategy to enhance the grasping diversity of grippers in response to the rapid expansion of application scenarios. Among various designs, the pinch-suction hybrid mechanism and the soft-rigid hybrid structure have proved to be two practical strategies to achieve multimodality. However, existing research on these two strategies still lacks simple and effective collaborative mechanisms to fully leverage the advantages of each mode while ensuring mutual noninterference. In this article, we propose a pinch-suction and soft-rigid hybrid multimodal gripper (HMG), integrating four operating modes into a compact structure. Two simple and effective collaborative mechanisms are introduced to coordinate between pinch and suction operation and between soft and rigid components, respectively. Through the collaboration of different modes, the HMG exhibits a competitive grasping diversity across four aspects, including weight (from 0.2 g to 10 kg), fragility (from jelly to aluminum profile), size scale (from 0.46 mm to 0.55 m), and shape (from poorly pinchable to poorly suckable). We further demonstrate its adaptability and robustness in handling irregular-shaped objects, and its proficiency in executing complex real-world manipulation tasks, underwater operations, and closed-loop grasping. Its enhanced grasping diversity is poised to accelerate diverse applications in daily life, industrial settings, and underwater scenarios.**

***Index Terms*—Grasping diversity, grasping mechanism, multimodal gripper, soft-rigid design.**

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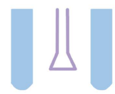
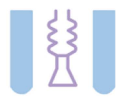
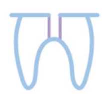
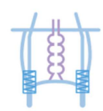
I. Introduction

UNIVERSA grasping is a desirable functionality in robotic manipulation, essential for a wide array of applications spanning industries, logistics, agriculture, and the consumer goods domain [1], [2], [3]. Attaining universal grasping of diverse objects presents a complex challenge, given the varied characteristics of target objects (e.g., weight, fragility, size scale, and shape). Integrating multiple operating modes into a single gripper proves to be an effective means to enhance grasping diversity in some aspects. Previous article has explored various strategies to achieve the multimodality of robotic grippers, with two typical approaches being the combination of multiple grasping mechanisms or the integration of soft and rigid structures [4], [5].

Prominent grasping mechanisms employed in robotic grippers include pinching [6], [7], enveloping [8], [9], coiling [10], [11], suction [12], [13], and adhesion [14], [15]. Each grasping mechanism exhibits its suitability and challenges in handling various objects. For example, enveloping-based grippers are preferred to handle objects of various shapes, excluding the flat items [9], [16]. Grippers utilizing suction mechanism are well-suited for the objects significantly larger in size scale than the grippers themselves, but meet difficulties in picking up porous objects [13]. To apply one robotic gripper across a broader spectrum of scenarios, multiple grasping mechanisms are incorporated into a unified robotic design to enhance its grasping diversity [17], [18], [19], [20], [21], [22]. Among various combinations, the integration of pinching and suction is a complementary and robust method, especially in handling objects in various sizes and shapes, with numerous examples in industry [23].

Parallel with advances in robotic grippers with multiple grasping mechanisms, considerable efforts have also been directed toward the soft-rigid hybrid design, which combine the advantages of both rigid and soft structures, enabling the execution of a wider range of tasks [24]. Traditional rigid grippers possess advantages in terms of high output force and precision, necessitating sophisticated sensing devices and control systems to grasp objects securely [25]. In contrast, soft grippers can actively or passively reconfigure their elastic bodies to accommodate various objects and unstructured environments without requiring highly complicated control strategies [26], [27], [28].

TABLE I
COMPARISON OF DIFFERENT PINCH-SUCTION HYBRID GRIPPERS

Typical gripper	Finger and suction cup integration	Suction cup position	Diagram	Switching strategy	Additional actuators for switching modes	Interference between pinch and suction
[32], [33]	Integrated	Fingertip		No switching strategy	0	High (suction cup impedes the fingers when pinching tiny objects)
[22], [34]	Integrated	Finger pad		Manual (actively adjust finger)	0 / 1	Medium
[35]	Separated	Between Fingers		No / Manual (actively adjust fingers)	0	High (suction cup position limits the size of objects that can be pinched and sucked)
[36]	Separated	Between Fingers		Manual (actively adjust suction cup)	1	Low
[38]	Integrated	Between Fingers		No switching strategy	0	High (suction cup limits the size of objects that can be pinched)
Our design	**Integrated**	**Between retractable fingers**		**Self-adaptive (passively adjust finger and suction cup as needed)**	**0**	**Low**

Blue and purple parts represent the fingers and the suction cups, respectively.

For example, an ultra-gentle soft robotic gripper proposed by Sinatra et al. [29] is capable of grasping delicate marine life such as jellyfish (fragility aspect). Nonetheless, softness provides the soft grippers with compliance and gentleness while diminishing their strength and precision [30], [31]. Integrating rigid and soft components into one gripper may effectively resolve this issue. Soft-rigid hybrid grippers benefit from both structures, offering high load capacity and excellent interaction safety, which allows for a broader operational range in terms of the fragility and weight aspects [5].

The aforementioned strategies exhibit distinct, complementary advantages; therefore, combining these two strategies into a gripper could potentially achieve comprehensive improvements in the grasping diversity, especially across the four aspects of weight, fragility, size scale, and shape. However, efficiently integrating these two strategies into a single gripper while ensuring both compactness and high performance presents a challenging issue, which requires simple and effective coupling mechanisms, that has been seldom explored in previous article.

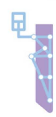
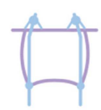
A. Related Work

1) Pinch-Suction Hybrid Grippers: Existing literature identifies four main configurations, including fingertip-integrated suction cup [32], [33], finger pad-integrated suction cup [22], [34], fixed suction cup between fingers [35], and retractable suction cup between fingers [36], [37], as listed in Table I. For grippers with suction-cup-integrated fingers, when the suction cup is located at the fingertip, no additional actions is required to switch between pinching and suction modes. However, the presence of the suction cup impedes the finger from pinching small objects [33]. Conversely, when the suction cup is positioned at the finger pad, the interference between pinching and suction operation can be reduced, but additional manual control is required to adjust the finger to an appropriate angle for the suction cup to contact the object [22]. For grippers that adopt a configuration where suction cup and finger are separate, when the suction cup is fixed, it limits the size of objects the gripper can grasp, and manual adjustment of the fingers may be required for switching between two modes [35]. Although the retractable suction cup can reduce the inference between pinching and suction operations, additional actuators are still required to drive the suction cup to retract for mode switching [36]. In addition to these typical configurations, researchers have proposed other designs that also effectively combine the advantages of pinching and suction. For example, Washio et al. [38] took inspirations from elephant fingers to develop a multimodal soft gripper that with a finger-suction-cup-integrated configuration. While the manual control is not necessary for switching between two modes, the suction cup still limits the size of the objects that can be pinched.

Therefore, for existing pinch-suction hybrid grippers, the challenge lies in ensuring both low-interference between pinching and suction modes and the simplicity of mode-switching strategy.

2) Soft-Rigid Hybrid Grippers: According to Chen et al. [5], the collaboration strategies of the existing soft-rigid hybrid grippers can be categorized into three fashions: rigid-active-soft-passive [39], [40], [41], rigid-passive-soft-active [6], [42], [43], [44], and rigid-active-soft-active [45], [46], [47], as

TABLE II
COMPARISON OF DIFFERENT SOFT-RIGID HYBRID GRIPPERS

Typical gripper	**Active components**	**Components providing active output force**	**Diagram**	**Actuators per finger**	**Holding force range**	**Fragile/ deformable objects**	**Interference between rigid and soft components**
[39]	Rigid	Rigid		1	Up to 30 N	Yes (requiring feedback control)	High (soft structures only have limited passive conformal capability)
[42]	Soft	Soft		1	0.0067 – 7.2 N	Yes	High (rigid structures only have limited structural enhancement capability)
[46]	Rigid and soft	Soft		2	Up to 10 N	Yes	High (rigid structures can only provide on-demand high stiffness and cannot enable operations like powerful pinch)
[47]	Rigid and soft	Soft		2	Up to 90 N	Yes	High (rigid structures can only provide on-demand high stiffness and cannot enable operations like powerful pinch)
[45]	Rigid and soft	Rigid and soft		2	0.001 – 270 N	Yes	Medium (rigid actuators restrict the free motion of the soft ones, requiring additional compensatory air pressure for decoupling)
Our design	**Rigid and soft**	**Rigid and soft**		**1.5**	**0.002 - 100 N**	**Yes**	**Low (soft and rigid actuators can be completely decoupled and both can actively output forces)**

Here, the components providing active output force refers to the element capable of actuating the gripper to deform and grasp, while the stiffness-modulating components can only provide passive output force after the deformation is complete. Purple and blue parts represent the soft and the rigid components, respectively.

listed in Table II. Grippers employing a rigid-active-soft-passive collaboration strategy demonstrate an extended holding force range compared with soft grippers but still face challenges when grasping diverse fragile objects [39]. The benefit of soft structures, particularly compliance and adaptability, are somewhat limited during passive interaction process. Conversely, the rigid-passive-soft-active hybrid grippers are capable of grasping various fragile objects without the need for close-loop control, but meet difficulties in achieving a high load capacity, because of the inherent softness of the active components [42]. Therefore, more attention has recently been focused on the rigid-active-soft-active grippers. The most common examples are to incorporate stiffness-modulating mechanisms such as ratchets and endoskeletons into soft fingers, thereby enhancing their load capacity while maintaining the inherent advantages of soft structures [46], [47]. However, in these designs, the rigid structures are only employed to provide passive structural stiffness, rather than active gripping force. In other words, the rigid structures cannot actively actuate the gripper to deform and grasp, which prevents the gripper from exerting operations such as powerful pinching, active manipulation, etc. Our previous article proposed a rigid-active-soft-active hybrid gripper that both two components can provide active output force, which demonstrate a wider grasping range in weight and fragility aspects [45]. However, in this design, the soft and rigid actuators cannot be fully decoupled, and the rigid ones restrict the free motion of the soft ones. Additional compensating air pressure is needed to weaken their interference with each other.

Therefore, for existing soft-rigid hybrid grippers, the challenge persists in fully combining the advantages of rigid components, such as high output force and stiffness, with that of the soft ones, such as excellent gentleness and compliance, within a compact structure, while ensuring complete decoupling between them.

To date, both the aforementioned strategies still require further development of effective collaborative mechanisms to fully exploit the advantages of each mode while ensuring noninterference among them. Also, research exploring simultaneous combination of pinch-suction hybrid mechanism and the soft-rigid hybrid configuration to significantly expand a single compact gripper's grasping diversity remains limited. This is likely due to considerable challenging of achieving this goal in a compact system that relies on current collaborative mechanisms, which have difficulty in balancing simplicity and effectiveness.

B. Contributions

To solve these issues, herein, we introduce a hybrid multimodal gripper (HMG) that combines a pinch-suction hybrid mechanism with a soft-rigid hybrid structure, demonstrating excellent grasping diversity. Two simple and effective collaborate mechanisms, namely, compliant self-adaptive mechanism and selectively activated mechanism (SAM), are introduced to coordinate between pinch and suction operations and between soft and rigid components, respectively. The HMG consists of a rigid actuation system (RAS), a soft actuation system (SAS),

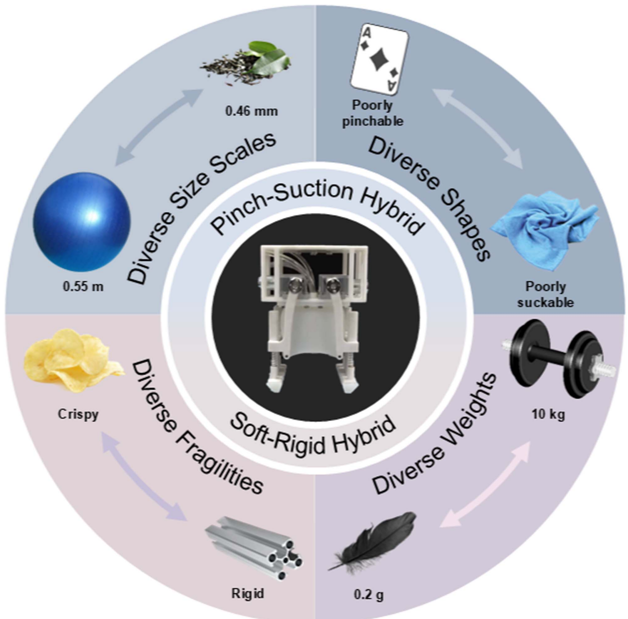


Fig. 1. Combining the advantages of both pinch-suction hybrid mechanism and the soft-rigid hybrid structure, the hybrid multimodal gripper (HMG) exhibits an extensive grasping diversity in four aspects. The pinch-suction hybrid mechanism mainly empowers the HMG to handle objects across diverse size scales and shapes, while the soft-rigid hybrid structure mainly endows the HMG with the capability to grasp objects exhibiting a broad spectrum of fragilities and weights.

and a pair of retractable fingers. By actuating RAS and SAS separately or cooperatively, the HMG can operate in four distinct operating modes, including robust pinch, gentle pinch, suction, and hybrid mode. These modes can bestow the HMG with extended grasping diversity in handling a spectrum of objects vary in these four aspects (namely, weight, fragility, size scale, and shape, as shown in Fig. 1), and good robustness and adaptability in handling irregular-shaped objects. Moreover, through the sequential collaboration of distinct modes, the HMG also demonstrates its strong ability for undertaking complex real-world manipulation tasks, such as book organizing, milk service, and rib soup cooking. In addition, we further showcase the HMG's potential in underwater applications and sensor-based closed-loop grasping.

The main contributions of this article are summarized as follows.

1) Propose a simple and effective compliant self-adaptive mechanism which can adaptively switch between pinch and suction modes and fully utilize the respective advantages of these modes without the need for additional actuators or active control operations.
2) Propose a simple and effective SAM that well combines the respective advantages of rigid and soft structures and realizes the full decoupling between them.
3) Demonstrate an HMG based on the two mechanisms, which integrates a pinch-suction mechanism and a soft-rigid configuration simultaneously in a compact design, featuring four distinct operating modes, including robust pinch, gentle pinch, suction, and hybrid modes.
4) Experimental evaluation of the HMG for its excellent grasping diversity, especially in weight, fragility, size scale, and shape aspects, good robustness, and adaptability in handling irregular-shaped objects, strong capability in undertaking real-world manipulation tasks, and potential in underwater operation and closed-loop grasping.

C. Outline

The rest of the article is organized as follows. In Section II, the concept design of the multimodal operation and the design of two collaborative mechanisms for smooth switching between pinch and suction operations and between soft and rigid actuators are introduced, along with the detailed description of the structural design. In Section III, mathematical models are developed to describe the fingertip motion, pinching force, and suction force. Section IV presents the experimental characterization of performance of the gripper, including deformation characteristic, pinching force, adsorption force, and success rate of grasping objects in diverse size scales and changing thicknesses. Section V demonstrates its excellent grasping diversity, good robustness, and adaptability in handling irregular-shaped objects, and its capabilities of conducting real-world manipulation tasks, underwater operations, and closed-loop grasping. Finally, Section VI concludes this article.

II. Mechanical Design

A. Multimodal Operation Design

Here, we propose an HMG, consisting of two actuation systems: RAS and SAS, along with a pair of retractable fingers. The RAS and SAS can be activated independently or cooperatively, providing us possibilities to address varying needs by only adjusting the actuation logic. Here, we introduce four operating modes of this compact design to deal with different grasping tasks (Fig. 2), which are as follows.

Mode 1 (Robust pinch mode): By activating the RAS alone, the gripper can exhibit a robust pinch mode. This mode empowers the gripper to generate substantial output force, enabling it to grasp and lift rigid and heavy objects, for example, a dumbbell.

Mode 2 (Gentle pinch mode): When applying negative pressure P_1 to the soft chamber of the SAS, the deformation of the chamber can actuate the fingers to gently close, representing a gentle pinch mode. The gripper in this mode is preferable for handling delicate and lightweight objects, such as a strawberry or a cake.

Mode 3 (Suction mode): To pick up small-scale objects such as drug capsules, or larger objects exceeding the pinchable dimension of the fingers like basketball, or objects with shapes challenging to handle using pinch motion (e.g., flat objects like playing card), we can switch the gripper to a suction mode by applying negative pressure P_2 through the suction cup of SAS, thus generating inlet airflow.

Mode 4 (Hybrid mode): In addition to their individual operability, the preceding three operating modes can collaboratively engage in a sequential or simultaneous manner, enabling the gripper to handle objects that are challenging for a single mode.

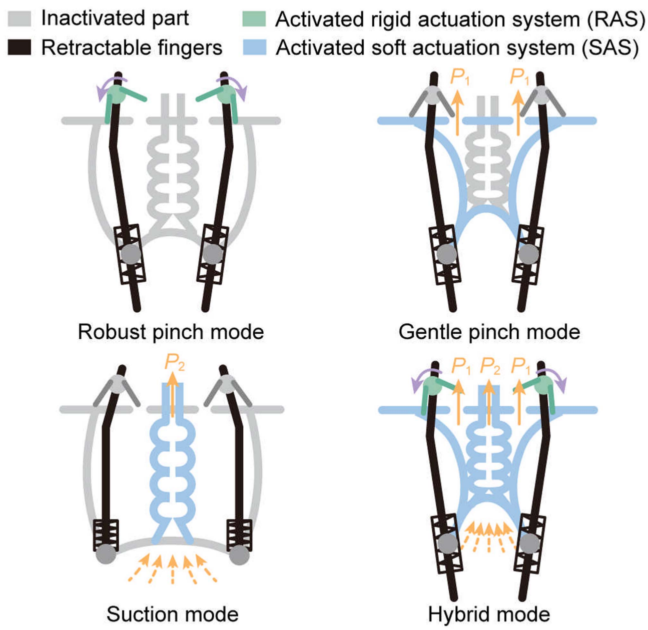


Fig. 2. Concept design of the pinch-suction and soft-rigid hybrid multimodal gripper (HMG). Schematics of the multiple operating modes of the HMG. The light grey markers indicate the inactivated parts, whereas the markers in other colors indicate the activated parts.

Two typical combinations include sequential gentle pinch and robust pinch as well as simultaneous pinch and suction. The former allows the HMG to efficiently grasp fragile and heavy objects like tofu, while the latter allows the HMG to securely grasp some hard-to-grip and heavy objects, such as ice cubes with slippery surfaces.

B. Selectively Activated Mechanism (SAM)

To well combine the respective advantages of RAS and SAS and realize the full decoupling between them, we introduce a simple and effective SAM within the RAS, as shown in Fig. 3(b1). When the SAM is configured as depicted in Fig. 3(b2), inward rotation of the motors can drive the fingers to pinch (the soft chamber is inactivated at this moment). This is because the V-shaped baffles of the sleeve couplings fixed to the motor shafts can push the fingers to rotate when they are in contact with the spines of the shafts fixed to the fingers. In contrast, in the SAM arrangement illustrated in Fig. 3(b3), the sleeve couplings provide sufficient margin for the shafts fixed to the fingers to rotate inward under the actuation of the soft chamber, thus avoiding interference with the gentle pinch mode. Hence, by adjusting the SAM, we can achieve completely independent operation of both soft and rigid actuators, thus allowing them to take full advantage of their respective strengths.

C. Compliant Self-Adaptive Mechanism

To fully exploit the respective advantages of pinch and suction operations and realize convenient mode switching, we introduce a simple and effective compliant self-adaptive mechanism composed of a pair of passively retractable fingers and a soft

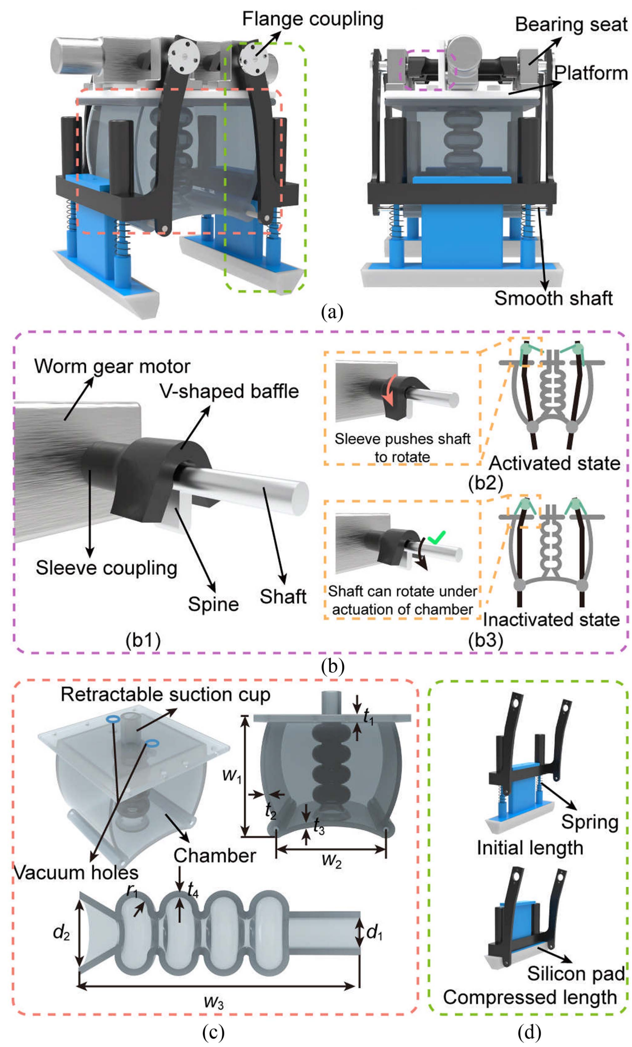


Fig. 3. Structural design of the HMG. (a) Overall structure. (b) Rigid actuation system (RAS). (b1) Composition of RAS. (b2–b3) Configurations of the selectively activated mechanism (SAM) when the chamber is in activated state and inactivated state, respectively. (c) Soft actuation system (SAS). (d) Passively retractable finger. The finger can be compliant compressed to allow the suction cup to make contact with the target surface.

retractable suction cup, as shown in Fig. 3(c) and (d). When the gripper pinches a tall object, the extended fingers allow firm contact between the fingers and the objects, and the inherent softness and bellows-like structure of the suction cup also allow it to passively adapt to the object, thereby reducing interference with the pinch operation. When need to employ the suction cup to pick a flat object, the fingers can passively compress their length, allowing the suction cup to be sufficiently close to the surface of the target objects to generate enough suction force. This compliant mechanism endows the gripper with the ability to adaptively switch between pinch and suction modes without the need for additional actuators or active control operation, significantly reducing system complexity. Here, the springs with a wire diameter of 0.6 mm and an outer diameter of 10 mm are chosen to be inserted into the retractable fingers. The selection of the springs of the fingers can be found in Fig. A2 and "*Selection of Finger Springs*" section in Appendix.

TABLE III
PERFORMANCE PARAMETERS OF HMG

Performance parameter	Value
Response time of the SAS	~0.4 s
Lifetime of the SAS	No less than 6000 cycles
Intermodal switching time	~0.5 s

D. Structural Design

The overall structure of the HMG is demonstrated in Fig. 3(a) and Supplementary Video S1, and its actuation system is shown in Fig. A1. The RAS and SAS are fixed to an assembly platform with bearing seats and bolts, and are coupled with retractable fingers through flange couplings and smooth shafts, respectively. The RAS is mainly designed to accurately control and provide sufficient bearing loads to the pinch motion. Therefore, the worm gear motors (JG370-2460, speed: 6 r/min, rated torque: 25 kgf·cm) with high torque, high precision, and the ability to lock when powered off are selected as power sources [48]. The SAM consists of four sleeve couplings with V-shaped baffles fixed with the output shafts of the motors and shafts with splines fixed with the fingers. The two kinds of components can contact with each other by rotating to transmit mechanical forces. To fabricate the RAS, the shafts and the sleeve couplings are three-dimensional (3-D)-printed using stainless-steel powder materials and high-performance resin, respectively.

As a crucial part, the SAS enables the gripper to achieve gentle operations, including gentle pinch and suction. As shown in Fig. 3(c), the SAS consists of a soft chamber and a retractable suction cup passing through the center of the chamber, forming two independent air pathways. The chamber forms a sealed soft structure so that it undergoes contraction under negative pressure and recovers under atmospheric pressure. Pumping air from the chamber induces its side and bottom surfaces to contract inward, compressing the internal suction cup. It is worth noting that the longitudinal compressibility of the suction cup may affect the deformation of the chamber. To reduce its adverse effects, here, the soft suction cup is designed to be a foldable configuration, akin to a bellow [49], [50], [51]. The fabrication process of SAS can be found in Fig. A3 and "*Fabrication of Soft Actuation System (SAS)*" section in Appendix. The fingers are the components responsible for executing pinching motion, which need to withstand large loads; therefore, high performance nylon is selected to fabricate the fingers with a selective laser sintering 3-D printer (EOS P396E, EOS, Germany). The fingertips are designed as rectangular rather than circular areas like human fingertips to ensure that the center of gravity of most items remains within the length range of the fingertips during grasping. In addition, the fingertips are covered with silicone pads made with Dragon-skin 30 to increase the contact area and enhance the friction between the fingertips and objects. The performance parameters of the HMG are listed in Table III. The result of the lifecycle experiment on SAS can be found in Fig. A4.

TABLE IV
GEOMETRIC DIMENSIONS OF SOFT ACTUATION SYSTEM

Parameter	Value	Parameter	Value
Height of the soft chamber, w_1	86 mm	Bottom wall thickness of the soft chamber, t_3	3 mm
Spacing between the smooth shaft holes, w_2	80 mm	Radius of the bellows-like structure of the suction cup, r_1	5 mm
Length of the suction cup, w_3	106 mm	Diameter of the suction cup outlet, d_1	10 mm
Top wall thickness of the soft chamber, t_1	5 mm	Diameter of the suction cup inlet, d_2	26 mm

E. Parameter Design of SAS

To effectively perform both gentle pinch and suction functions, the SAS needs to meet the following requirements.

1) *Gentle pinch functionality:* The effective deformation of the soft chamber under the negative pressure should be large enough to ensure better closure of the fingers.
2) *Suction functionality:* The bellows-like structure of the suction cup should have a relatively low stiffness to avoid obstructing the deformation of the soft chamber and affecting the pinch functions. Meanwhile, it is also required to have sufficient stiffness to avoid structural collapse during vacuum adsorption.

To achieve these requirements, we first determine the overall geometric dimensions of the SAS according to the dimensions of the worm gear motor ($80 \times 60 \times 32$ mm), as listed in Fig. 3(c) and Table IV. Then, we focus on analyzing the effect of two key parameters: the side wall thickness t_2 of the soft chamber and the wall thickness t_4 of the suction cup on the deformation of the SAS. Due to the SAS being made of silicone rubber, the hyperelasticity of the material poses significant challenges for precise modeling. Therefore, we employ finite-element analysis (FEA) to investigate the deformation of SAS. The details of the FEA setting can be found in "*Finite Element Analysis Experiment Setup*" section in Appendix.

To investigate the effect of varying side wall thickness t_2 of the soft chamber on the deformation of SAS, the suction cup wall thickness t_4 is set constant to 2.5 mm, and t_2 varies from 2 to 4 mm. The FEA results under a pinch pressure of -3 kPa are shown in Fig. 4(a). We classify the deformation of the SAS into two directions: horizontal and vertical. The horizontal deformation helps the fingers to close for pinch function, thus considered effective deformation. The variation of deformation in both directions with pinch pressure is shown in Fig. 4(b). The results demonstrate that when $t_2 = 2$ mm, the horizontal distance stabilizes to ~55 mm when pressure reaches -1.5 kPa, and further increasing the negative pressure induces vertical deformation. Conversely, when $t_2 = 4$ mm, although the deformation remains primarily horizontal throughout the negative

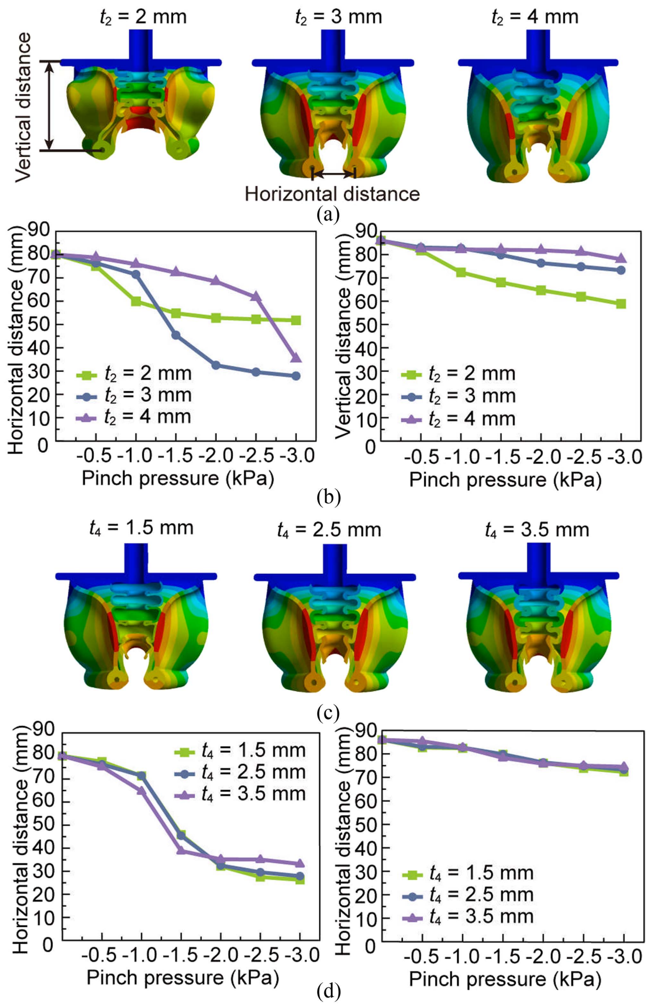


Fig. 4. Finite-element analysis (FEA) of SAS. (a) Deformation of SAS with constant $t_4 = 2.5$ mm and varying $t_2 = 2, 3, 4$ mm, respectively, under a pinch pressure of -3 kPa. (b) Horizontal and vertical distances of the SAS with different t_2 related to the pinch pressure. (c) Deformation of SAS with constant $t_2 = 3$ mm and varying $t_4 = 1.5, 2.5, 3.5$ mm, respectively, under a pinch pressure of -3 kPa. (d) Horizontal and vertical distances of the SAS with different t_4 related to the pinch pressure.

pressurization, its horizontal deformation is smaller compared to that with $t_2 = 3$ mm at the same pressure. Therefore, $t_2 = 3$ mm is selected as the final side wall thickness of the soft chamber.

We then set t_2 constant to 3 mm and vary t_4 from 1.5 to 3.5 mm to investigate the effect of varying suction cup wall thickness t_4 on the deformation of SAS. The FEA results under a pinch pressure of -3 kPa are shown in Fig. 4(c). The variation of deformation in both directions with pinch pressure is shown in Fig. 4(d). The results demonstrate that when the suction cup wall thickness is relatively large (e.g., $t_4 = 3.5$ mm), the effective deformation of the SAS under the same pressure is reduced. Specifically, when $t_4 = 3.5$ mm, the horizontal distance stabilizes to $\sim$35 mm when pressure reaches -2 kPa. In contrast, when $t_4 = 1.5$ and 2.5 mm, the minimal horizontal distance can reach $\sim$27 mm. Here, it is observed that the deformations for $t_4 = 1.5$ and 2.5 mm are nearly identical. To provide the suction cup with sufficient strength to resist potential collapse under vacuum suction, we select $t_4 = 2.5$ mm as the final wall thickness parameter for the suction cup.

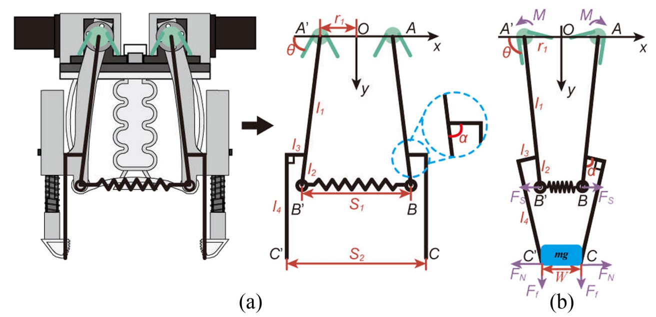


Fig. 5. Kinematic and force analysis of the gripper driven by the rigid actuation system (RAS). (a) Kinematic model of the gripper. (b) Force analysis of simplified gripper mechanism driven by motors.

III. Modeling Analysis

A. Fingertip Motion Analysis

Benefiting from its hybrid structure, the HMG can be modeled analytically from its rigid kinematics. The gripper mechanism can be simplified as shown in Fig. 5(a). When the V-shaped baffle of the sleeve coupling is in contact with the shaft in SAM, the rotation angle of the motor shaft (denoted as θ) is aligned with the angle between the inclined beam of the finger $A'B'$ and the x-axis. Thus, any inward rotation of the motor shaft will immediately drive the finger to rotate. The distance between the two points where SAS is coupled to the fingers S_1 and the distance between the fingertips S_2 can be expressed as

$$\begin{cases} S_1 = 2[r_1 + (l_1 + l_2)\cos\theta] \\ S_2 = 2[r_1 + l_1\cos\theta + l_3\cos(\theta-\alpha) - l_4\sin(\theta-\alpha)] \end{cases} \tag{1}$$

where r_1 is distance from the pivot axis A to the coordinate origin O; $l_1 = 87$ mm, $l_2 = 22$ mm, $l_3 = 13$ mm, and l_4 represent the length of each part of the fingers, among which l_4 is passively adjustable in this design; $\alpha = 83^\circ$ represents the angle between the transverse beam and inclined beam of the finger [see the subfigure in Fig. 5(a)]. Equation (1) reveals the relationship between the motor angle θ and the fingertip distance S_2 when the gripper is driven by RAS.

B. Force Analysis

We first focus on the pinching force of HMG generated by the motors of RAS; therefore, a mechanical model is built to describe the relationship between the driving torque and the pinching force of the gripper, as illustrated in Fig. 5(b). The pinching force F_N can be calculated as

$$F_N = \frac{M - k_S\Delta S_1(l_1+l_2)\sin\theta - \frac{mg}{2}\left(\frac{W}{2} - r_1\right)}{l_1\sin\theta + l_3\sin(\theta-\alpha) + l_4\cos(\theta-\alpha)} \tag{2}$$

where M denotes the output torque of the motor; ΔS_1 denotes the change in the distance between the two smooth shafts; k_S, m, and g are the equivalent stiffness of SAS, the weight of the object, and the acceleration due to gravity, respectively; and W denotes the width of the object. Full derivation process and experimental validation can be found in Fig. A5 and "*Pinching Force Analysis during Robust Pinch*" section in Appendix.

The suction cup can produce strong suction under the air actuation generated by a vacuum pump. The suction is characterized by two factors: the inhale force exerted on an object when not in contact with it (F_{inhale}) and the adsorption force when the object contacts with the suction cup and forms a sealed space (F_{ads}), which can be calculated as

$$\begin{cases} F_{\text{inhale}} = \frac{d_1^4}{256L_O^4} P_{\text{out}} A \\ F_{\text{ads}} = \Delta P S \end{cases} \tag{3}$$

where L_O is the distance between the object and suction cup, P_{out} is the air pressure at the outlet of the suction cup, A denotes the area of one surface of the object, and ΔP and S denote the differential pressure and the contact area of the suction cup with objects, respectively. Full derivation process and experimental validation can be found in Fig. A6 and "*Suction Force Analysis*" section in Appendix.

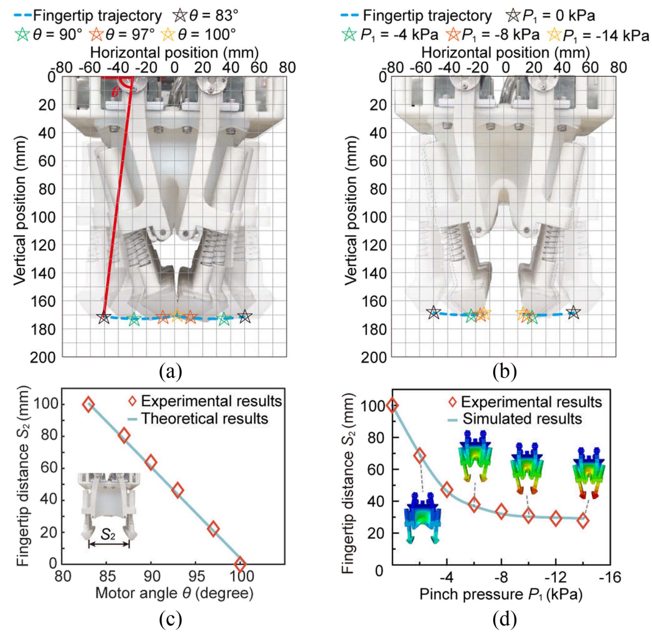


Fig. 6. Deformation characteristics. Fingertip trajectories of gripper (a) driven by RAS and (b) SAS, respectively. (c) Relationship between motor angle θ and fingertip distance S_2. (d) Relationship between pinch pressure P_1 and fingertip distance S_2.

IV. Experimental Characterization

A. Deformation Characteristics

Capturing the kinematic properties of robotic grippers has consistently held significance in revealing their working principles. In this section, we quantify the deformation characteristics of the gripper driven by RAS and SAS, respectively. The gripper is affixed to a framework, and a camera (FDR-AX60, Sony, Japan) is employed to record its deformation under varying motor angle θ or pinch pressure P_1. The fingertip trajectories are depicted in Fig. 6(a) for RAS and 6(b) for SAS, with the coordinate origin set at the midpoint between the axes of rotation of the two fingers. The gripper in robust pinch mode initiates with a motor angle of $\theta = 83°$ and the two fingers fully close when the motor angle reaches 100°. When driven by the SAS, the gripper cannot completely close, as the compression of the suction cup results in increased stiffness, preventing further contraction to drive the fingers.

Then, we focus on the variation in fingertip distance, which determines the size of objects the HMG can handle in pinch mode. The correlation between the motor angle θ and fingertip distance S_2 is illustrated in Fig. 6(c). The analytical and experimental results align well, and the relationship can be aptly represented as linear, highlighting the straightforward control of fingertip distance in the gripper's robust pinch mode. FEA is then conducted to simulate the deformation performance under different pinch pressure P_1. In Fig. 6(d), we compare the simulated and experimental results, finding a good coincidence. The fingertip distance of the gripper in gentle pinch mode can be predicted using the relationship between the pinch pressure P_1 and fingertip distance S_2 as follows:

$$S_2(mm) = 73.4e^{P_1(\text{kPa})}/3.3 + 27.1. \tag{4}$$

This relation can be employed to estimate the requisite applied pressure P_1 for objects of varying sizes. For the current version of our gripper, the minimum fingertip distance in gentle pinch mode can reach 28 mm (28% of the initial distance), and can already perform most of the common operations. In the future, we will further optimize the parameters of SAS to allow the fingers to close completely in this mode. The simulated and experimental results demonstrate that the fingertip distance of the gripper is highly predictable in both robust and gentle pinch modes, which is crucial for the implementation of closed-loop control in the following operations. Moreover, the use of effective simulation tools can provide valuable prior reference data for applying our HMG in new unstructured environments or executing challenging tasks.

B. Pinching Force During Gentle Pinch

To investigate the grasping capabilities of the gripper in gentle pinch mode, we quantitatively evaluate its pinching force when handling cylinder with diameters ranging from 50 to 80 mm, applying negative pinch pressure P_1 within the range of -5 to -15 kPa. As illustrated in Fig. 7(a), a flexible force sensor (FlexiForce B201, range: 111N, Tekscan Inc., USA) is attached to the surface of the cylinder to capture the pinching force exerted on the cylinder, while the negative pinch pressure P_1 is controlled by a regulator (IRV20-02, ZPCAC, China). Detailed experimental settings can be found in Fig. A7. Experimental results indicate that, in gentle pinch mode, the pinching force increases with the negative pinch pressure P_1 and the diameter of the objects [see Fig. 7(b)]. The maximum pinching force can reach 26.3±3.0 N under $P_1 = -15$ kPa when pinching a cylinder with 80 mm diameter. In addition, the pinching force of the gripper in robust pinch mode is associated with the torque of the motor and can be calculated with (2).

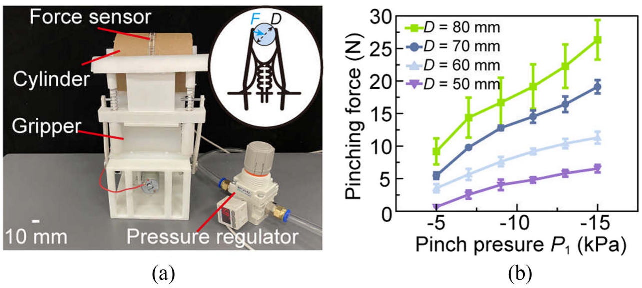


Fig. 7. Pinching force characterization in gentle pinch mode. (a) Experimental setup for measuring the pinching force. (b) Pinching force to cylinders with various diameters related to the pinch pressure P_1.

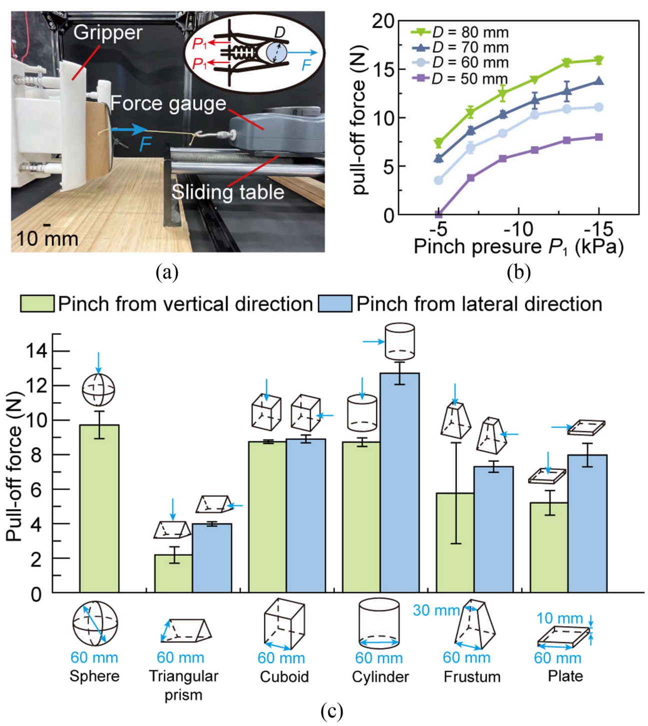


Fig. 8. Pull-off force characterization in gentle pinch mode. (a) Pull-off force measurement setup. (b) Pull-off force at changing pressures for three diameters of cylinders. (c) Histograms of horizontal pull-off force versus the shape of the object.

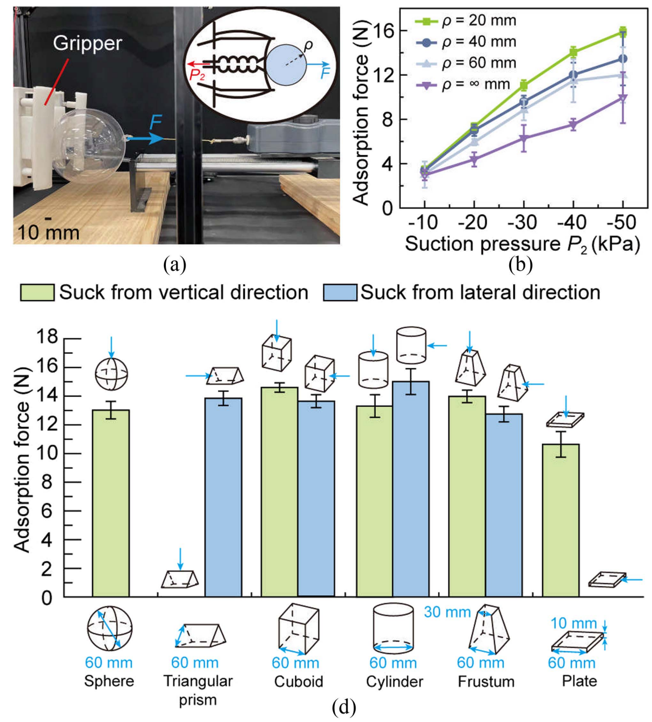


Fig. 9. Adsorption force characterization. (a) Experimental platform for the adsorption force. (b) Adsorption force versus the curvature radius of the object surfaces at different suction pressures. (c) Histograms of adsorption force versus the shape of the object.

C. Pull-Off Force During Gentle Pinch

To evaluate the load capability of the gripper in the gentle pinch mode, we first experimentally measure the pull-off force by horizontally pulling the cylinder with varying diameters. The peak force displayed by the force gauge is the pull-off force. In Fig. 8(b), we observe that the pull-off force is highest for the 80-mm diameter cylinder, reaching 15.9±0.4 N under $P_1 = -15$ kPa. This can be attributed to the fact that, with a larger cylinder, the gripper generates a greater pinching force, resulting in increased friction.

We then measure its pull-off force for objects with diverse shapes under a pinch pressure of $P_1 = -15$ kPa, as demonstrated in Fig. 8(c). Experimental results show that all six shapes of objects can be grasped by the gripper flexibly in the gentle pinch mode both from the vertical and lateral directions. The highest pull-off force is observed when grasping a cylinder laterally (12.7±0.7 N), because the gripper wraps around the cylinder, providing a pinching force to resist the pull-off force. Conversely, the pull-off force is the lowest when vertically grasping a triangular prism (2.2±0.5 N) due to the small contact area between the object and the gripper. In addition, the pull-off force of the gripper in robust pinch mode is related to the maximum load the rigid parts of the gripper can withstand, which is determined by the structural strength of rigid structures.

D. Adsorption Force in Suction Mode

The suction mode facilitates the gripper in handling smooth, flat, and curved objects, leveraging the self-adaption and adsorption functions of suction cup. We here experimentally measure the adsorption force on objects with varying curvature radius ρ. As shown in Fig. 9(a), the adsorption force is characterized as the force that enables peeling the contacting object from the suction cup. We prepare three hollow plastic balls with ρ ranging from 20 to 60 mm and a plastic plate ($\rho = \infty$ mm) for experiments. Fig. 9(b) demonstrates that for an object with a certain value of ρ, the adsorption force increases with the negative suction pressure P_2. Moreover, under the same suction pressure P_2, the gripper exhibits a greater adsorption force on objects with smaller curvature radius ρ. For instance, when applying a suction pressure of -50 kPa, the adsorption force on the sphere with

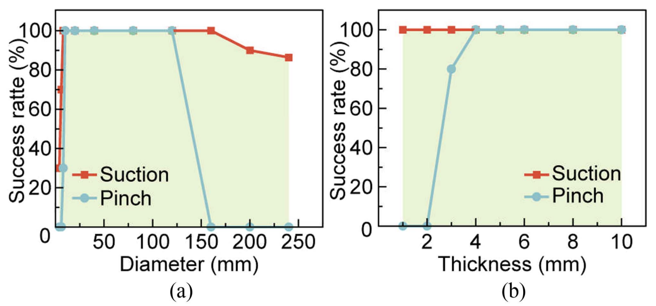


Fig. 10. Gripper grasps objects in diverse scales and changing thicknesses. Success rate of grasping (a) spheres in diameters ranging from 4 to 240 mm and (b) cards in thicknesses ranging from 1 to 10 mm.

$\rho = 20$ mm (15.9±0.4N) is 1.6 times greater than that on the plate with $\rho = \infty$ mm (9.9±2.3N). The reason is that the suction cup can generate a larger negative pressure area with object of smaller curvature radius.

We then evaluate its adsorption force on objects with different shapes at $P_2 = -50$ kPa. As demonstrated in Fig. 9(c), the gripper generates similar adsorption forces when sucking the object in an identical shape from different directions, with a maximum difference of only 1.7 N (for the cylinder), except for the triangular prism and flat plate. The gripper in suction mode encounters challenges in vertically lifting the triangular prism or horizontally picking up the flat plate. This arises from the limited contact area between the object and the suction cup, impeding the formation of a sealed negative pressure space—an issue commonly encountered by all suction-based grippers. Comparing Figs. 8(c) and 9(c), we can observe that the gripper in gentle pinch mode is versatile in handling objects with various shapes, while utilizing suction mode the gripper meets difficulties in dealing with objects with small adsorption surfaces.

E. Success Rate of Grasping Objects in Diverse Size Scales and Changing Thicknesses

Owing to scaling laws, grippers face challenges in cross-scale manipulating various objects. To investigate the grasping capabilities of the HMG on objects across a range of size scales, we perform experiments on grasping hollow plastic spheres with diverse sizes. The diameters of these spheres vary from 4 to 240 mm, corresponding size scales that are 0.04 times to 2.4 times the maximum grasping width of our gripper (100 mm). The experimental setup and the control flow of the 6-DoF robotic arm (ZU 7, JAKA, China) used to fix the gripper, are illustrated in Fig. A8(a), (b), and (c). Here, we calculate the success rate of grasping these spheres 10 times each using pinch and suction, respectively. As demonstrated in Fig. 10(a), the gripper exhibits a more reliable capability to grasp both the tiny objects (diameter below 10 mm) and the large objects (diameter exceeding 120 mm) when employing suction.

Furthermore, handling thin flat items on the ground poses an additional challenge for the existing soft grippers. Here, we evaluate the effectiveness of the HMG in terms of its success rate in an additional challenge for the existing grippers. Humans always adopt a flipping strategy for grasping thin objects, that elevating one side of the object before ultimately pinching it. However, transposing this strategy onto robotic manipulators necessitates the incorporation of finger-like joint designs and intricate control mechanisms [52]. Here, we evaluate the effectiveness of the HMG in terms of grasping thin, sheet-like objects through pinch or suction methods solely. We prepare a class of thin flat cards with uniform dimensions of 60 mm in width and length, yet exhibiting thickness variations ranging from 1 to 10 mm. The experimental setup remains consistent with the preceding experiment, and the control flow of the robotic arm and the applied pressure is delineated in Fig. A8(d) and (e). The grasping is repeated 10 times for each card thickness. The results presented in Fig. 10(b) reveal that, for card thicknesses below 4 mm, the gripper achieves more reliable grasping when utilizing suction compared to pinching. This phenomenon arises from the curved trajectories of fingertips when the gripper operates in pinch mode. As they approach the card, the elevation of the fingertips hinders effective contact with thinner cards.

V. Grasping Demonstration

A. Grasping Diversity

The inherent compliance of the soft structure (soft chamber and retractable suction cup) empowers the HMG to gently contact with diverse fragile objects through its gentle pinch and suction modes, thus greatly broadening the gripper's capability to securely handle lightweight and delicate items; whereas the complementary rigid mode, namely, robust pinch mode, markedly enhances its proficiency in grasping weighty and rigid objects. Hence, the soft-rigid hybrid configuration can endow the HMG with an extensive range of grasping objects with diverse weight and fragility. Moreover, with regard to size scale and shape aspects, the pinch-based grasping mechanism proves suitable for middle sized objects (relative to the maximum open width of the HMG) and objects of various shapes, excluding those that are poorly pinchable such as flake and inverted cone. Meanwhile, the suction-based grasping mechanism is preferable for grasping varying sized objects (especially small and large-sized objects), as well as those with smooth, flat, and curved shapes, except for some poorly suckable shapes such as porous and spiny objects. Therefore, the multiple grasping mechanisms, pinch and suction, complement each other, endowing the HMG with a wide-range graspable objects across the aspects of size scale and shape.

Harnessing the multimodality, we further showcase the enhanced grasping diversity of the HMG in grasping a spectrum of objects varying in weights, fragilities, size scales, and shapes, as exemplified in Fig. 11 and Supplementary Movie S2. The dimensions and the weight of the tested objects are listed in Table AI.

First, as depicted in Fig. 11(a), the HMG exhibits the ability to grasp a wide range of objects in the weight aspect, ranging from a lightweight feather (0.2 g) utilizing a gentle pinch to a 10-kg dumbbell employing robust pinch. Notably, due to the self-locking functionality inherent in the worm gear motors,

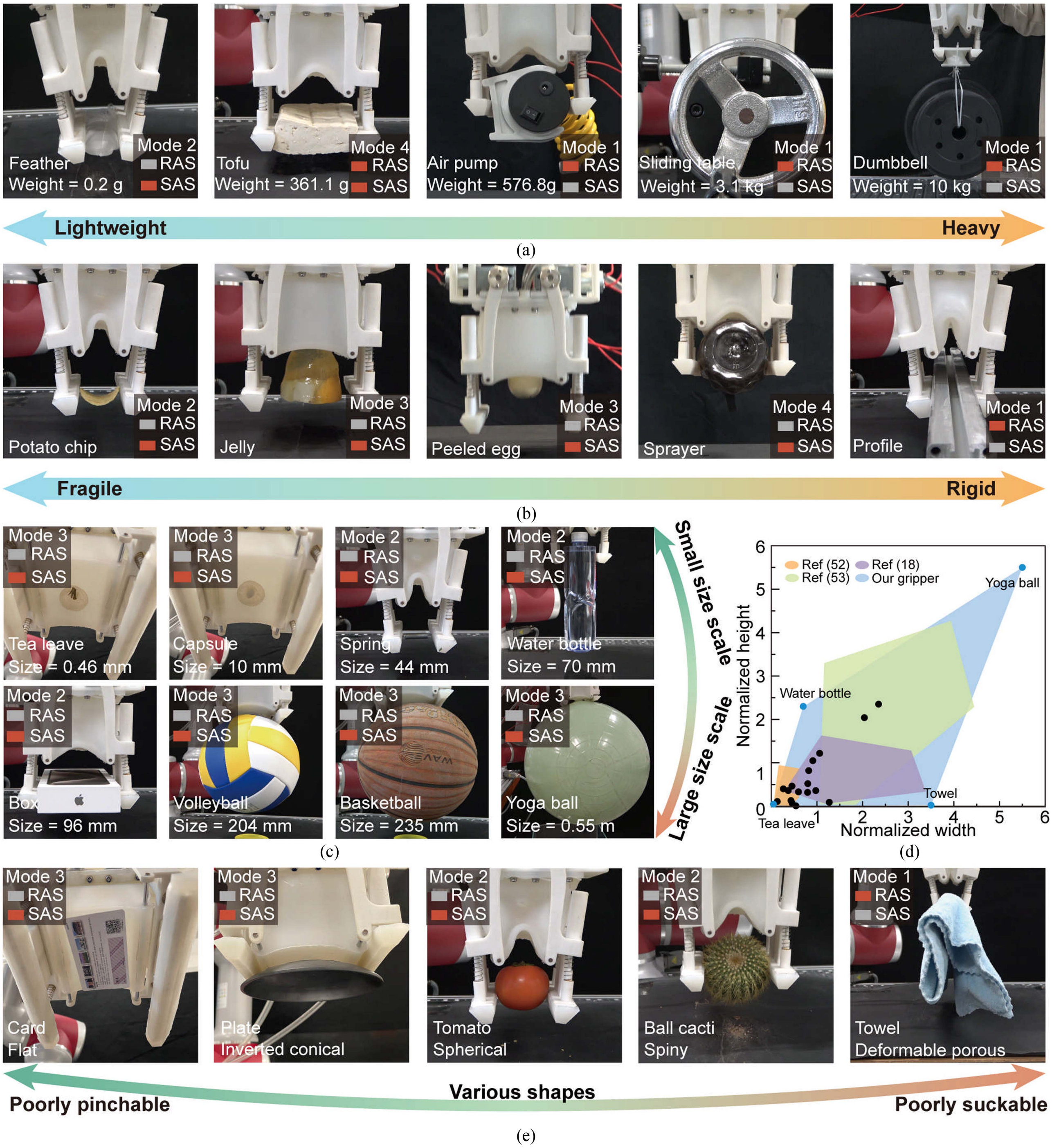


Fig. 11. Enhanced grasping diversity of the HMG. (a) Weight aspect, from lightweight to heavy. (b) Fragility aspect, from fragile to rigid. (c) Size scale aspect, from small size to large size in both width and height. (d) Comparison of the grasping diversity in size scale aspect (width and height) between our gripper and other work. All the labeled points in the diagram represent tested items successfully gripped by our HMG. (e) Shape aspect, ranging from those challenging to pinch to those challenging to suction.

continuous application of power in robust pinch mode is unnecessary. Moreover, the gripper can employ a hybrid mode to quickly pick up a delicate yet weighty tofu (361.1 g) by initially activating the SAS to gently pinch the tofu, and subsequently engaging the RAS to provide sufficient force for lifting. This combined rigid-soft manipulation approach prevents rigid impacts during high-efficiency grasping.

Second, the HGM can delicately grasp fragile objects (such as a piece of potato chip) utilizing gentle pinch, lift a smooth and deformable jelly and a peeled egg in suction mode, employ a hybrid mode (suction and gentle pinch simultaneously) to firmly pick up a sprayer, and grasp a rigid aluminum profile in robust pinch mode, showcasing a broad grasping range in the fragility aspect, as demonstrated in Fig. 11(b).

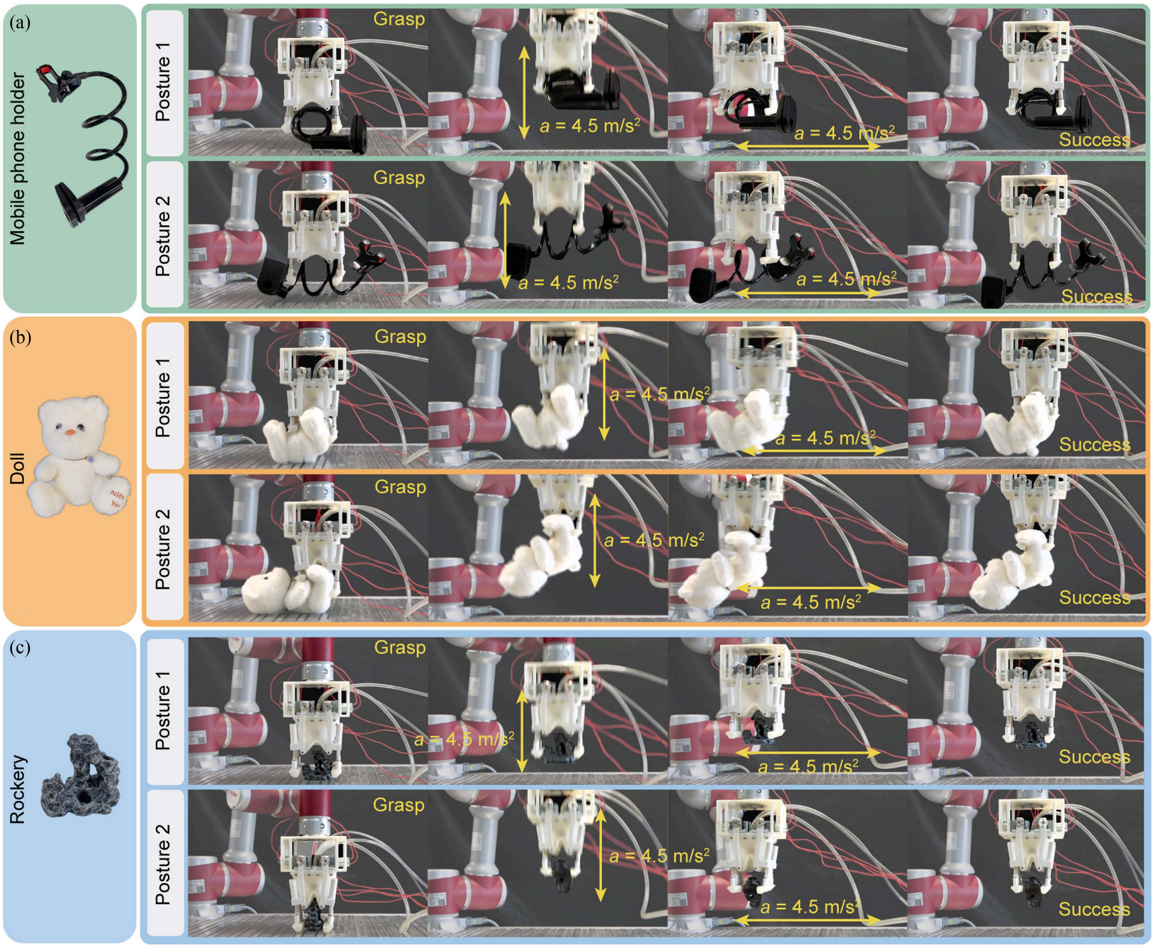


Fig. 12. Grasping of irregularly shaped objects in a dynamic environment, including (a) mobile phone holder, (b) doll, and (c) rockery.

Third, the MHG demonstrates its proficiency in grasping a diverse array of objects in terms of size scale, including both width and height, as illustrated in Fig. 11(c). For the middle-sized objects, such as a spring (44 mm) and a box (96 mm), the gripper can simply pick up them in gentle pinch mode. To handle objects in small scale and large scale (for example, a 0.46-mm-thickness tea leave and a 550-mm-diameter yoga ball), a task that proves challenging for existing finger-based grippers, our gripper can grasp them utilizing suction.

Combining suction and pinch, the HMG achieves cross-scale manipulation. The dimensions of all the objects collectively form an extensive grasping range, as demonstrated in Fig. 11(d). Here, the thickness and width of the objects are normalized according to the maximum open width of the gripper (100 mm). Our HMG exhibits broader grasping range in size scale aspect compared to [18], [52], [53].

Last, the HMG can grasp objects in a wide range of shapes, ranging from poorly pinchable shapes (such as flat objects like a card and frustrum of a cone-shaped like an inverted plate) to poorly suckable shapes (such as spiny objects like ball cacti and deformable porous objects like a towel) [see Fig. 11(e)], which is challenging for robotic grippers solely relying on pinch or suction mechanisms.

B. Grasping Irregularly Shaped Objects in a Dynamic Environment

To demonstrate the robustness and adaptability of HMG in grasping irregularly shaped objects, we conduct a series of experiments, as shown in Fig. 12 and Supplementary Movie S3. Three objects are prepared for experiments: a mobile phone holder, a doll, and a rockery. During the experiments, these objects are first picked up and then moved with an acceleration of 4.5 m/s^2 in both the vertical and horizontal directions. A successful grasp is defined as the object not falling off during the entire process. Each object is tested five times in each of the two different postures.

During the grasping period, the irregular shapes of the objects make it challenge to predict the exact contact points between the gripper and the object. Traditional rigid grippers require the incorporation of sensors and closed-loop control to achieve stable grasping. In contrast, our HMG can grasp these objects without precise pressure control and sensors due to the compliance of the soft structure, which can passively adapt to the object's shape. The retractable fingers can also passively adapt to the contours of the objects, aiding in better grasping, as shown in Fig. 12(b) during the doll grasping.

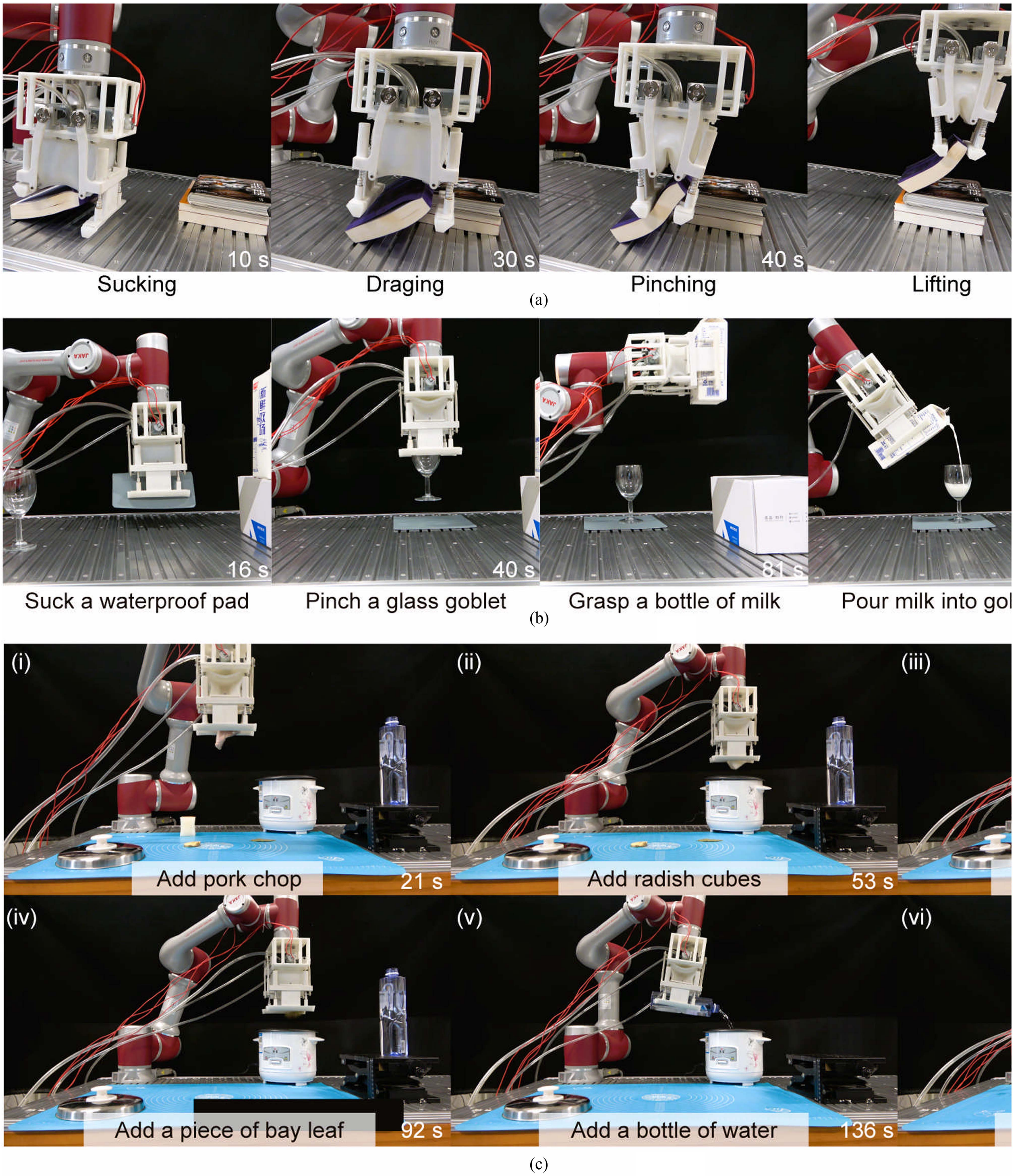


Fig. 13. Real-world manipulation tasks through the sequential activation of multiple operation modes. (a) Book organizing. (b) Milk service. (c) Cooking rib soup.

During the dynamic testing period, the HMG demonstrates a high success rate in grasping all three objects: 100% for both postures of the mobile phone holder, 100% for posture 1 and 80% for posture 2 of the doll, and 100% and 80% for posture 1 and 2 of the rockery. The reason for the single failure in grasping the doll in posture 2 is that, in this posture, the gripper can only grasp the doll's two feet, making it prone to swinging and slipping off during acceleration. When grasping the rockery in posture 2 utilizing a hybrid mode (first gentle pinch then robust pinch), the eccentric contact points between the gripper and rockery cause the rockery to rotate during lifting acceleration, as shown in Fig. 12(c). However, the HGM is still capable of securely

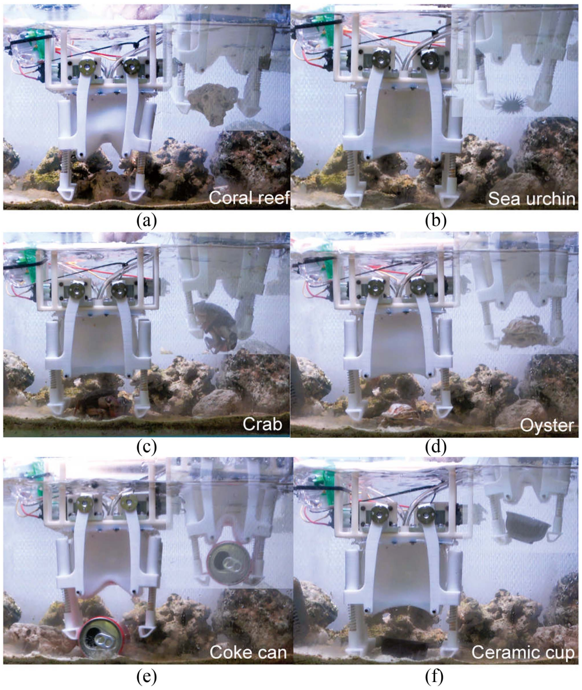


Fig. 14. Underwater operation demonstration. The HMG exhibits its ability in (a)–(d) nondestructive sampling, (e) litter collection, and (f) archeological exploration.

holding the rockery during the subsequent process, with only one drop out of five tests. In summary, the HMG exhibits strong adaptability, high robustness, and a high success rate (an average of 93.3%) in grasping irregularly shaped objects in dynamic environments.

C. Practical Application Demonstration

To evaluate the performance of the HMG in practical applications, we employ the HMG to execute a series of real-world manipulation tasks through sequential collaboration of its multiple operating modes, as demonstrated in Fig. 13. In the first book organizing task, the HMG initially employes suction mode to lift the corner of a misplaced book, and drags it to the vicinity of the book stack. Subsequently, it switches to robust pinch mode to grasp the spine of the book, lifting it, and ultimately placing it above the book stack, completing the book organizing task [see Fig. 13(a) and Supplementary Video S4]. In the second milk service task, the HMG can first prepare a waterproof pad using suction and gently place a glass goblet onto the pad. Then, the HMG steadily grasps a bottle of milk, pours the milk into the goblet, and ultimately hands the goblet to a person [see Fig. 13(b) and Supplementary Video S5]. During this process, although the excessive acceleration caused by the rapid start and stop of the robotic arm results in slight shaking of the goblet, this phenomenon can be eliminated by smoothing the motion of the robotic arm through programming. Moreover, the HMG can accomplish a more complicated task of rib soup cooking, as demonstrated in Fig. 13(c) and Supplementary Video S6. Specifically, the HMG delicately picks up a piece of pork chop and two stacked radish cubes, and sucks a slice of ginger and a piece of bay leaf, placing them into the pot in succession. Then, it grasps a bottle of water and pours it into the pot, followed by covering the pot with a lid.

Objects are also critical, such as pipelining. Thus, we construct a pipeline setup to test the gripper's ability to stably grasp moving objects, with a fragile and heavy moving rake citrus as an example (see Supplementary Video S7). As shown in the video, since grasping fragile objects through robust pinch mode is difficult and might require fine and slow control of the gripper, gentle pinch mode should be utilized to achieve a fast capture. However, gentle pinch mode alone is still difficult to grasp heavy and in practical applications, the stable grasping of moving fragile objects due to insufficient pinch force, and may cause the object to fall during rapid movement. Therefore, gentle pinch can be used to hold the object quickly and gently, followed by robust pinch to obtain enough output force to grasp the object stably.

In addition, after waterproofing the electronic components of the HMG, we employ it to carry out underwater operations. The details about the waterproof treatment can be found in the "*Waterproof Treatment*" section in Appendix. As demonstrated in Fig. 14 and Supplementary Movie S8, the HMG, along with its pulsewidth modulation (PWM) controller, can be fully submerged underwater to perform tasks such as nondestructive sampling of seafloor sediment (such as coral reef) and living creatures (such as sea urchin, crab, and oyster), litter collection (like coke can), and archeological exploration (such as ceramic cup), highlighting its versatility in underwater applications.

D. Sensor-Based Closed-Loop Grasping

The normalized object size range here is defined as the largest (smallest) graspable object's diameter to the maximum open width of the gripper. This definition excludes scenarios involving large objects with small protruding features that facilitate grasping, for example, gripping a dumbbell with a diminutive handle.

To enable the HMG with closed-loop grasping capability, we introduce a control system. The composition of the system and the control diagram are illustrated in Fig. 15(a) and (b). A micro controller (Arduino Uno, Arduino, Germany) is used to perform PWM, which regulates the variations in pinch pressure and suction pressure. The pressure is controlled by two solenoid valves (VT307V-5G1-02, DELIXI, China) connected to two pressure regulators (IRV20-02, ZPCAC, China) and a vacuum pump (FY-2C-N, Feiyue, China). Two tailored flexible pressure sensors are fixed to the fingertip and the inlet of suction cup, respectively, endowing the HMG with interaction perception. The working principle and calibration curves of the pressure sensors are shown in Fig. A9.

Here, four representative objects with different sizes and weights are tested (coke and solenoid valve for gentle pinch, light bulb, and card for suction). The testing procedure can be found in the Supplementary Video S9. Each pinching trial includes three stages: pinching, holding, and releasing. Specifically, the gripper is programmed to first pinch the object, gradually increasing the

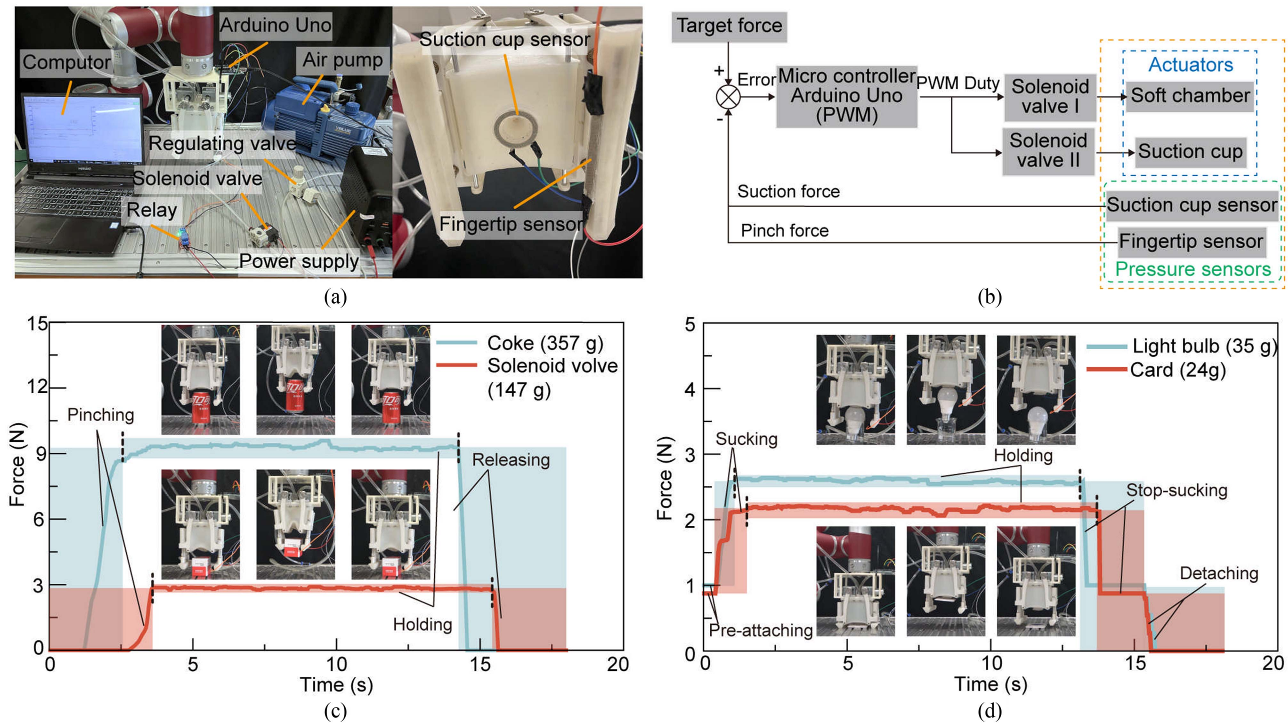


Fig. 15. Sensor-based grasping demonstration. (a) Components of the control system. (b) Control diagram of the gripper. (c) Perception of the fingertip during pinching a coke and a solenoid. (d) Perception of the suction cup during sucking a light bulb and a card.

TABLE V
PERFORMANCE COMPARISON OF DIFFERENT ROBOTIC GRIPPERS

Robotic gripper	Structure	Grasping mechanism	Maximum holding force	Fragile/deformable objects	Normalized object size range	Vertically grasp flat/ inverted cone/spiny/ porous objects on ground
Our gripper	**Hybrid**	**Pinch + suction**	**100 N**	**Yes (e.g., potato chip and jelly)**	**~0 to 5.5**	**All**
Hannes hand prosthesis [54]	Rigid	Pinch	141 N	No	Unknown	Unknown
Linkage- driven anthropomorphic robotic hand [55]	Rigid	Pinch	180 N	Yes (e.g., egg), using sensor feedback	Unknown	Unknown
Kirigami gripper [29]	Soft	Pinch	64 N	Yes (e.g., water droplet)	~0-1	Flat/spiny/porous
WebGripper [56]	Soft	Envelop	700 N	Yes (e.g., tomato)	~0 to 0.6	Inverted cone/spiny/ porous
Filamentous gripper [57]	Soft	Coiling	~ 15 N	Yes (e.g., house plant)	~0.3 to ~1.2	Unknown
Shape-conformable suction cup [53]	Soft	Suction	41.64 N	Yes (e.g., balloon)	~1.1 to ~4.4	Flat/inverted cone
Suction and friction enhanced gripper [58]	Soft	Pinch + suction	4.9 N	Yes (e.g., sea cucumber)	up to ~2	Unknown
Elephant fingers-inspired gripper [38]	Soft	Pinch + suction	2.4 N	Unknown	0.4 to 1.8	Unknown
Multimodal enveloping gripper [18]	Soft	Envelop + adhesion + suction	~20 N	Yes (e.g., grape)	~0.15 to ~3.2	Flat/inverted cone
Multimodal multipose fingers [45]	Hybrid	Pinch	270 N	Yes (e.g., potato chip and jelly)	0.05 to 0.94	Porous
Octopus-inspired gripper [20]	Hybrid	Envelop + suction	~100 N	Yes (e.g., banana)	0.5 to ~1.5	Flat/inverted cone / porous
Gecko-inspired multifinger gripper [21]	Hybrid	Pinch + adhesion	30 N	Yes (e.g., grape)	~0.15 to ~1.2	Unknown

The normalized object size range here is defined as the largest (smallest) graspable object's diameter to the maximum open width of the gripper. This definition excludes scenarios involving large objects with small protruding features that facilitate grasping, for example, gripping a dumbbell with a diminutive handle.

pinch force until reaching a predefined value, then maintaining this force for 12 s before release. Different from pinching tests, the suction test process is divided into five stages: preattaching, sucking, holding, stop-sucking, and detaching. Before the suction operation begins, the suction cup must preattach to the surface of the target object to create a sealed environment for the suction process. After the holding period ends, the suction is first stopped, followed by lifting the gripper to achieve detachment. As illustrated in Fig. 15(c) and (d), the gripper successfully follows the predefined command and lifts all the four objects as required, demonstrating its capability in closed-loop grasping with this control system.

VI. Conclusion

We propose a robotic gripper that simultaneously combines a pinch-suction hybrid mechanism and a soft-rigid hybrid structure, demonstrating an extensive range of graspable objects across multiple aspects, such as weight, fragility, size scale, and shape. Two simple and effective collaborative mechanisms (the SAM and the compliant self-adaptive mechanism) are introduced to enable such a compact design and promote full complementarity between different operation modes (robust pinch, gentle pinch, suction, and hybrid modes). To showcase the outstanding comprehensive performance of our gripper more directly, we select some representative related works in recent years for comparison, as shown in Table V. Our gripper is highly competitive in all performance aspects, which proves the effectiveness of our design.

Based on the excellent grasping diversity showcased by HMG in multiple aspects, we further demonstrate its capability to grasp irregularly shaped objects in a dynamic environment and to perform complex real-world operational tasks through the sequential collaboration of its multiple modes. In addition, the HMG also exhibits its potential in underwater operations and sensor-based closed-loop grasping. The good execution of these tasks that fit in real scenarios shows the potential of our gripper to be applied in various fields such as daily life, industrial production, and underwater biological sample collection in the future.

However, the presented HMG is still in its early prototype stage and retains several limitations. First, the maximum holding force of our gripper is already comparable to that of the rigid prosthetic hands [54], [55], fulfilling the majority of daily life requirements, but it can be further improved to expand the gripper's application scope. Utilizing higher strength materials or introducing structural strength topological optimization to design and fabricate rigid structures may be some feasible ways. In addition, the diverse properties of different target objects, such as surface roughness, smoothness, softness, etc., introduce some uncertainties in grasping tasks. Therefore, future article may consider to incorporate tactile sensors and visual modules to establish a more sophisticated control system for automated grasping of various objects.

The HMG initially demonstrated the huge potential of expanding the grasping diversity by simultaneously combining multiple grasping mechanisms as well as soft-rigid hybrid structures into a single gripper, and provided simple and effective collaborative mechanisms for multimodal collaboration. Its principle and structural design may serve as a valuable reference for the future development of high-performance robotic grippers.

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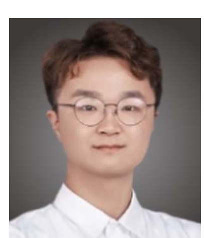

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