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A Soft Robotic Approach to Robust and Dexterous Grasping

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***Abstract*—In this paper, we present a compliant robotic gripper, Edgy-2, with 4-DOF dexterity, enabling four grasping modes: parallel grasping, power grasping, finger-tip pinch and fully-actuated grasping. The robotic finger is based on soft-rigid-hybrid structures, combining fiber-reinforced soft pneumatic actuators with rigid joints, which exhibit reliable structural rigidity and grasping robustness while maintaining excellent adaptability and inherent compliance. With both grasping dexterity and grasping robustness, the Edgy-2 achieves excellent grasping reliability with various daily objects, from a fragile cherry to a 2 kg water bottled water. The relationship of design parameters and grasping strength is presented with analytical models. The performance of a prototype Edgy-2 is verified by dedicated experiments. The proposed hybrid dexterous grasping approach can be easily extended into different end-effector designs according to application requirements. The proposed mechanism for grasping provides excellent human-robot interaction safety and reliability.**

I. Introduction

Soft robotics is expanding into multiple aspects of robotics research and industry, with pioneering research works and visionary industrial explorations by institutions around the globe [1, 2]. One of the earliest, and arguably the most thoroughly investigated topic in this area is soft grasping, where the soft pneumatic actuators (SPAs) actuated by compressed air is the most typical design for the end-effectors [3-8]. Such design combines the inherent compliance features from the natural compressibility of the driving media, and the hyper-elasticity of the material properties, therefore, achieves outstanding passive adaptability and excellent conformability when manipulating complex objects in unknown and unmodeled environment as well as interacting with humans.

Many excellent pneumatic soft end-effectors have been presented recently, and some of them have already played important roles. For example, there are soft grippers designed to safely deal with delicate materials, ranging from deep sea reef to daily vegetable [3-6]. Soft anthropomorphic hand not only mimics configuration of human hands but also works dexterously which brings promising future for newly soft artificial hand to interact with human beings [7, 8].

However, the inherent compliance of soft end-effector also brings remarkable drawbacks, especially the lack of structural rigidity. To enhance structural rigidity, some attempts have been made such as using soft rigid hybrid structure [9-14] and variable stiffness mechanism [15, 16]. Although these attempts strikingly enhanced the stiffness of soft robotic grippers, the tradeoff between structural rigidity and compliance is actually a design problem.

Figure.1.The 4-DOF compliant gripper Edgy-2.

Besides, due to deformational characteristics of soft actuators, which uses simple actuation input can realize a predefined motion [17-22]. The predefined motion usually is a bending curve for robotic finger, which limits the grasping dexterity of soft robotic grippers. For example, soft grippers often form a hollow grasping volume between fingers. This is appropriate for power and envelope grasping but not for parallel grasping. To increase grasping dexterity, one reliable solution is adding DOF in the end effector. Our previous work has presented the substantial grasping dexterity improvements of using 2-DOF soft robotic fingers for grasping tasks [5].

In this study, we aim to improve the soft grippers in aspects of structure rigidity, grasping robustness and grasping dexterity. A 4-DOF compliant gripper, Edgy-2 as shown in Figure.1, is proposed. We demonstrate dexterous grasping modes of Edgy-2: parallel grasping, power grasping, finger-tip pinch and fully-actuated grasping. Soft-rigid-hybrid finger provides inherent compliance and reliable structural rigidity. Combining with the dexterous grasping modes, the Edgy-2 performs excellent grasping reliability towards various daily objects, which ranges from fragile cherry to 2 kg bottle of water. Dedicated experiments are conducted on the Edgy-2 to validate grasping dexterity and grasping reliability.

II. Intended Grasping Capability

A. Dexterous grasping modes

The tradeoff between grasping dexterity and system complexity is a design problem for robotic end-effector. Conventionally, in order to achieve dexterous grasping

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capability, end-effector needs complex mechanical structure combining high accuracy sensor feedback and sophisticated algorithms. This potentially hinders the promotion of those complex versatile end-effectors due to the affordability consideration. In real applications, the most promoted end-effectors are grippers with minimalist structures, which are dedicated for one or several grasping modes [23].

We aim to design a compliant versatile end-effector leveraging the inherent compliant soft robotic approach. The anticipated end-effector should keep minimalist structure and achieve versatile grasping capability towards a wide variety of objects. Thus providing active selected versatile grasping modes for different targets is a viable solution. Here we classify four typical and useful grasping modes [24, 25]:

(1) Parallel grasping, as shown in Figure.2 (a), is intended for objects with flat surface, such as CD, book, rectangular box, etc.
(2) Enveloping grasping, as shown in Figure.2 (b), is dedicated for spherical objects, like cylinder, ball, etc.
(3) Finger-tip pinch. For small objects, finger-tip pinch is useful as shown in Figure.2 (c).
(4) Fully actuated grasping is to actuate each joint of the end-effector individually in a desired order, as shown in Figure.2 (d), which can enable simple in hand or contact manipulation, such as adjusting the orientation of grasping target.

B. Grasping reliability

Form closure, force closure, and grasping stability are several important properties for evaluating the performance of grasping [21]. Selection of contact form and control of contact force require dexterous algorithms and high accuracy sensors for traditional rigid end-effectors. We want to leverage the inherent compliance of soft robotics to compensate part of the requirement for algorithms and sensor feedbacks. Thus, the desired end-effector is intended to provide suitable contact form and force for successful grasping, only if the grasping target is in the range of grasping volume. Besides, the intended gripper should keep successful grasping under common disturbances such as trembling and shocking to achieve well grasping stability.

III. Edgy-2 Design and Fabrication

A. *Soft-rigid-hybrid finger joint design.*

Grasping robustness is highly related to the mechanism of robotic finger. Most existing soft end-effectors are directly taking various bending soft pneumatic actuators (SPAs) as finger components. The inherent compliance of SPAs results in weak structure rigidity of fingers. This rigidity is dependent on the properties of composed soft biological material with Young's modulus on the order of 10^4-10^9 Pa. The variable stiffness mechanism provides a solution to enhance finger stiffness, which can increase finger's Young's modulus around two order [15, 16]. The soft-rigid-hybrid approach can further enhance stiffness of soft robotic finger especially in lateral direction [9, 14]. The lateral stiffness depends on the

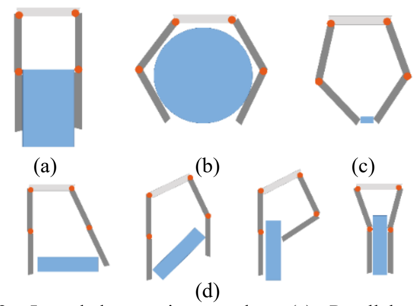


Figure.2. Intended grasping modes. (a) Parallel grasping. (b) Enveloping grasp. (c) Finger-tip pinch. (d) Fully actuated grasp.

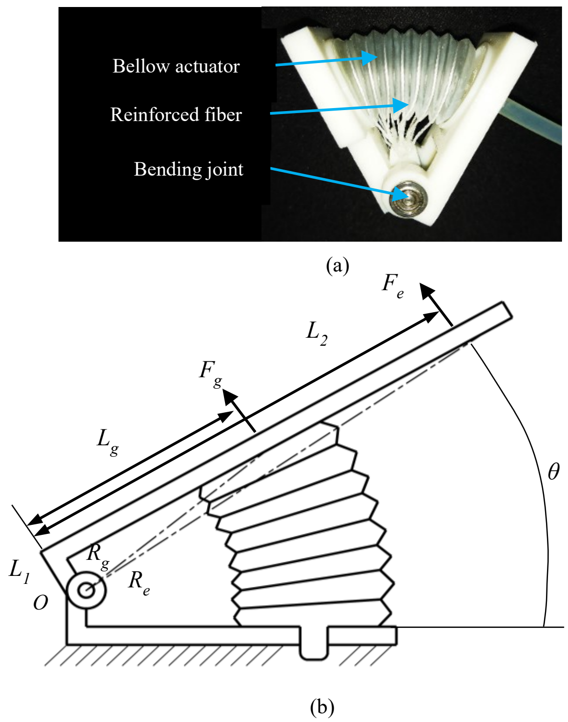


Figure.3. The proposed soft-rigid-hybrid joint. (a) Photo of the fiber reinforced soft-rigid-hybrid joint. (b) Joint modeling

hard material usually with Young's modulus on the order of 10^9-10^{12} Pa. Besides, the soft-rigid-hybrid approach satisfies easy control and affordable consideration, which is suitable for robotic finger design for its light weight, affordability, and high efficient merits [10-14]. For example, the underactuated pneumatic finger presents well adaptability [10], the soft fluid bending actuator exhibits nearly linear actuation property [11], the hybrid actuator based soft finger can bend forward and backward actively [12], and highly integrated hybrid joints system for robotic hand design [13]. After compared the presented impressive works, we proposed three desired characteristics of our intended finger joint: rigid pin joint with adequate lateral stiffness, forward and backward bending active control, and modular structure for multi-DOF system design. The prototype modular soft-rigid-hybrid joint is presented in Figure.3(a). By supplying positive and negative pressure, the joint can bend forward and backward actively. We use thin-wall thickness bellows in our design with fiber reinforcement. On the one hand, thin-wall thickness bellows

Table I. Pneumatic bellows design parameters

Chamber diameter (mm)	21
Effective diameter (mm)	20
Maximum chamber length (mm）	40
Minimum chamber length (mm)	8
Number of segments	8
Initial segment angle (degree)	80
Thickness of inner chamber (mm)	0.2
Maximum extension ratio (%)	200
L1 (mm)	2
L2 (mm)	20

with reinforced fiber can endure larger input pressure than the counterpart without fiber; on the other hand, thin-wall thickness bellows present more dexterous motion compared to thick-wall thickness bellow, which can reach larger motion range under smaller actuation pressure.

Parameters design for pneumatic bellows are mainl1y based on two aspects: the effective diameter and the transformation range. Effective diameter of pneumatic bellows is selected according to the intended joint force. The transformation range, including elongation and compression range, is determined by parameters such as the number of segments and initial segment angle. Two kinds of bellows, a thicker type and a thinner type, are customized based on the bellows fabrication technology. The thinner type is 0.2 mm and the thicker type is 0.4 mm wall thickness respectively. We take the 0.2 mm type bellows to build our proposed fiber reinforced compliant joint, whose parameters are shown in Table II. The performance of proposed hybrid joints and the comparisons between two thickness bellows will be presented in Section. IV. B.

B. *Soft-rigid-hybrid finger joint modeling.*

In this section, we present an analytical model to quantify working performance the soft-rigid-hybrid joint.

The model describes the relationship between effective output force of the hybrid joint and design parameters, which provides a reference for parameters selection.

The hybrid joint model is presented in Figure.3(b), where F_g is the generated force by soft actuator, Fe is the effective output force of the joint. L_1, L_2, L_e, L_g, are design lengths of the related part of joint and θ is the bending angle of joint. In this mechanism, the pin joint confines the deformation of linear pneumatic actuators, which results in energy loss. Therefore, we assume a compensation part which is dependent on joint bending angle. The force generated by soft actuator and transferred to joint wall can be expressed as:

$$F_g = P\frac{\pi D_i^2}{4} + f(\theta) \qquad (1)$$

where $f(\theta)$ is the compensation part for energy loss, D_i is the diameter of soft actuator, P is the supplied pressure. The effective force at the arbitrary length L_e can be described by the generated force as:

$$F_e = F_g \frac{R_g}{R_e} \qquad (2)$$

where R_g and R_e are the arm of the force for bellows generated

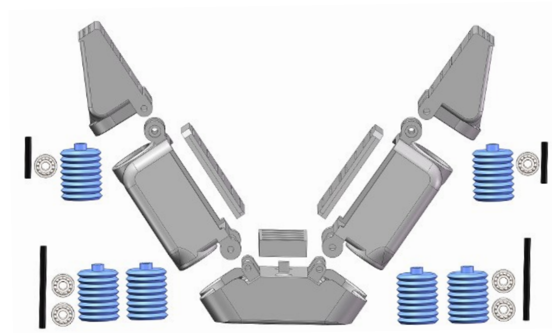


Figure.4. 3D assembly model of the proposed soft gripper, with 3D printed framework, dedicated pneumatic bellow, pins and bearings.

Table II. Pneumatic bellows design parameters

	Palm	Pro.Phalange	Dis.Phalange
Length(mm)	25	60	50
Width(mm)	50	50-35	35-25

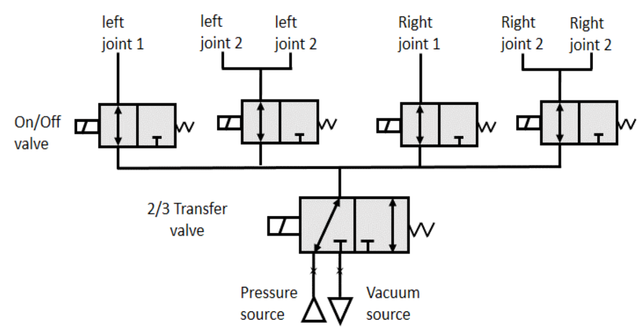


Figure.5. Actuation system for the Edgy-2 gripper.

and effective output respectively, which can be calculated by the design length L_e and the bellow mounting length L_g

$$R_g = \sqrt{L_1^2 + L_g^2},\ R_e = \sqrt{L_1^2 + L_e^2} \qquad (3)$$

Then, the effective force at arbitrary length is

$$F_e = \frac{\sqrt{L_1^2 + L_g^2}}{\sqrt{L_1^2 + L_e^2}}\left(P\frac{\pi D_i^2}{4} + f(\theta)\right) \qquad (4)$$

This relationship provides a reference for robotic finger design. The analytical model will be validated by comparing with experimental measurements in Section IV.

C. *4-DOF hybrid gripper design and fabrication*

Following the discussion in Section. II and Section. III.A, B, we choose two-finger gripper structure, each finger with two phalanges, to realize our design intention. Two-finger gripper is minimalist and enough for realizing our intended versatile grasping modes. If the gripper based on our proposed actuation mechanism works well in two fingers design, it could be applied as modular work cell and adjusted into various kinds of end-effectors, with different finger and phalange numbers, according to the application requirements.

Referring to previous optimization results and considering our equipped manipulator [25, 26], we choose gripper design parameters as shown in Table II. The CAD assembly is presented in Figure.4. The smaller the ratio between the number of the proximal joint and the number of the distal joint is, the better the compliance of the gripper will be. Therefore, we set two pneumatic bellows at proximal joint and one at distal joint. This helps to provide different joint stiffness when applying same pressure, which performs better compliance to the grasping target. To enhance contact friction, all contact surfaces of gripper are covered with a layer of silicone using Dragon skin 10. The prototype gripper is mainly fabricated by a commercial available Delta 3D printer.

D. Actuation system design

Schematic of the actuation system is presented in Figure.5. Two pumps provide positive and negative pressure, four solenoid valves (SMC-VX210EA) direct gas flow to each joint, and a 2/3 reversing valve (SMC-VQZ212R-5LB1-C6) switches between positive and negative pressure source.

Three actuation commands and one expanding command can be selected. The finger-tip pinch can be realized by parallel grasping with the silicone wrapped finger-tip.

(1) Expanding mode: Four joints are supplied with negative pressure to open the gripper. Four solenoid valves are opened together.

(2) Power grasping mode: Four joints are actuated simultaneously with positive pressure. Four solenoid valves are opened together.

(3) Parallel grasping mode: Only the proximal joints are actuated and the distal joint keeps the initial state. The solenoid valves for distal joints are closed and four proximal joints are open. The distal phalanges sweep to form a parallel grasping volume between fingers. Small objects could be pinched by the finger-tip.

(4) Fully actuated mode: Four joints can work at different pressure by controlling four valves independently.

The control system and its performances are validated collaborating with the Edgy-2 gripper in the next Section.

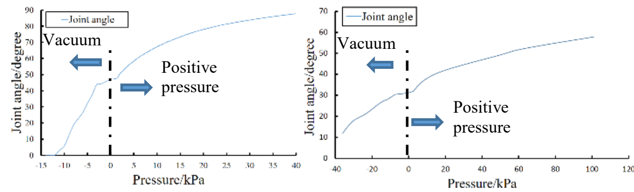
IV. Experimental Validation and Performance

A. Hybrid joint effectiveness validation

We processed four dedicated experiments to validate the effectiveness of our proposed hybrid joint. The validation experiments were processed on a dedicated test platform as shown in Figure.6 [5, 19]. We fabricated a prototype joint for test, which is mounted on one side of the test platform. The air pressure for the joint was regulated by a pressure valve (SMC ITV2030). The flow rate and direction were adjusted by a proportional valve (Festo MPYE-5-1/8-HF-010-B). A rotation encoder was connected to the joint shaft by the clutch, and a force sensor was mounted on the linear stage. One unstretchable cable connected the force sensor and the rotation side of the joint. The test platform was controlled by a microcontroller STM32f429IGT.

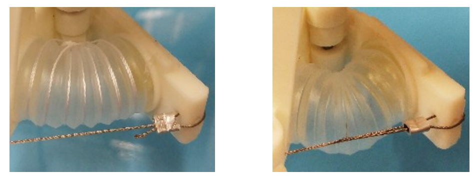
Firstly, we measured the relationship between joint bending angle and supplied pressure under zero payload to present the joint bending performance. The result as shown in Figure.7, presents a large working range the thinner joint

Figure.6. Joint test platform.



(a) (b)

Figure.7. Pressure and bending angle relationship. (a) The relationship of 0.2 mm bellow joint. (b) The relationship of 0.4 mm



(a) (b)

Figure.8. Joint performance test. (a) Fiber reinforced joint works well under 160 kPa. (b) Un-reinforced joint bulges up severely at 40 kPa.

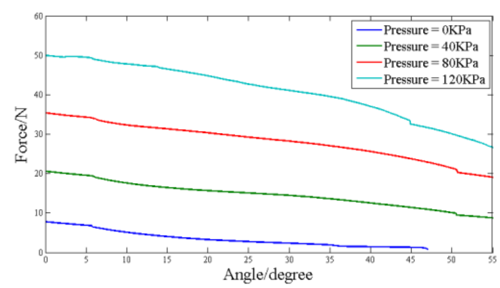


Figure.9. Joint fore test. The relationship between joint force behavior and pressure under different bending angles.

can achieve, which is up to 90 degrees, with low supplied pressure within 40 kPa. For thicker bellows joint, the motion range is around 60 degrees, and the required pressure arrived 100 kPa. The thin-wall thickness bellows joint present larger working range under lower actuation pressure.

Then, we measured the relationship between joint force and input pressure under different bending angles. The proposed joint achieved 50 N output force within 120 kPa. As shown in Figure. 8, the joint without reinforced fiber bulged severely when the applied pressure is larger than 50 kPa, which results in little force increment when increasing pressure over 50 kPa. On the contrary, the fiber reinforced joint worked well under 160 kPa. The line in Figure.9 under barometric pressure, 0 kPa, is determined by the inherent material deformation resistance of pneumatic bellows. We fitted the inherent resistance angle relationship curve depending on 0 kPa test result. The first-order fitted line is

$$f(\theta) = -0.052411x + 8.1268 \tag{5}$$

Then the effective force can be described as

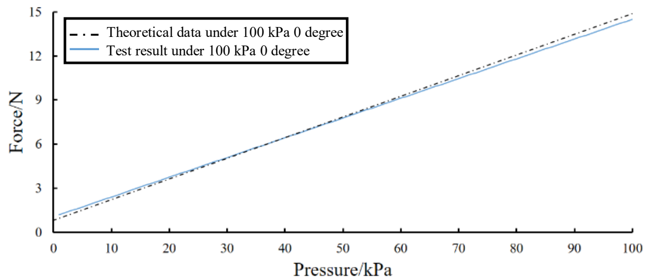


Figure.10. Finger output force test.

$$F_e = \frac{\sqrt{L_1^2 + L_g^2}}{\sqrt{L_1^2 + L_e^2}} (P\frac{\pi D_i^2}{4} - 0.052411x + 8.1268) \qquad (6)$$

Thirdly, we measured the real finger-tip effective force under 0 degrees bending angle. The result shown in Figure.10 is well consistent with our analytical result.

Finally, we made a preliminary working durability test for the proposed joint. We supplied 160 kPa pressure kept five minutes and recorded the output force. The output force had minimum decrease. Besides, a 1000-cylce repeatability test was processed under computer controlled valve actuation. During the process, the relationship between the input pressure and joint bending angle had minimum variations.

All tests were processed five times and the results were averaged. Up to 50 N joint generated force and 12 N finger-tip effective force were realized within 120 kPa. At the same bending angle, tuning the magnitude of input pressure provided different joint output force, which exhibits different joint stiffness at the same bending position. The joint presented the capability to function as finger joint in anticipated robotic grasping system.

B. *Performance of the Edgy-2 soft gripper*

In this section, we present the grasping performances of the Edgy-2, including intended versatile grasping modes, grasping reliability, and grasping capability of daily objects.

The proposed actuation system was integrated on a control board as shown in Figure.11. The control board can be operated by physical buttons or microcontroller through the computer. The following grasping works were finished cooperated with a six-axis robotic manipulator.

Under physical button control state, one grasping and one expanding button were used to give the grasping and expanding command respectively, which switches the input gas source between positive and negative. Working methods can be selected by two selection buttons. Four working modes can be selected:

(1) Power grasp: four joints will work together for grasping, and the process shown in Figure.12.(a).

(2) Parallel grasp: only two proximal joints, Figure.12.(b).

(3) Finger-tip pinch: Finger-tip pinch can be realized under parallel grasping mode as shown in Figure.12.(b). Furthermore, under parallel grasping condition, distal and proximal joints can be actuated in a desired order for fine tiny object pinch, as presented in the followed test and video.

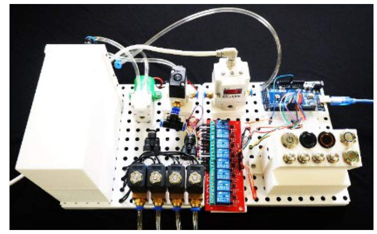


Figure.11. Specialized control board for Edgy-2 gripper.

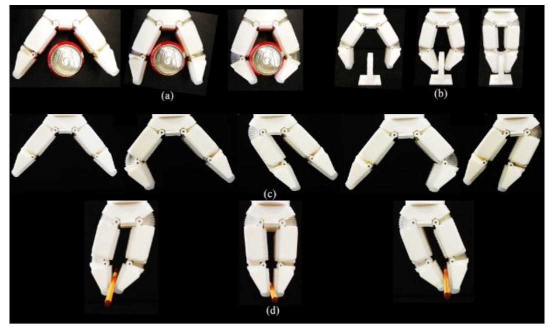


Figure.12. (a) Envelope grasping process. (b) Parallel grasping process. (c) Joint independent actuation. (d) Simple in hand manipulation.

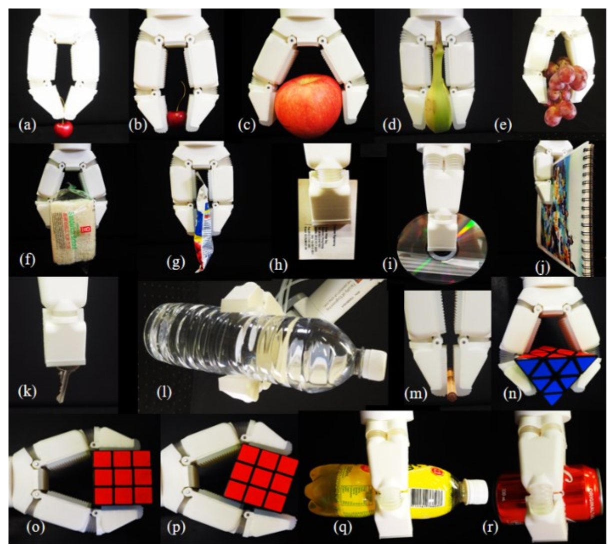


Figure.13. (a) Cherry tip (b) Cheery (c)Apple (d)Banana (e)Grape (f) Sandwich (g) Food bag (h) Business card (i) CD (j) Large book (k) Key (l) 1.5 L water (m) Pen (n) Pyramid (p) Cube mode 1(q) Cube mode 2 (r) Drink bottle (s) Drink can.

(4) 4-DOF independent actuation: Without pressing the two working method buttons, four joints will be selected individually by the four selecting buttons. The individual joint motion is presented in Figure.12.(c). In this mode, simple in hand manipulation was achieved, see Figure.12.(d), with 4 independently controlled DOF.

Daily objects grasping is presented in Figure.13. Thanks for the inherent compliance, robust structure rigidity, and versatile grasping modes, Edgy-2 performs reliable grasping capability to a wide variety of daily objects with different physical properties. The proposed four types of grasping modes can be selected effectively, which helps to deal with extremely delicate objects like fruits or even tip of cherry as shown in Figure.13 (a-e). Reliable parallel grasping for thin and flat objects like a business card, CD and book can be successfully realized as shown in Figure.13 (h-j), which is hard to achieve for previous soft end-effectors. The robust grasping for a 2 kg bottle of water is presented in Figure.13 (l). The dynamic process of above presented grasping and grasping reliability under disturbances, including hammer percussion of grasping objects, as shown in attached video.

Finally, the maximum grasping force was tested by pulling the test grasping targets out. The process was described in our previous work [4, 18]. For parallel grasping, flat objects up to 1.3 kg could be firmly grasped, and small objects down to 2 mm diameters. For envelope grasping, cylinders up to 100 mm diameter and 2.2 kg weight could be successfully picked up. With a gripper self-weight of 200 g, the effective payload-to-weight ratio achieved 11:1.

V. Conclusion and Future Work

In this paper, we use soft robotic approach present a versatile 4-DOF robotic gripper, Edgy-2 gripper, with four grasping modes: power grasping, parallel grasping, finger-tip pinch, and fully-actuated grasping. The robotic finger is based on soft-rigid hybrid mechanism, which remains inherent compliance of soft actuator and increase the finger rigidity strikingly. With modular joint design, the proposed gripper integrated four hybrid joints, two for each finger, which can be actuated independently. With the 4-DOF, the proposed robotic gripper equips versatile grasping capability and can manipulate objects in hand. Combining with the hybrid joint, the Edgy-2 gripper can successfully deal with most daily objects with various characteristics, from safely pinch a cherry to firmly grasp a 2 kg bottle of water. Dedicated experiments were performed to validate our proposed mechanism. The Edgy-2 gripper successfully satisfies the new design requirements of robotic end-effector, such as lightweight, safety, adaptability, task-worthiness, and affordability. The system is water-resistant, which can work reliably under harsh environment. This provides promising potential to promote our design to various human-centered robotic grasping applications.

Future works include: characterizing the actuator behavior for further design refinements; specific modeling of the pneumatic bellow joint and providing design instruction for the designer; further investigation on soft actuator control and strategies for improving adaptability and reliability.

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