GSG: A Granary-shaped Soft Gripper with Mechanical Sensing via Snap-Through Structure

Huixu Dong, Chao-Yu Chen, Chen Qiu, Chen-Hua Yeow, Haoyong Yu

***Abstract*—Soft robotic grippers have attracted considerable attention in terms of the advantages of the high compliance and robustness to variance in object geometry; however, they are still limited by the corresponding sensing capabilities. We propose a novel soft gripper that looks like a 'granary' in the geometrical shape with a snap-through bistable mechanism fabricated by an ordered mold technology, which consists of a palm chamber, shell, cap and three fingers. It can achieve 'sensing' mechanically and perform pinching, enveloping and caging grasps for objects with various profiles. In particular, the snap-through bistable mechanism in the proposed gripper allows us to reduce the complexity of the mechanism, control, and sensing designs. The grasping behavior is activated once the gripper's deformation or perceived pressure arrives at a certain value. First, after the theoretical model for snap-through behavior is constructed, the modularized design of the gripper is described in detail. Then, the ordered molding method is employed to fabricate the proposed gripper. Finally, the finite element (FE) simulations are conducted to verify the built theoretical model. Further, a series of grasping experiments are carried out to assess the performance of the proposed gripper on grasping and sensing. The experimental results illustrate that the proposed gripper can manipulate a variety of soft and rigid objects and remain stable even though it undergoes external disturbances. (YouTube video: https://youtu.be/74h9A-qlv28)**

***Index Terms*—Soft gripper, Snap-through, Compliant mechanism, Mechanical sensing, Robotic grasp.**

I. INTRODUCTION

GRASP is the critical capability of some robots, allowing these robots to be deployed in practical scenarios [1-3]. The limitation of rigid grippers, owing to complex mechanical and control systems, has been overcome by soft grippers [4]. In particular, soft grippers offer better compliance and safe interactions among involved surroundings. In recent years, soft grippers have attracted considerable attention due to the advantages of their high compliance and robustness to variance in object geometry [5].

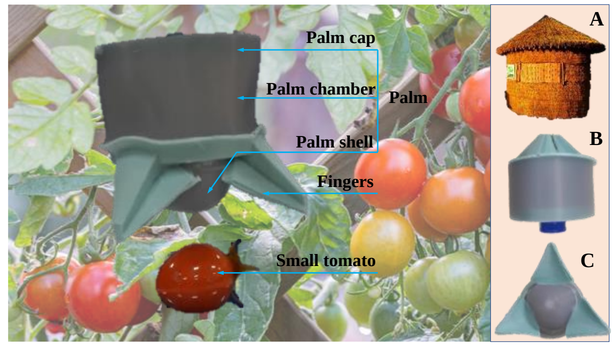

Figure. 1. The application scenario where the proposed GSG grasps small tomatoes. The real granary storing grain(A) and the two views of the gripper (B, C). The shape of the proposed gripper looks like a granary that stores grain(A).

One of the critical characteristics of compliant grippers is self-adaptive to the geometries of objects [6, 7]. Compliant mechanisms, such as bistable buckled beams, are applied to soft robots. The two states of stable positions can be transformed under external disturbance, which is called a snap-through phenomenon. A sufficient force or bending moment allows the snap-through mechanism to be triggered [8]. Snap-through characterizes a motion, which is applied in constructing mechanisms of climbing robots [9] and jumping robots [10], actuators and sensors [11].

A few bistable grippers based on the snap-through mechanism have also been proposed over the years [4, 5, 12-14]. A design of the gripper with parallelogram bars achieves a bistable mechanism based on the snap-through phenomenon [5]. The gripper presented in [5] is limited to grasping soft objects owing to the lack of sufficiently compliant capability. Thuruthel *et al*. [4] proposes a soft robotic gripper combing a ring and a cross-shaped structure, which enable the gripper to have the bistable characteristics for realizing a grasp with soft sensor-less sensing. The fully soft bistable gripper is capable of grasping rigid and soft objects, but the gripper cannot be opened automatically [4]. Moreover, without the actuation, the gripper cannot adjust the holding force. To solve the issue for the above gripper without the actuation, Lerner *et al*. [14] presented an updated version of a soft bistable gripper with variable stiffness by heating a shape memory polymer (SMP) material. However, owing to the SMP actuation property, the gripper costs a long time to tightly grasp an object after arriving

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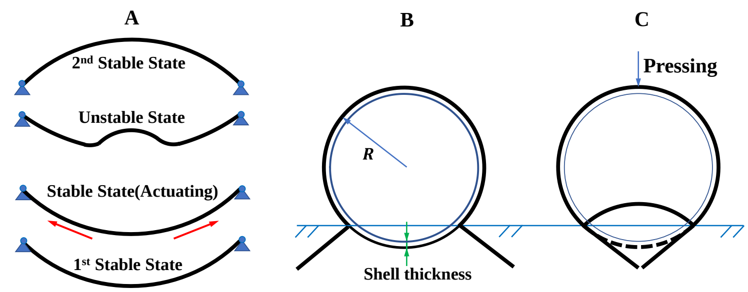

Figure. 2. The bistable snap-through phenomenon with two stable states(A). The deformed configurations of the thin-walled spherical shells for the initial status(B) and after the snap-through behavior(C). The blue circles indicate the grasped objects(D, E, F). The three grasp modes, such as the pinching grasp that use fingertips to grasp objects(D), enveloping grasp which is one for which the fingers surround the object and hold it securely against the palm (E) as well as caging grasp that forms a cage to avoid object's escaping whenever these fingers move rigidly for obtaining a better form-closure grasp(F). Note that the form-closure property of robotic grasping is considered as a purely geometric property of a set of unilateral (contact) constraints.

at the snap-through stable status. Zhang *et al.* [12] built a soft gripper with a bistable morphing structure driven by the magnetic actuator. The morphing structure and the magnetic actuator are separated, which results in big space occupation Follador *et al.* [13] proposed a gripper consisting of two double-bistable structures based on dielectric elastomer actuators and Lin *et al.* [15] presented a high-speed soft gripper built by snap-through mechanism. These grippers just can conduct pinching and enveloping grasps, respectively.

In this work, we present a highly compact and compliance granary-shaped soft gripper (GSG) with a compliant bistable snap-through mechanism to bridge the gaps of non-actuation [4], slow-response [14], low-compliance [5], big-size [12], single-grasp-mode [13, 15] of bistable grippers. This GSG can perform multiple grasp modes, such as pinching [16], enveloping [17] and caging grasps [18] of soft, brittle, fragile, light, or heavy objects, achieving "sensing" in grasping and "self-actuation" in some scenarios. It is potentially applied to picking up fruit in agricultural scenarios (see Fig.1 and Fig.2). Note that 'granary' mentioned in this work means 'granary-shaped'. In terms of design, the proposed GSG, which consists of a palm chamber, shell, cap and three symmetrical fingers, is actuated by the pneumatic system, as shown in Fig.1. We first design the GSG according to the modularized concept. For instance, the palm chamber and shell are considered as the whole one module; the palm cap is used for connecting interface, which is one module; three fingers as one module have the same geometrical shapes. According to the GSG modularized design, for better combining different parts of the GSG, we propose a fabrication approach of ordered molding to improve the robustness of the GSG. The palm (chamber and shell), three fingers and the cap are fabricated by two materials in order. Finally, grasping experiments are carried out to evaluate the performance of the GSG.

Here we briefly describe how the GSG utilizes the designed bistable snap-through mechanism to realize "sensing" in grasping and "self-actuation" in some scenarios. In particular, the procedure for the GSG grasping an object is made up of four steps, as illustrated in Fig.3. First, at the default closing status of the GSG, the GSG's palm chamber is inflated by the pneumatic system. Second, after opening three fingers, the GSG moves towards the target. At the current status, the proposed snap-through mechanism can store strain energy that

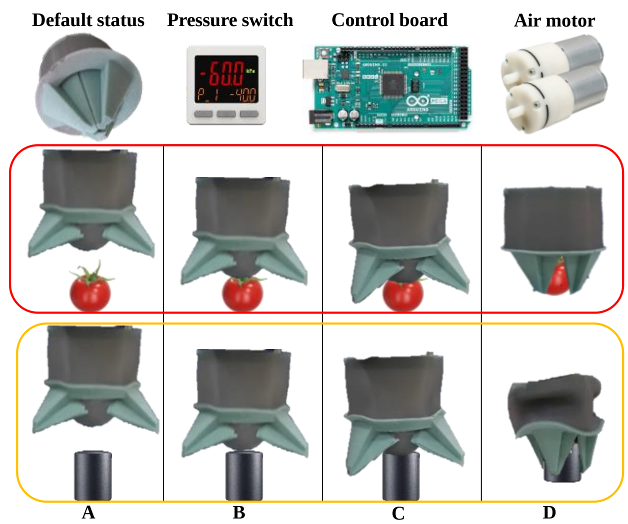

Figure. 3. The GSG grasping system and two grasping modes (such as passive grasping and active grasping illustrated in the red and yellow frames, respectively). The pressure switch is applied to measure the pressure of the palm chamber and the control-board-Arduino drives air motors to inhale and exhale air. One air motor takes charge of inhaling air and the other is used in exhaust air. The default status of the GSG is closing. The GSG moves towards at the opening status (A), touches(B), continues pressing(C) and grasps the targets(D). The GSG grasps a relatively light object such as a small tomato (the red frame) and a relatively heavy object such as a weight is grasped by the GSG (the yellow frame). From the default status to the opening status of the grasping process, one inhalation motor can allow air into the gripper's chamber and then, the bistable structure enables fingers to open. After touching the target, the other motor can exhaust air from the chamber and result in a closing status of the gripper.

can then be readily released upon a sufficient deformation. Third, when the palm shell touches an object, the GSG starts "sensing" it due to the change of air pressure in the palm chamber and then, the palm shell continues pressing it. Fourth, when the deformation of the palm shell or the air pressure value measured by a digital pressure switch arrives at a threshold, the bistable structures enable fingers to grasp the object, while the sensing is completely passive. Indeed, there is a passively grasping mode for the gripper at the opening status and actively grasping modes for the proposed bistable mechanism, as shown in Fig.3. When grasping some light objects, the GSG can use passively grasping mode. In this case, the GSG automatically generates snap-through grasping action due to large deformation of the palm shell, without the actuation from the pneumatic system, which is named "self-actuation". Further, it is not required for the pneumatic system to inhale air from the palm chamber for obtaining a stronger grasping force. Thus, in terms of open-close transmission, it is no surprise that there is no power being consumed while the gripper is holding a light object. As for actively grasping mode, when a pressure sensor reads the threshold, inhaling from the palm chamber brings the fingers to close. This grasping mode generates a strong grasping force, which is preferred for grasping heavy objects.

Thus, we summarize the three main contributions as follows:

- A soft gripper that conducts pinching, enveloping and caging grasps is constructed based on the designed bistable structures, which realizes mechanical sensing. The snap-through mechanism enables a gripper to reduce the complexities of the actuation mechanisms and control system.
- The proposed fabrication method of ordered and modularized molding can leave out the complexity of 3D printing, manually assembling and bonding, just employing the molding process owing to the simple structure.
- A series of grasping experiments are implemented by the proposed GSG to illustrate that the proposed GSG can be used for grasping objects with various ranges of weights and dimensions.

We organize the rest of the paper as follows. The construction of GSG is introduced in detail in Section II. A series of grasping experiments are conducted for evaluating the capabilities of GSG in section III. After presenting some discussions in Section IV, we make a conclusion in Section V.

II. Methodology

In this section, we first construct the theoretical model based on the snap-through mechanism and then, modularly design the GSG. Second, the ordered mold method is presented for fabricating the GSG.

A. *Design Strategy of the GSG*

A gripper with three fingers is sufficient to achieve stable grasps for various objects to be grasped [19]. Moreover, it is easy for the three-finger gripper to achieve a caging grasp [18], which is a better form-closure grasp [20] since it is not always possible to stably pick up some objects via enveloping [17] and pinching grasps [16] without a palm involved. The gripper with the capability of mechanical "sensing" is required for simplifying the design and control. Thus, we design a soft three-finger gripper that can be capable of pinching, enveloping as well as caging grasps. Its palm can perceive touching the target by its deformation. The GSG is modeled as just one single component, consisting of fingers in a symmetrical tri-fingered configuration, a palm chamber, shell and cap to offer significant flexibility and versatility in tackling different profiles of objects. In terms of the detailed design, we need to consider a few factors, but the primary ones are (1) high payload capacity (0.2kg); (2) capability to stably grasp various objects (e.g., spherical, cubic, cylindrical, irregular geometrics, small, heavy objects).

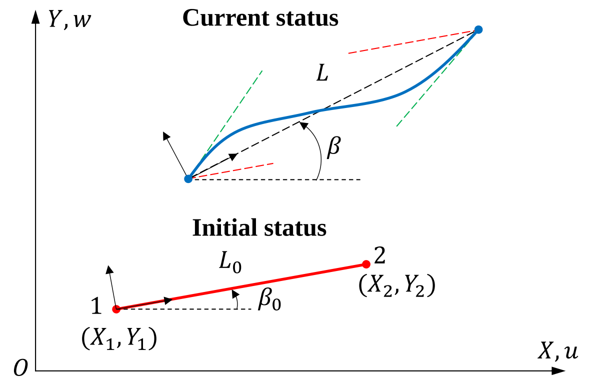

Figure. 4. Relationship between global coordinates and local coordinates of the nodes of each beam element. (X_1, Y_1) and (X_2, Y_2) represent the coordinates of node 1 and node 2 in the reference frame of the global coordinate $\{O, X, Y\}$, respectively. β_0 and L_0 represent the initial angle and length of the beam, respectively. β and L denote the current incline angle and length, respectively. In the current status; red dash lines indicate the initial direction of the beam; green dash lines represent tangent lines for the corresponding curves.

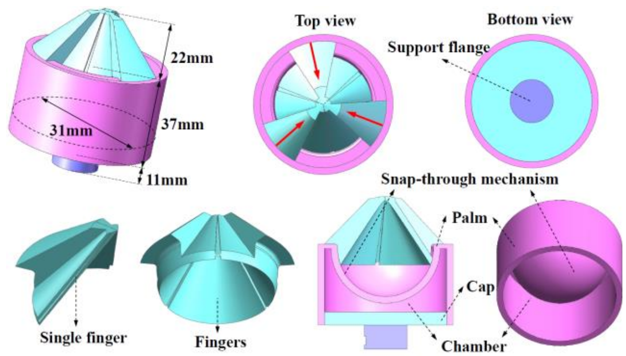

Figure. 5. The design of the proposed GSG.

1) *Model construction*

The theoretical model of the deformation of snap-through behavior is investigated for estimating the dynamic effects on the response such as the deformations and axial stresses of the snap-through motion in the palm shell of the proposed GSG. The mechanism of the GSG is considered as a snap-through structure of the thin-walled elastic spherical shell with bistable characteristics. To simplify the calculation, the snap-through structures in [4] and our work are considered 2D arched beams. The work proposed in [4] assumes that the two ends of a bistable beam with the snap-through phenomenon are fixed without rotations; however, the rotations at the ends arise while the gripper grasps an object. Without losing the generality, we construct a general theoretical model of the snap-through mechanism with rotations at the ends based on the 2D structural system using the co-rotational approach [21].

In terms of each beam element, it includes two ends such as node 1 and node 2, as shown in Fig.4. In the reference frame of the global coordinate $\{O, X, Y\}$, the coordinates of node 1 and node 2 are (X_1, Y_1) and (X_2, Y_2) at the initial configuration, respectively. Then, the initial angle and length of the beam are denoted by β_0 and L_0, correspondingly. When the beam undertakes an external load, it will be changed to the current configuration where two nodes have displacements (u_1, w_1) and (u_2, w_2) for arriving at the current positions with the current incline angle β and length L that can be derived from nodes'

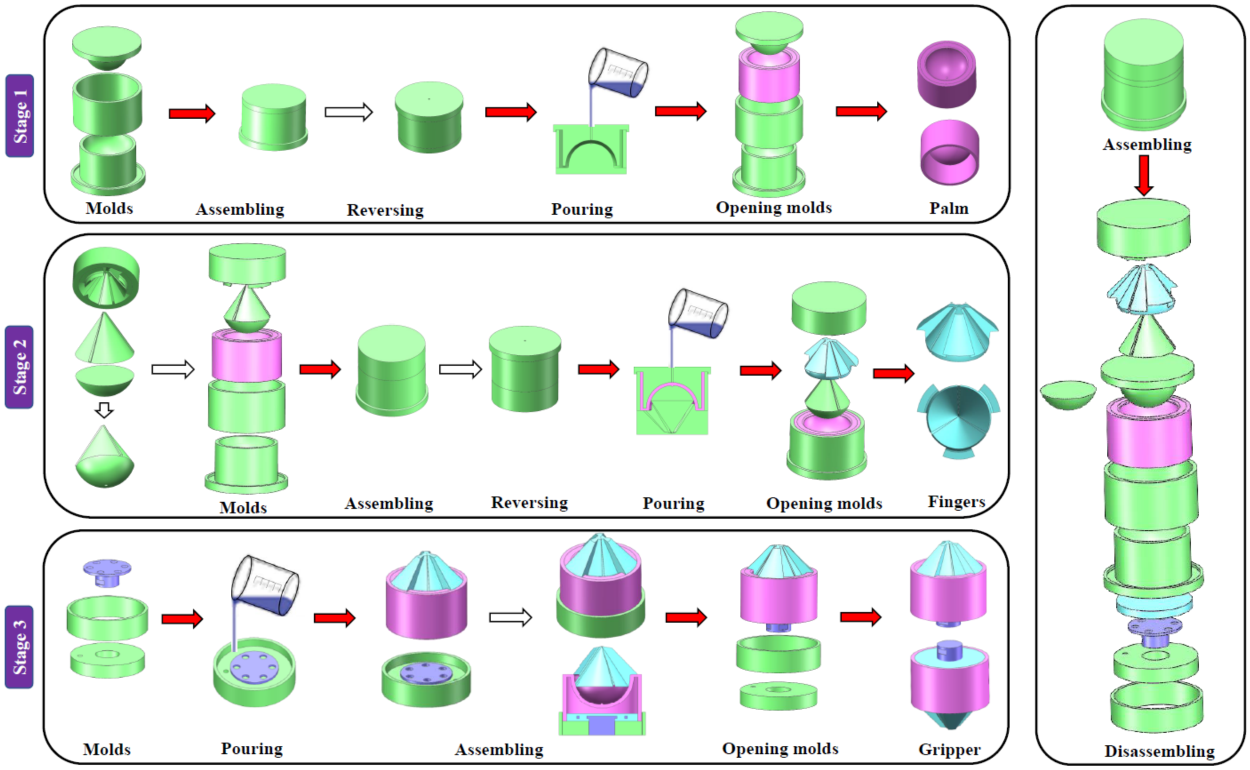

Figure. 6. The fabrication stages of the proposed GS gripper. The first stage introduces how to mold the gripper's palm(chamber and shell); the second one describes the fabrication process of the fingers; the third stage illustrates how to obtain the gripper by opening the molds after molding the palm cap.

coordinates. As for the beam, its axial deformation u_l can be achieved from the length change from L_0 to L. Thus, we can derive the axial force F_N along the beam as follows

$$dX = (X_2 + u_2) - (X_1 + u_1)$$
$$dY = (Y_2 + w_2) - (Y_1 + w_1) \tag{1}$$
$$L_0 = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}$$
$$L = \sqrt{(dX)^2 + (dY)^2} \tag{2}$$
$$u_l = \frac{L^2 - {L_0}^2}{L + L_0} \tag{3}$$
$$\cos\beta = \frac{dX}{L}, \sin\beta = \frac{dY}{L} \tag{4}$$
$$F_N = \frac{EAu_l}{L_0} \tag{5}$$

where E and A represent Young's modulus and cross-sectional area, respectively. Indeed, by constructing the theoretical model, we can qualitatively explore the effects of design parameters and material property of the proposed gripper on the deformations and the equivalent stresses. The theoretical model can provide theoretical support regarding how to improve the deformations and the equivalent stresses by adjusting design parameters and choosing suitable materials. For instance, with a big deformation, the gripper can readily realize enveloping and caging grasps. Moreover, we use a kind of high-hardness material to build fingers with strong stresses for getting a strong grasping force. Thus, we can optimally design the gripper via the constructed model.

2) Modularized Design of the GSG

The detailed design of the GSG is shown in Fig.5. The three fingers with one single degree of freedom (DOF) are actuated simultaneously. The soft fingers can open and close with the palm chamber stretching. The fingers are designed to be curved with a gradual thinner taper from the contact point and the finger ends for realizing a sealing state when the gripper is at the default mode. In addition, such a design for the fingers enables the palm shell to touch an object ahead of the fingers while the GSG keeps an opening state. The GSG's palm shell is designed as a mechanical sensor to perceive the touching between the gripper and a target. The palm shell is also involved in increasing the contact areas of grasping an object, which improves grasp force and enables better contact for an object with an irregular shape to achieve high grasping stability. When the center of the palm shell touches an object, the mechanical deformation from the palm chamber allows the fingers to enclose the object based on the snap-through phenomenon. Further, to achieve a stable grasp, the positive pressure is brought to bear on the palm chamber for increasing the grasp/holding force. A thick joint is in the inner side of the palm and finger, which makes it inextensible yet flexible for bending along the backward and lateral directions. When the air pressure is applied to the palm chamber, a net bending motion is created to open the fingers due to the positive pressure and close the fingers owing to the negative pressure. The palm cap fixed on the palm chamber is designed as a mechanical interface.

B. Fabrication of the GSG

It is in general difficult for traditional 3D-printing, assembling and bonding approaches to fabricate soft robots [22]. In this work, we proposed the ordered molding method to

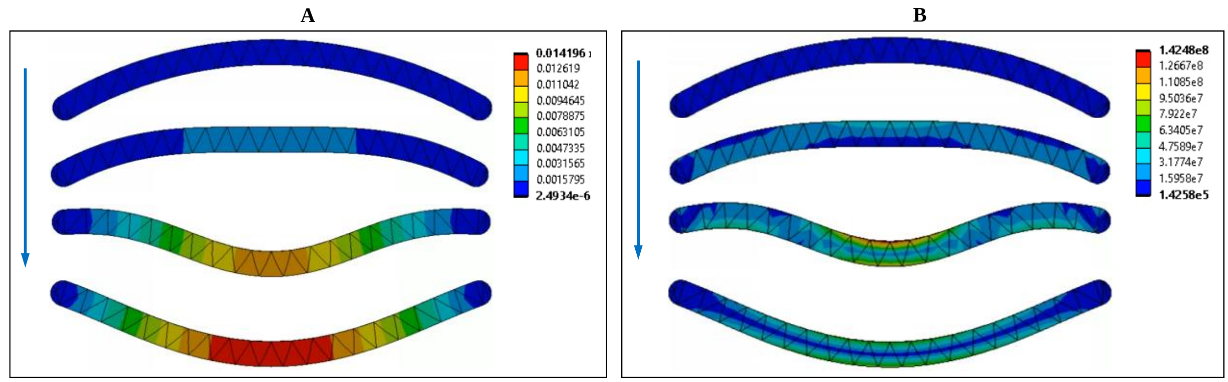

Figure. 7. The deformations(A) and the equivalent stresses(B) of snap-through phenomenon based on the finite element analysis. The units are Meter for the deformation (A) and Pascal for the force/stress(B), respectively.

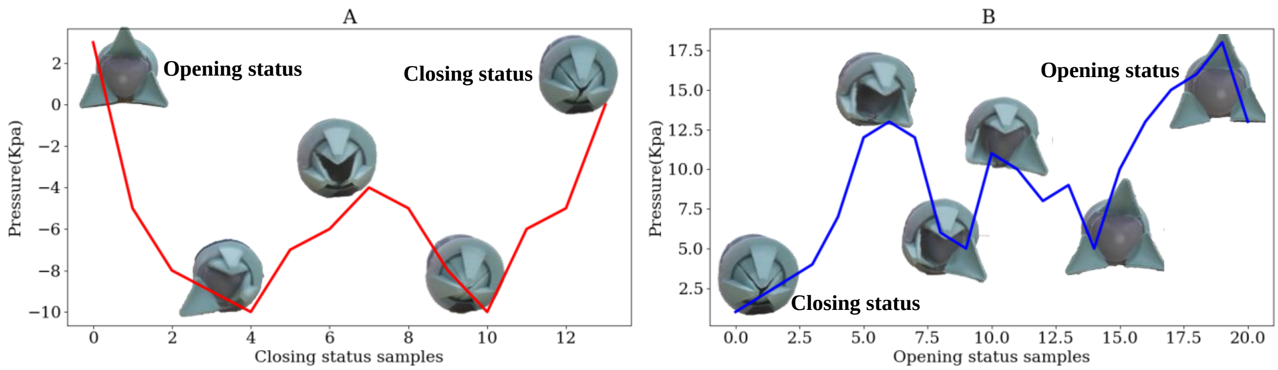

Figure. 8. The pressures of the closing process (A) and the opening process (B) with the corresponding samples. During the period of the closing process, the pressure magnitude first increases with the fingers closing and then, the pressure magnitude became small once the fingers reach the stable status. For the opening process, there are two pressure peaks of the palm chamber before fully opening since three fingers reached stable status at different time samples.

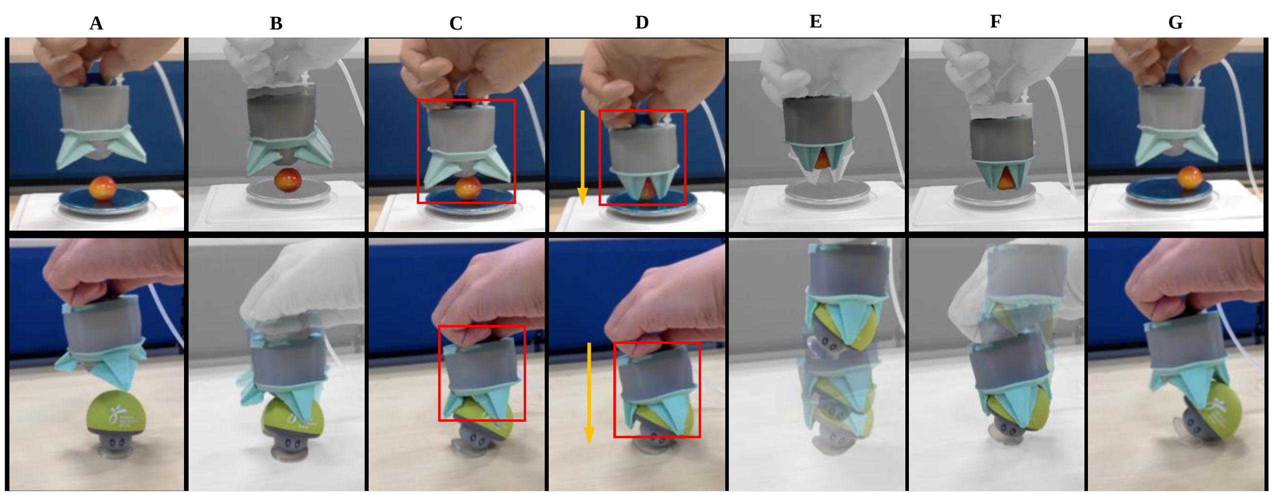

Figure. 9. The detail procedures of the GSG grasping objects with relatively light (cherry in the first row) and heavy (speaker in the second row) weights, respectively. Tending to grasp(A); moving down(B); mechanical sensing(C); enveloping grasp(D); lifting(E); placing(F) and opening(G). The yellow arrows represent the moving directions and the red frames denote the current positions of the GSG, respectively.

construct the GSG according to its modularized design. The major fabrication procedure is illustrated in detail in Fig.6, with relevant steps labeled. The gripper is fabricated with Smooth Sil 960 (Smooth-On, USA, Shore 60A) for the fingers and palm cap, and Dragon Skin 30 (Smooth-On, USA, Shore A hardness of 30) for the palm (chamber and shell) since the fingers need to have a good performance at preventing objects from slipping.

The GSG fabrication begins with designing the molds that are applied to building the proposed GS gripper. There are three main stages for this fabrication. In terms of the first stage, these molds are 3D printed from a silicone elastomer by a MakerBot Replicator 2 (MakerBot Industries, LLC). After assembling these molds, we pour the mixed liquid silicone rubber (Smooth Sil 960, Smooth-On, USA) into the assembled mold that consists of three molds from a port. It is noted that the operations require being careful and slow for avoiding air bubbles when the mixed liquid silicone rubber is poured into the 3D-printed molds. After putting them into an oven at 35°C for 24 hours to solidify the soft material, we open the assembled mold to obtain the palm. As for the second stage, the palm is also regarded as a mold for fabricating fingers (see Fig.6). The steps are similar to the above stage. The poured liquid silicone rubber is changed to Dragon Skin 30. It is noted that the three fingers are made as a whole part with three thin walls that are easy to be separated. In the third stage, the blue fiber-reinforced structure with six holes, as shown in Fig.6, can enhance the stiffness of the cap by being installed into the cap in case the stretching of the palm causes large deformation of the cap as a contacting flange. After pouring, we considered the palm chamber as a mold and cover it on the bottom mold tightly. Further, these assembled molds are placed again into an oven at the same time and temperature mentioned above. Finally, we take the soft gripper out of the molds after the cured skeletons are removed from the molds. All the molds and components of the proposed GS gripper are assembled and disassembled, as shown in Fig.6.

III. Experiments

We first demonstrate the grasp behaviors of the proposed GS gripper via a detailed analysis of the gripper grasping an object. Then, to evaluate the grasping performance of the gripper, we implement a series of grasping tasks that show the full functions and potential agricultural applications of gathering fruits.

A. *The GSG Grasping Behaviors*

The holding force of the proposed GS gripper is investigated. It is well-known that two factors, including target geometry and palm actuation, contribute to characterizing gripper force. We printed two objects, including a sphere with a 30 mm diameter and a cube with a 30 mm size, for the experiments. The object was firmly attached to the load cell so that an external force could be applied to pulling the gripper until the grasped object was released. The readings of the pulling force were recorded during the pulling period. The peak holding force was again achieved while the gripper held the sphere, reaching approximately 10 N. For the holding force concerning the cube, the peak holding force is about 4 N. It is significantly smaller than that of the sphere since three fingers and a soft palm form a cage to prevent the sphere from sliding out, with the same vacuum pressure applying.

The finite element (FE) simulations of the GSG are conducted to verify the constructed theoretical model. The beam (palm shell) is configured along the horizontal direction and the applied force is executed in two steps. First, only its gravity is considered in the finite element model. Second, an applied force is imposed on the beam to bring fingers to the open state. The corresponding simulations of the deformations and equivalent forces inside of the palm shell are illustrated in Fig.7. During the period of the snap-through motion, the axis force F_N increases with the deformation u_l becoming, which indicates the constructed model is in line with the forecast.

We used a pressure sensor to approximately record the pressure of the palm chamber, as shown in Fig.8. In terms of the closing process (see Fig.8-A), at the initial phase, the pressure magnitude smoothly increased with the fingers closing. At a moment, the fingers reached a stable status so that the required vacuum pressure magnitude became small. The snap-

Table I. The dimensions and weights of objects. D(mm) and W(g) represent the dimension and weight, respectively.

Items	D	W	Items	D	W
Motor box	2	17.6	Grape	27	2.3
Cartridge	5	2	Weight	28	200
Jujube	12	1.5	Small tomato	29	7
Glue	17	15.9	Cherry	31	1.3
USB driver	18	9.2	Strawberry	37	3.5
Medicine bottle	18	12.2	Maize cob	45	57
Plum	24	1.6	Speaker	54	69.2

through characteristics resulted in the pressure saltation. To close fingers tightly, the big pressure magnitude was applied to the palm. The default state of the proposed GS gripper is closed. For the opening process, the pressure frequently changed until the two fingers opened to arrive at a stable status. Figure 8(B) illustrates that there are two pressure peaks, such as 13 and 11, of the palm chamber before fully opening since three fingers reached stable status at different time samples. The manually molding method results in the difference between the two jointing structures (between the fingers and palm) and the third one. This also indirectly verifies that the experimental results have a good agreement with the design of the GSG.

To demonstrate passively and actively grasping modes, we carried out some grasping experiments, as shown in Fig.9. For instance, in terms of passively grasping mode, the palm shell touches a cherry and continues pressing it; when the deformation of the palm reaches a certain value to cause the snap-through phenomenon, the fingers passively close to grasp this cherry. As for active grasping mode, the fingers actively close to grip the object when the pressure in the palm chamber measured by the pressure sensor is larger than the set threshold.

B. *Grasping Evaluation*

We conducted the grasping experiments to evaluate the GSG's performance in grasping tasks, as illustrated in Fig.10. The GSG could pick up a wide variety of objects spanning different geometries, and surface finishes and payloads, such as delicate sphere-like items (small tomatoes, grapes, and cherries), irregular-shaped objects (maize cob, medicine bottle and box) (see Table I). In grasping experiments, to assess grasping stability, if the GSG swayed each object three times without dropping it, this is considered a successful grasp.

To obtain the maximum weight and size of the object to be successfully grasped, we perform two groups of grasping experiments. As for the first group, the weight of the object with the initial value of 100g was gradually increased by 20g every time after the gripper accomplishes a few pick-and-place actions for each object. Through repeating many grasp trails, we conclude that the proposed gripper could reliably grasp a range of targets with weights reaching nearly 200g (the weight information in deep gray color mentioned in Table I), as shown in Fig.10. In this case, the maximum internal air pressure is around -25KPa. The maximum payload is almost three times the weight (74g) of the GSG. For the experimental result, it is found that the maximum payload is much than the measured peak holding force (10 N). The maximum payload and peak holding force have different measurement metrics. During the force characterization, to achieve the peak holding force, we

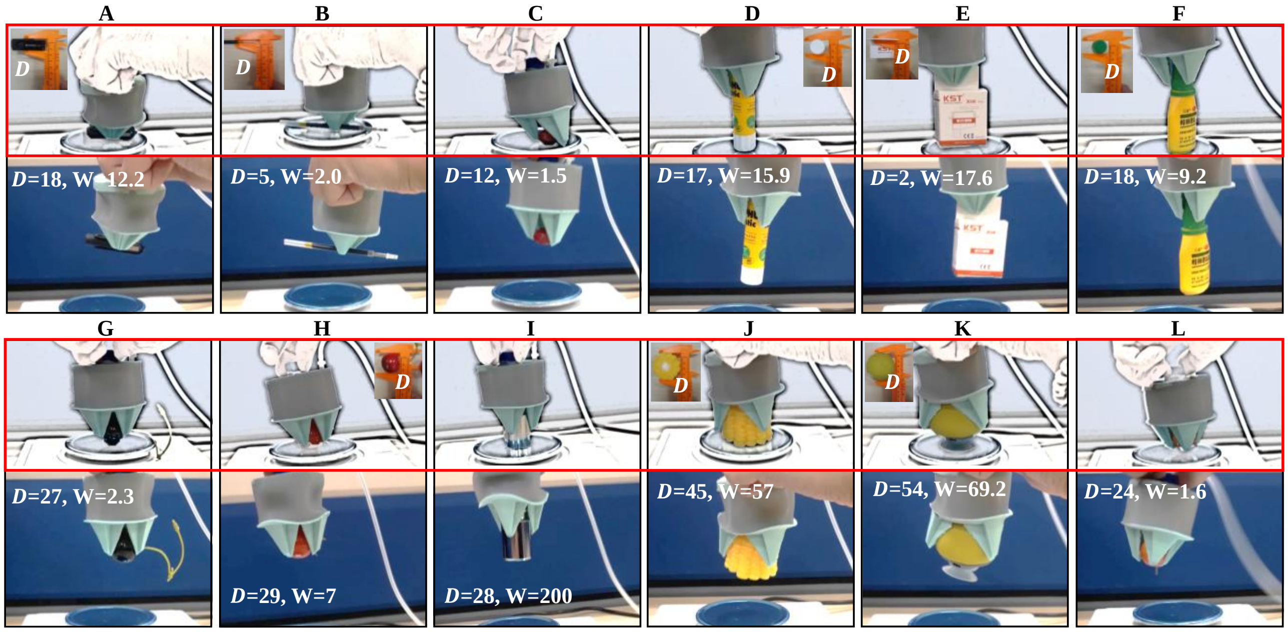

Figure. 10. The proposed GS gripper grasps objects including USB driver(A), Cartridge(B), Jujube(C), Glue(D), Motor box(E), Medicine bottle(F), Grape(G), Small tomato(H), Weight(I), Maize cob(J), Speaker(K) and Plum(L). For each item, the top and bottom pictures show the gripper grasps and lifts up the object steadily, respectively. The pinching grasps(A, B, C), enveloping grasps(D, E, F, G, H, I, J, K) and caging grasps(L). D(mm) and W(g) represent the grasping dimension and the weight of an object, respectively. The dimension measurement cases for some objects with complex shapes in (A, B, D, E, F, H, J, K).

used a large suction pressure to actuate the GSG for conducting a caging grasp of a sphere object so that it is difficult for a sphere to be removed from the gripper; however, it is very likely to break this soft gripper. We test the maximum payload of the proposed GSG, considering it is used safely and repeatedly in a wide variety of situations. In a practical application, we implement a suitable pressure to this soft gripper for achieving stable grasps. Therefore, we suggest that the maximum safe payload of the GSP is around 200g. Similarly, we conduct the second experimental group to achieve a range of objects' sizes. The maximum diameter of the object was 54mm which is approximately 174% of the GSG's diameter (31mm) (see the speaker information in black color at Table I). The proposed GSG could perform pinching grasps for small objects, enveloping grasps for objects with big sizes and caging grasps for small sphere-like objects. For instance, the pinching grasp tests were carried out for demonstrating how the GSG could manipulate objects with small profiles, which is not specially designed for sphere-like objects, as shown in Fig.10(A, B). In terms of sphere-like objects (Jujube, Plum, Grape, Small tomato, Cherry), the gripper performed enveloping and caging grasps. Here we define a caging grasp that the palm and all the fingers are involved in covering the object. Although some objects' contours fit poorly inside the gripper's grasping diameter, the proposed GSG can still be conformed to irregular shapes, allowing to grasp them such as the maize cob and speaker (see Fig.10). In addition, when performing an enveloping or a caging grasp, the gripper tended to move down for allowing the object to enter the space of the palm to achieve a stable grasp. When the gripper with the opening status is not actuated by the air pump, it can hold light objects such as a Motor box and glue until the object is disturbed by an external force. In terms of heavy objects (e.g., Weight), the gripper cannot hold the weight without air actuation. Actuated by the air pump, the proposed gripper can stably hold these objects. In addition, for the passive gripping mode, we can obtain the maximum load 20g of the GSG and the maximum size 25mm of the loading via a similarly experimental method. In this grasping mode, the GSG just relies on the default configuration to envelop or cage the target, which is suitable for grasping light and small objects.

IV. Discussions

In this section, we make some discussions about the advantages and disadvantages of the GSG, the integration with industrial robot for practical applications and potential application scenarios.

The proposed GSG is particularly well-suited for grasping sphere-like objects, soft and delicate objects due to their compliant skeleton and caging shape factor; however, it is in general not available for a gripper with two fingers to manipulate such spherical objects since two fingers of the gripper readily squeeze out a spherical object. Compared with bistable soft grippers presented in [14] and [4], the GSG can quickly increase holding force for achieving a stable grasp through changing the air pressure. Also, it is found that the gripper tended to perform caging gasps for heavy objects. The caging grasp offers a more stable grasp than enveloping, pinching grasps. In this case, the contact surface is adequately big among the object, fingers and palm, which allows the grasping force to be distributed based on the design of the GSG; otherwise, the object would be easily damaged or be dropped. In addition, we compare the GSG with the soft gripper [15]. The advantage of the soft gripper is that it can conduct enveloping grasps of relatively heavy and big objects; however, it is in general invalid for grasping small objects since the so gripper cannot perform pinching grasps. Contrastively, the GSG can perform grasps of objects with a wide range of sizes.

Here we also make discussions regarding the shortcomings of the proposed GSG for the presented grasping performance. First, if the suction force is large, the gripper's palm chamber generates a deformation so that the grasping configuration of three fingers is unpredictable (see Fig.10-I), which may result in unstable grasps. Moreover, since the joint part of molded fingers and palm with different materials are molded together is relatively fragile, the GSG is readily broken undergoing a large air pressure. In future work, we will try to design a palm with a hard structure and a soft half-shell and allow the GSG to have more joint connections. Second, the current GSG is not capable of sensing grasping failures. A potential solution is that we need to install a tactile sensor on fingers for perceiving touching information.

We discuss how to combine the GSG and industrial robot arm to realize a better grasp. The pneumatic system of the GSG is controlled by an Arduino board. If the GSG is mounted on the end-effector of an industrial robot, its actuation system can be integrated into the robotic control system via the portal: rosserial_arduino in ROS(Robot Operating System) [23]. Thus, the robot can effectively control the inflating and releasing of the GSG. In particular, after receiving the object's position, the robot first brings the GSG with opening status to continuously press this target and then, the robot arm will stop when the pump regulator provides a pressure value that arrives at a threshold to the robot; next, the GSG closes fingers to grasp the target; finally, the robot holds the object to the destination.

In terms of the envisioned application scenario (see Fig. 1), we analyze the GSG's grasping performance. When the palm of the GSG mechanically touches an object against a table or floor, the GSG can carry out a grasp after the pressure arrives at a certain pressure. However, when the GSG grasps a target along other directions, it presents different performances. For instance, if the GSG tends to grasp a hanging object, this target is pushed away. Moreover, the GSG cannot give full play to the strength of mechanical sensing. The GSG just grasps small hanging fruits since it is usually possible for this gripper to eject fruits with big sizes.

V. Conclusion

In this work, we constructed a GSG based on the proposed snap-through structure that provides the actuation mechanism and sensor-less perception. Various experiments were carried out to verify that the GSG is capable of grasping a variety of rigid, soft, delicate objects with different profiles while being gentle enough to avoid causing damage.

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