2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
October 25-29, 2020, Las Vegas, NV, USA (Virtual)

Design and Experimentation of a Variable Stiffness Bistable Gripper

Elisha Lerner, Haijie Zhang, and Jianguo Zhao[1]

Abstract— **Grasping and manipulating objects is an integral part of many robotic systems. Both soft and rigid grippers have been investigated for manipulating objects in a multitude of different roles. Rigid grippers can hold heavy objects and apply large amounts of force, while soft grippers can conform to the size and shape of objects as well as protect fragile objects from excess stress. However, grippers that possess the qualities of both rigid and soft grippers are under-explored. In this paper, we present a novel gripper with two distinct properties: 1) it can vary its stiffness to become either a soft gripper that can conform its shape to fit complex objects or a rigid gripper that can hold a large weight; 2) when the gripper is soft, it has two stable states (i.e., bistable): open and closed: allowing it to be closed without an actuator but through contact force with a target object. The variable stiffness is accomplished by heating a shape memory polymer (SMP) material through its glass transition temperature. The bi-stability is achieved by shaping the gripper's energy landscape through two elastic elements. This paper details the design and fabrication process of this gripper, as well as quantifies the influence of temperature variations on this gripper. The capability of the gripper is experimentally verified by grasping different objects with various shapes and weights. We expect such a gripper to be suitable for many applications that traditionally require either a rigid or a soft gripper.**

I. INTRODUCTION

One of the most important parts of various robotic systems is the gripper for grasping or manipulating objects. Rigid grippers have been widely used in various industrial and medical applications. But they need sophisticated algorithms and various sensors (e.g. force or visual sensors) to grasp irregular or fragile objects [1]. These challenges can be partially addressed by using soft grippers since they can conform their shapes to complex objects and gently grasp fragile objects without complicated sensors or algorithms [2].

Soft grippers have been intensively investigated in recent years with a comprehensive review in [2]. Here we briefly review several papers related to variable stiffness grippers. Qiji *et al.* designed and fabricated a gripper that could actuate using magnetic fields. This gripper used a magnetic shape memory polymer that stiffened when in contact with certain magnetic fields to manipulate objects [3]. Through the use of granular jamming, Amend *et al.* designed gripper that could finely tune its stiffness depending on the differential pressure inside the gripper. This allowed the gripper to significantly change its stiffness and maintain its new stiffness with no energy input [4]. Utilizing the properties of SMP, Behl *et al.* fabricated a gripper that actuates based on temperature. When the gripper is heated, the arms both soften and extend. While cooling down, the arms close in and stiffen [5]. Moreover, McCoul *et al.* designed a gripper that utilizes a conductive shape memory polymer which can not only actuate based on the temperature of each electrode segment, but it could also give precise control over the stiffness of each section of the gripper's fingers through the temperature of the SMP electrode corresponding to that section [6]. Further, Firouzeh *et al.* produced a gripper with variable stiffness joints using tendons and origami based designs [7].

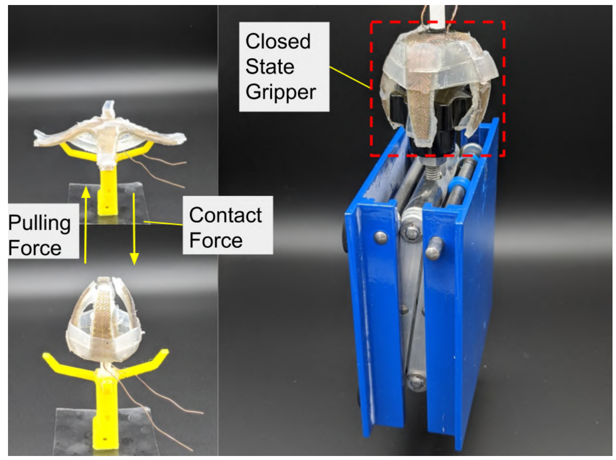


Fig. 1. Left: the gripper switches from open to closed states with contact force, and returns to an open state by puling strings attached to the fingers. Right: the 6.8 g gripper is holding a 453 g object.

Unlike existing grippers that need guided actuation to both open and close, a bistable gripper has two stable states; therefore, it can rely on contact force alone to close the gripper, and no energy input is needed after the grasping process [8], [9]. This property makes bistable mechanisms attractive for a variety of different research (e.g., metamaterials [10]) and real world applications (e.g., robotic perching [9]). Here we briefly review related work on bistability with a focus on soft robots and grippers. A multi-material 3D printed bistable mechanism was designed to build various deployable structures [11]. Based on this, the researchers created a bistable mechanism for untethered swimming robots [12]. An origami based bistable mechanism with stretching and bending soft joints is leveraged for foldable wings and grippers [13]. A soft bistable valve is developed to actuate autonomous soft robots [14]. A bistable gripper is designed to enable perching capability for aerial robots so that they can perch passively through the contact impact [9].

*This work is partially supported by the National Science Foundation under Grant IIS-1815476.

[1]Elisha Lerner, Haijie Zhang, and Jianguo Zhao are all with Department of Mechanical Engineering, Colorado State University, Fort Collins, CO 80523, USA. elerner@rams.colostate.edu, Jianguo.Zhao@colostate.edu, zhanghaijason@gmail.com

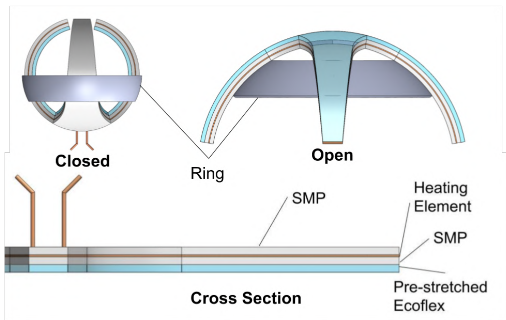


Fig. 2. The parts of the gripper in open and closed configurations, as well as a cross section of the layers of the gripper base.

This paper presents a unique gripper that integrates bistability with variable stiffness, exhibiting two distinctive characteristics: 1) it can lower its stiffness to become a soft gripper that can conform to complex objects, or increase its stiffness to become a rigid gripper that can hold a large weight; 2) when the gripper is soft, it is bistable and can be closed without an actuator but through contact force with a target object. The gripper is shown in both open and closed states as well as gripping a heavy, complex object in Fig. 1. A shape memory polymer (SMP) serves as the base of the gripper. The gripper can switch between open and closed states when the SMP reaches or exceeds its glass transition temperature. With this design, we combine the advantages of rigid and soft grippers, which can hold heavy objects, adapt to complex geometries, and require no actuators to close. We also conduct several experiments to quantify how different temperatures influence the gripping force, holding force, and actuation forces. In addition, we also conduct catching and grasping experiments to identify the gripper's speed and adaptability.

The rest of this paper is organized as follows. Section II introduces the working principle of the proposed gripper. Section III describes the design and fabrication of the gripper. Section IV details the experimental results for the gripper in terms of holding, gripping, opening, and closing forces.

II. Working Principle

As shown in Fig. 2, the gripper contains four major parts: a shape memory polymer (SMP) layer for variable stiffness, a heating element (inside the SMP) for Joule heating, a pre-stretched elastic layer bonded to the SMP layer, and one or two elastic rings surrounding the four fingers. The SMP, heating element, and pre-stretch layer are used as the palm and fingers of the gripper. The heating element can heat the SMP to its glass transition temperature to soften the gripper. The pre-stretched layer makes the SMP bend biased in one direction, and it provides a desired curvature for the fingers. The rings then generate the two stable states of the gripper.

When the gripper is soft, it has two stable states that it can rapidly snap between: open and closed as shown in Fig. 3.

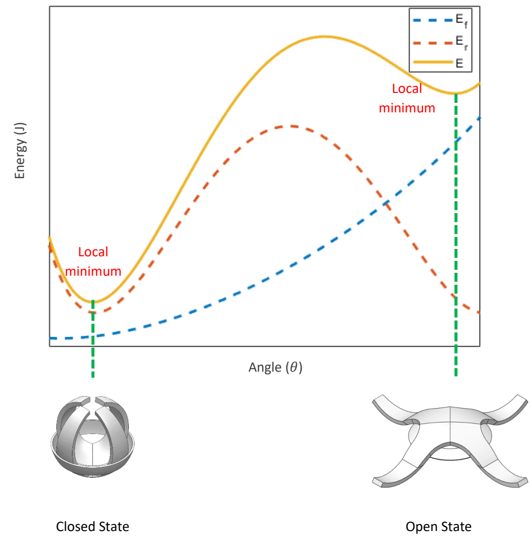


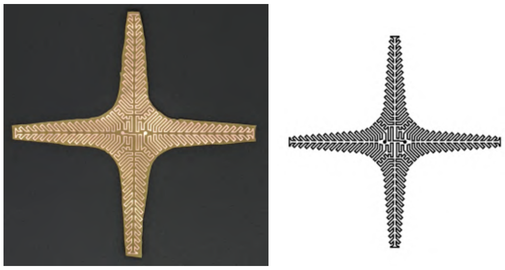
Fig. 3. Two stable states of the gripper correspond to the two local minima of the energy landscape. Left is the closed state, and right is the open state

When it is open, a force can be applied to the center of the palm of the gripper to close the gripper. This force can come directly from the contact force between the gripper and an object. After it closes, the SMP layer can cool down below its glass transition temperature to become rigid so that it can hold many times its own weight. Further, it does not require energy input to stay in this closed state. To open the gripper, we use the heating element to warm the SMP to lower its stiffness. In this case, the shape memory effect of SMP can potentially open the gripper, but in this paper, since the force generated from SMP is small, the gripper is opened using a motor to drag strings attached to each of the fingers (Fig. 7).

The two stable states of the gripper in the soft state are generated from the competition of strain energy from the four fingers (E_f) and the ring (E_r). We use Fig. 3 to illustrate the influence of the strain energy to bistability. When it is in closed state as shown in the lower left corner of Fig. 3, both fingers and the ring store some strain energy. However, when the gripper is being opened, E_f in the fingers will monotonically increase since the pre-stretch layer is being stretched more and more. Meanwhile, E_r in the ring will first increase and then decrease as the ring will be stretched first and then recover. Combining E_f and E_r, the total strain energy $E = E_f + E_r$ will have two minima (Fig. 3), corresponding to two stable states (open and close). Note that by choosing different parameters (e.g., E_f dominates E_r), the local minimum on the right for E may disappear, resulting in only one local minimum. In this case, the gripper will be monostable [15]. The detailed analysis for bistability is left for future work, and in this paper, we select specific parameters to enable bistability (e.g., E_r dominates E_f).

III. Design and Fabrication

In this section, we discuss the fabrication of the gripper made from the following parts: palm, heating element, rings, and the motor-driven mechanism. The base of the gripper is



(a) Final Heating Element (b) Heating Element Pattern

Fig. 4. The final heating element and heating element schematic.

composed of four layers (Fig. 2): an SMP layer, a heating element, another SMP layer, and a layer of stretched silicone.

A. Heating element

To generate uniform heating for the SMP layers, we fabricate a flexible heating element using laser engraving and acid etching. A sheet of *Pyralux*® AP353500E (DuPont Industries) is coated with a matt black spray paint (Rust-Oleum 2x Ultra Cover). A laser engraver (Full Spectrum H-Series 20 x 12) is then used to remove the paint on the outside of the heating element circuit. The exposed copper is then removed by acid etching with a 42 Baume ferric chloride etching solution (MG Chemicals). Etching should take 1 hour. The heating element should be removed and the corroded copper on the surface should be wiped off every 15 min. Once the exposed copper is fully removed, the remaining acid is cleaned off using water. After drying, acetone is used to remove the paint from the heating element circuit. The heating element is then trimmed to match the design of the gripper using a precision knife. Two holes are punched into the heating element at integrated connection points. Copper wires are then soldered to the connection points. The final heating element is shown in Fig. 4. The pattern of the heating element is designed to ensure that the heating element has a resistance of 2 Ω and can be accurately engraved. At 2 Ω, the heating element provides a balance between reliability and speed when powered with a current of 2 A.

B. Palm and Fingers

The palm and fingers consist of two layers: a pre-stretch layer made of Ecoflex 00-30™ (Smooth-On) and an SMP layer embedded with the heating element. A polymer with a relatively low glass transition temperature and high change in stiffness should be used to form the base of the gripper. It is also desirable that it can return to its base state, which requires an SMP. Specifically, we choose a mixture of Jeffamine D400 (Huntsman Inc) and Epon 828 (Hexion) for this application due to the relative ease of manufacturing and the large variation in stiffness as it heats through its glass transition temperature [16]. A mixture of 37.9 percent Jeffamine D400 and 62.1 percent Epon 828 is used to make the polymer. These weight percentages were calculated from a 2:1 molar ratio of Epon 828 to Jeffamine D400 by assuming each amine completely reacted to two epoxy molecules. To fabricate the SMP, Jeffamine D400 is first mixed with the Epon 828 thoroughly. The resulting mixture is then heated in an oven to $90°C$. It is then mixed again and degassed in a vacuum chamber at 0.1 Mpa for 20 min. This heating and degassing process is repeated twice to ensure that no air bubbles remain in the final mixture. Once the solution is thoroughly degassed and homogeneously mixed, a small layer of it is poured into a mold made of Dragon Skin 30 (Smooth-on Inc) fabricated from a 3D printed mold. The Dragon Skin mold allows us to remove the SMP base easier and prevent damaging it after curing.

The heating element is then placed on top of the SMP layer (Fig. 5(b)) and another layer of SMP is poured over it as (Fig. 5(c)). It is important that the heating element is close to the center of the two uncured SMP layers. The copper wires soldered to the heating element should be poking out of the topmost SMP layer. A thin, flat square made of Dragon Skin 30 is then pressed over the mold, with holes to make sure it does not harm the copper wires connected to the heating element. The Dragon Skin 30 is placed over the mold to ensure uniform thickness of the cured SMP. The entire assembly is then placed into an oven at $140°C$ for 14 hours to cure. A successfully designed SMP and heating element should be the same as shown in Fig. 6(d). The SMP should completely encapsulate the heating element after the curing process. Each finger should be 45 mm long from the center of the base, and the tips of each finger are 5 mm wide.

The pre-stretched layer is made from a 40 mm wide, 0.75 mm thick square of Ecoflex 00-30™. These dimensions can provide the maximum amount of tensile force without breaking for the size of the gripper made in this paper. It is stretched in all directions using a 3D printed stretching platform (Fig. 6). The Ecoflex square is created using a 3D printed PLA plastic mold. The Ecoflex is clipped into position on the stretching platform such that it remains in its stretched state while it is installed onto the gripper base. The SMP layer is bonded to the stretched Ecoflex using a silicon epoxy glue, Sil-Poxy (Smooth-on Inc). The copper wires from the SMP base should be pointed outwards (Fig. 6(c)). The assembly is then left to cure for at least 1 hour. The SMP layer is then heated to lower its stiffness which prevents the gripper from breaking as the clips on the Ecoflex square are removed. The Ecoflex square will now act as a guide for the shape of the gripper and enable it to have distinct open and closed states. The excess Ecoflex between the gripper fingers is then trimmed off (Fig. 6(d)).

C. Rings

A ring made of Ecoflex 30 is manufactured to go around the fingers of the gripper and allow for the gripper to be stable in an open state. The ring is 8 mm wide and has a 60 mm perimeter. These ring dimensions allow the gripper to stably hold an open and closed state, while still allowing for more rings to be placed later to alter the properties of the gripper. An 8 mm wide strip of Ecoflex 30 is cut to a length of 65 mm. The excess 5 mm is used to adhere the strip to

(a) Pouring the first SMP layer (b) Placing the heating element (c) Pouring the second SMP layer (d) Cured SMP base

Fig. 5. Steps for manufacturing the SMP base.

(a) Place Eco-flex square (b) Stretch Eco-flex square (c) Place/adhere SMP base (d) Trim Eco-flex

Fig. 6. Steps for manufacturing the pre-stretched eco-flex layer.

itself in a ring shape using Sil-Poxy glue. The ring is left to cure for at least 30 min.

After curing, the ring is attached to the base gripper using Sil-Poxy glue. It is placed 8 mm above the base of the gripper. The ring must be moved such that the overlapping sections of the strip are on a finger; otherwise, the difference in elastic quality could affect the gripper's characteristics. The assembly should be left to cure for at least 30 min. More rings can be added above the base ring to increase the grip force and actuation force of the gripper. Additionally, the original ring can be trimmed width wise to lower the grip force and actuation force of the gripper. A ring can be added below the initial ring (closer to the base of the gripper) in order to give the final gripper a more steady open state without majorly affecting the grip force. For our purposes, two rings were used, one slightly above the initial ring. The final weight of the gripper with two rings is 6.8 g.

D. Motor-driven mount

In order to open the gripper and to allow the gripper to close while mounted, a motor-driven mount made from 5 parts was designed (Fig. 7): a base mount frame, piston, piston cap, spool, and motor. The piston allows the gripper to move and actuate on the motor-driven mount, while the spool and motor allow the gripper to open and provide leverage for the motor. In order to attach the gripper to the motor-driven system, 4 nylon strings are pushed through the gripper's fingers approximately 1 cm from the tip of each finger. The strings are then secured to the gripper with washers on the side with the pre-stretched Ecoflex layer. The strings' other ends are threaded through the four finger holes and base holes in the motor mount and attached to the spool. Additionally, the base of the gripper needs to be adhered to the piston using an epoxy.

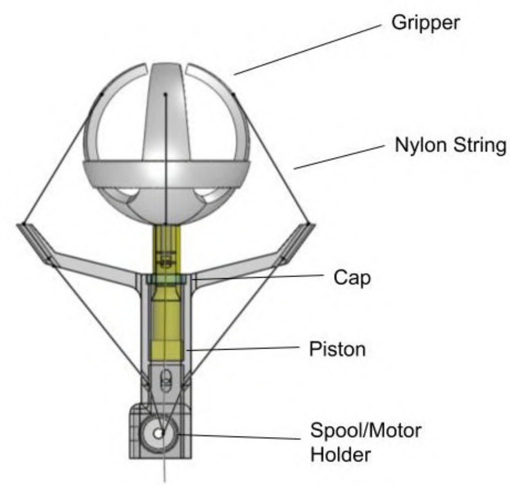


Fig. 7. Motor-driven mount design. This system opens the gripper using strings. One string is attached to each finger, and all four strings are driven by a single DC motor.

IV. Experimental Results

For the fabricated gripper, its properties will change with respect to stiffness. Therefore, we conduct four sets of experiments to quantify how the change in stiffness influences: 1) gripping force (i.e., how large of a force it can generate when the four fingertips contact an object without encapsulating it); 2) holding force (i.e., how much weight it can hold when the gripper encloses an object); 3) actuation force required from close to open; 4) actuation force required from open to close. Note that the stiffness of the gripper is determined by the SMP's temperature, which is further determined by the electrical power applied to the heating element. Two additional tests were conducted, a catching and grasping test, to determine the gripper's speed and adaptability.

For each experiment, the gripper started with room temperature and was heated by supplying a current of 2 A to the heating element. A Flir thermal camera was used to determine the gripper's temperature, which was inferred from the thermal images based on the temperature of the base of the gripper. The temperature color scale on the camera

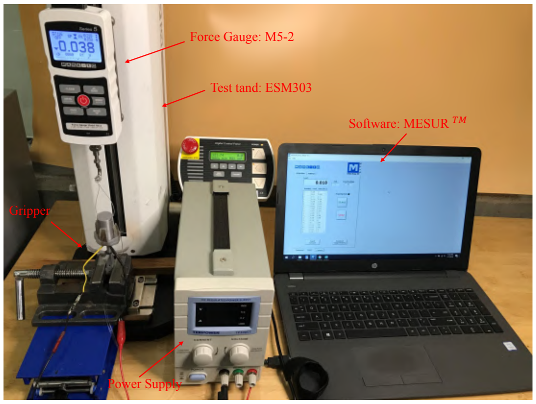


Fig. 8. Gripping force testing experiment setup. The gripper is fixed on a test stand, after reaching the desired temperature, the force gauge will drag a 3D printed cylinder upwards. Meanwhile, the software records both time and gripping force.

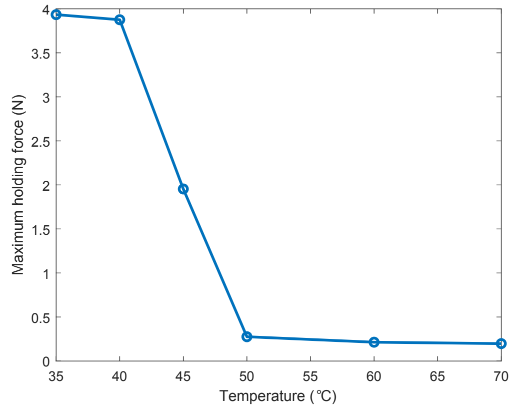


Fig. 9. Holding experiment result: the holding force increases drastically below the glass transition temperature due to increased stiffness.

was used to determine when the base's temperature reached the required temperature for the experiments. The power was then lowered until the gripper maintained the intended temperature during each test. The primary testing apparatus was a motorized tension/compression test stand (ESM303, Mark-10). With a force gauge (M5-2, Mark-10) connected, the stand can move with a constant speed both upward and downward while measuring both tensile and compressive force. The measuring range of M5-2 is 10 N with a precision of 0.002 N. A proprietary software (MESUR^{TM} gauge Plus, Mark-10) was used for recording the force and time data. Displacement was then calculated afterwards based on the set speed of the Mark-10 and the time taken for each test. A typical experiment scenario is shown in Fig. 8.

A. Holding experiment

The holding experiment aims to quantify how much force the gripper can "hold" (i.e., with its fingers wrapped around the object) with respect to its stiffness. A sphere was used in this test since the fingers could easily wrap around it. Objects with other geometries may generate higher holding forces, but they may also have edges that can catch on the rings of gripper or dig into the gripper itself, potentially creating inconsistent data. The sphere, with a diameter of 25 mm, was attached to the Test Stand using a taut copper cable to decrease the effect of tension and slack affecting the results. It was then slowly pulled out until it was completely removed from the gripper's fingers. The maximum force was then calculated and plotted for each tested temperature: 70, 60, 50, 45, 40, and 35 °C (Fig. 9).

As expected, the gripper's holding force is the largest when it is rigid. It then decreases proportionally to its stiffness as the SMP reaches its glass transition temperature, between 40 and 50°C. When the gripper is completely soft, further increasing the temperature will not further decrease the holding capability, which is illustrated by the plateau around 50-70°C. The maximum holding force when rigid was 3.93 N, meaning that it can hold 400.74 g when it is fully cooled down. Considering the weight of the gripper is only 6.8 g, the holding force to weight ratio when rigid is $59:1$.

B. Gripping Experiment

The gripping experiment was performed using the same testing setup as the holding experiment. However, the goal of this experiment was to find the force the fingers and rings put on an object (i.e., when the tips of all the four fingers contact the object). The results of this experiment should show an opposite trend when compared to the holding force experiment, because the rings could only exert pressure on an object when the gripper is soft. To generate consistent data, we use a cylinder object that is taller than the gripper's fingers, and let the gripper grab it vertically. The cylinder was tied to the Test Stand using a copper wire. It was then slowly pulled out of the gripper's fingers and the maximum force was calculated as the gripping force. The experiment is repeated for the following temperature: 70, 60, 50, 45, and 40 °C, and the results are plotted in Fig. 10.

From Fig. 10, the gripping force increases as the gripper heated through its glass transition temperature. The slope of the gripping force as it goes through the glass transition temperature is similar to that of the holding experiment. The results are expected as the gripping force is generated by the rings. As the fingers become softer, the rings could apply more force to the cylinder. The fully rigid state of the gripper at 40°C had the lowest gripping force, likely due to the fingers not applying any pressure when the cylinder slipped out of the fingers. In this case, the gripping force is simply due to the friction between the cylinder and the gripper as the cylinder was pulled out.

C. Opening Experiment

To properly actuate the gripper, we need to determine how much force is required to open the gripper when it is soft, as doing so when it's rigid would break the gripper. For the opening experiment, the gripper is initially closed. The opening force was determined at three different temperatures: 70, 60, and 50°C. If the temperature is below 50°C, the gripper would not release enough elastic potential energy

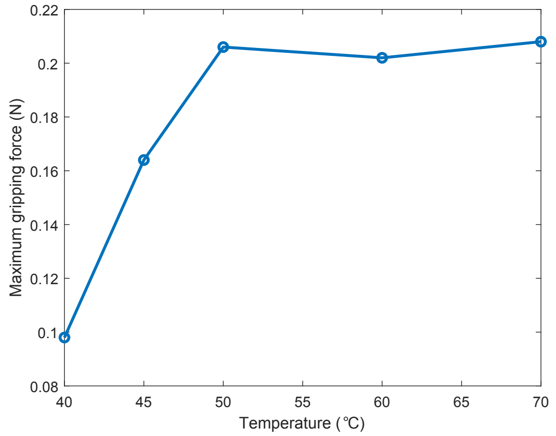


Fig. 10. Gripping experiment result: the gripping force decreases as the temperature decreases near the glass transition temperature.

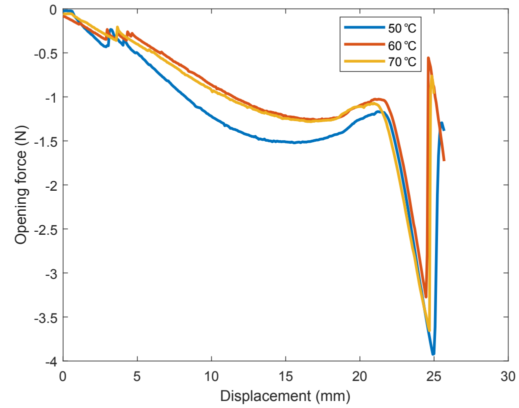


Fig. 11. Opening experiment result: the sharp point at the bottom of the curve indicates a change to open state.

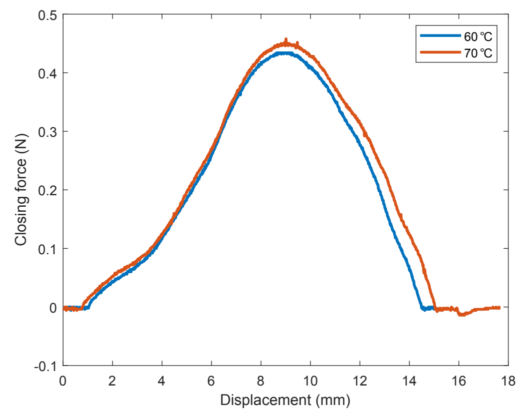


Fig. 12. Closing experiment result. After reaching the actuation force, the gripper closes, and the force is reduced.

to switch states due to its stiffness. The opening force measurements were taken by attaching the strings from the motor-driven system to the Test Stand. The strings are then drawn back by the test stand until the gripper switches to an open state. Fig. 11 shows the experiment results. The figure does not display a zero force when the gripper swaps from closed to open states due to the force attributed to compressing the piston when dragging back the strings at the beginning of the test. The lower spike shows the peak force needed for the gripper to begin swapping to an open state through stored elastic energy, and the second spike is due to the Mark-10 no longer applying force as the bistable mechanism is triggered.

The results in Fig. 11 show that it takes slightly more force to open a colder gripper (50 °C) than it does to open a warm one (60, 70 °C); however, the difference is almost negligible ($<$ 0.5 N). The difference between opening the gripper at 60°C and 70°C was negligible and likely due to a slight variance in test factors between warming up the gripper. The first sharp spike in the figure, at 25 mm displacement, shows the distinct change between open and closed states. This point is practically the same for all three temperatures tested, indicating that the gripper switches states at a very precise finger displacement.

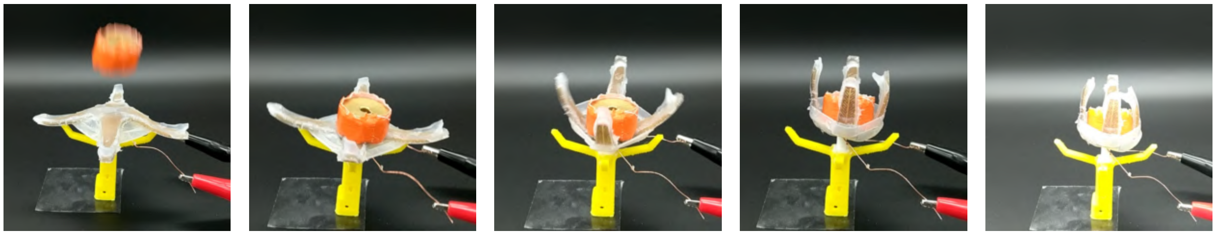
D. Closing Experiment

We also conducted closing experiments to quantify the force required for closing from an open state. Unlike the opening experiment, this experiment was only performed at two temperatures: 70 and 60°C. 50°C was just slightly stiffer than the higher temperatures and did not allow for the gripper to fully swap states. The experiment was performed by equipping the Test Stand with a press tip, which was then pushed into the center of the gripper while it was open. The force was recorded until the gripper swapped states. The motor mount was removed for the experiment as the friction from the mount and strings caused too much noise.

Fig. 12 shows the results for the experiment. From the figure, it takes slightly less than 0.5 N to close the gripper. This is consistent at either temperature. The differences between the closing actuation forces at 60 and 70°C were negligible as both of these temperatures were well above the glass transition temperature of the SMP. This experiment does show that it takes significantly less force to close the gripper than open it. This is due to the gripper being designed to be ”triggered” using elastic force in the open state.

E. Catching Experiment

A catching test was performed to characterize the motion of the gripper and to demonstrate its capability to catch falling objects without the aid of sensors/actuators. A 40 g weight was dropped from a height of 8 cm directly onto the gripper's palm. The gripper was heated to 70°C before the experiment and maintained at 70°C throughout the catching process. Fig. 13 shows the motion and speed of the gripper as it goes from open to closed states. This test confirms the gripper's ability to successfully grasp fast moving objects since the grasping process happens in less than 1 s which is fast enough to catch most objects that fall into the gripper's palm. This ability further expands the gripper's potential uses to allow for aerial grasping or perching without using complicated sensing and control algorithms.



(a) 0 seconds (b) 0.25 seconds (c) 0.5 seconds (d) 0.75 seconds (e) 1 second

Fig. 13. Catching test: a mass of 40 g was dropped from a certain height to demonstrate the gripper can passively close upon contact force to catch incoming objects.

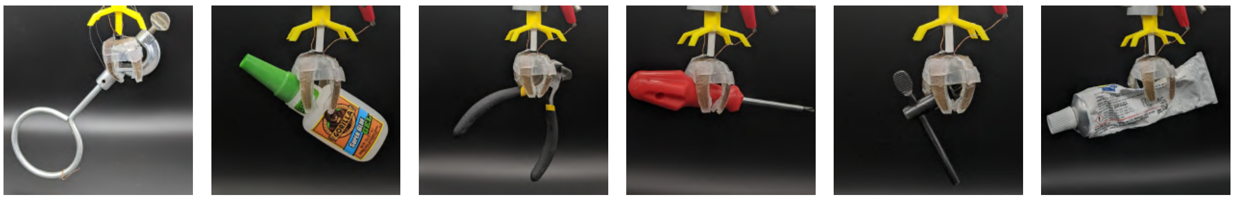


Fig. 14. The gripper can hold objects of varying weight and shapes.

F. Grasping Different Objects

We also conduct various experiments to demonstrate the grasping capability of the gripper. As shown in Fig. 14, the gripper can grasp a variety of objects and hold them. For each test, the gripper is heated and made to grasp an object. We then wait for 2 minutes to allow the gripper to fully cool down so that the objects can be held stably.

V. Conclusions

This paper details the design, fabrication, and experimentation of a bistable variable stiffness gripper. The gripper exhibits the advantages of both rigid and soft grippers, as well as having sensor-less grasping due to the actuation mechanism of the gripper. The variable stiffness of the gripper allows it to conform to the shape of complicated objects and become rigid to hold much larger weights. It gives the user some level of control, through temperature variation, on the forces that the gripper exerts on objects. We envision such a gripper will be particularly useful for aerial grasping and manipulation [17] as it can mold itself around a complicated object in its soft state, freeze around the object, lift up, and release the object upon Joule heating. Further, such grasping does not need sophisticated sensors/actuators, exhibiting mechanical intelligence that can alleviate the requirement for computational intelligence.

References

[1] N. Fazeli, M. Oller, J. Wu, Z. Wu, J. B. Tenenbaum, and A. Rodriguez, "See, feel, act: Hierarchical learning for complex manipulation skills with multisensory fusion," *Science Robotics*, vol. 4, no. 26, p. eaav3123, 2019.

[2] J. Shintake, V. Cacucciolo, D. Floreano, and H. Shea, "Soft robotic grippers," *Advanced Materials*, vol. 30, no. 29, p. 1707035, 2018.

[3] Q. Ze, X. Kuang, J. Wong, M. Montgomery, R. Zhang, J. Kovitz, F. Yang, j. Qi, and R. Zhao, "Magnetic shape memory polymers with integrated multifunctional shape manipulation," *Advanced Materials*, vol. 32, no. 4, p. 1906657, 2019.

[4] J. Amend, N. Cheng, S. Fakhouri, and B. Culley, "Soft robotics commercialization: Jamming grippers from research to product," *Soft robot*, vol. 3, no. 4, pp. 213–222, 2016.

[5] M. Behl, K. Kratz, J. Zotzmann, U. Nochel, and A. Lendlein, "Reversible bidirectional shape-memory polymers," *Advanced Materials*, vol. 25, no. 32, pp. 4466–4469, 2013.

[6] D. McCoul, S. Rosset, N. Besse, and H. Shea, "Multifunctional shape memory electrodes for dielectric elastomer actuators enabling high holding force and low-voltage multisegment addressing," *Smart Materials and Structures*, vol. 26, no. 2, pp. 1361–1371, 2016.

[7] A. Firouzeh and J. Paik, "Grasp mode and compliance control of an underactuated origami gripper using adjustable stiffness joints," *IEEE/ASME Transactions on Mechatronics*, vol. 22, no. 5, pp. 2165–2173, 2017.

[8] T. G. Thuruthel, S. H. Abidi, M. Cianchetti, C. Laschi, and E. Falotico, "A bistable soft gripper with mechanically embedded sensing and actuation for fast closed-loop grasping," *arXiv preprint arXiv:1902.04896*, 2019.

[9] H. Zhang, J. Sun, and J. Zhao, "Compliant bistable gripper for aerial perching and grasping," in *2019 International Conference on Robotics and Automation (ICRA)*, pp. 1248–1253, IEEE, 2019.

[10] K. Bertoldi, V. Vitelli, J. Christensen, and M. van Hecke, "Flexible mechanical metamaterials," *Nature Reviews Materials*, vol. 2, no. 11, pp. 1–11, 2017.

[11] T. Chen, J. Mueller, and K. Shea, "Integrated design and simulation of tunable, multi-state structures fabricated monolithically with multi-material 3d printing," *Scientific reports*, vol. 7, p. 45671, 2017.

[12] T. Chen, O. R. Bilal, K. Shea, and C. Daraio, "Harnessing bistability for directional propulsion of soft, untethered robots," *Proceedings of the National Academy of Sciences*, vol. 115, no. 22, pp. 5698–5702, 2018.

[13] J. A. Faber, A. F. Arrieta, and A. R. Studart, "Bioinspired spring origami," *Science*, vol. 359, no. 6382, pp. 1386–1391, 2018.

[14] P. Rothemund, A. Ainla, L. Belding, D. J. Preston, S. Kurihara, Z. Suo, and G. M. Whitesides, "A soft, bistable valve for autonomous control of soft actuators," *Science Robotics*, vol. 3, no. 16, p. eaar7986, 2018.

[15] L. L. Howell, "Compliant mechanisms," in *21st Century Kinematics*, pp. 189–216, Springer, 2013.

[16] T. L. Buckner, M. C. Yuen, S. Y. Kim, and R. Kramer-Bottiglio, "Enhanced variable stiffness and variable stretchability enabled by phase-changing particulate additives," *Advanced Functional Materials*, p. 1903368, 2019.

[17] A. McLaren, Z. Fitzgerald, and M. Liarokapis, "A passive closing, tendon driven, adaptive robot hand for ultra-fast, aerial grasping and perching," in *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems*.