2019 2nd IEEE International Conference on Soft Robotics (RoboSoft)
COEX, Seoul, Korea, April 14-18, 2019

An Origami-Inspired Monolithic Soft Gripper Based on Geometric Design Method

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***Abstract*— Soft end-effectors have great potential on object manipulation. The top-down approach using origami spring structure to create robots is increasingly spreading, with capabilities of simplification and acceleration for the design and fabrication procedure at low cost. In this study, a synergy is achieved through combination of origami pattern with 3D-printed soft robotics. In this letter, we have developed a monolithic soft gripper which deforms based on the constrained configuration space induced by origami structure. A geometric design method is proposed to model the hyperelastic deformation of elastomer material and the trajectory of fingertips is iteratively computed with residuals in geometric objective as approximated deformation using Newton's minimization method. Two characteristic tests quantifying the gripping capability of the soft gripper and a grasping demonstration of daily objects are conducted to show its practical performance. The experimental results indicate the linear relationship between input and output variables with a scale factor of 3.79 on the displacement amplification, showing that the required control scheme could be simple. Besides, handling a range of target objects presents the versatility and universality of the manipulator in daily life.**

I. INTRODUCTION

Nowadays soft robots are drawing increasing attention owing to their inherent advantages compared to rigid body robots, e.g. generally lighter on weight; mostly simpler on the structure; safer interaction with human; higher adaptability to external environments and various unknown tasks; free from the complex motion-control mechanisms [1]–[3]. With versatile 3D printing technology, fabrication of elastomer-bodied robots can be easily achieved which is generally challenging for conventional manufacture process [4]. Made from the deformable rubber-like soft materials, soft grippers have been developed with various actuation mechanisms, which basically can be divided into five categories [5], i.e. passive morphing structures and anthropomorphic hands with tendon-driven actuation; fluidic elastomer actuators by pneumatic and hydraulic sources depending on the application environment; electroactive-material-based actuation; shape memory polymer/alloy actuators (SMP/SMA) making use of phase transition property; and other actuation mechanisms including hydrogel actuation based on response to stimuli. Field of tendon-based actuation mechanism can date back to biomimetic systems [6] in which Hirose et al. [7] pioneered the study with a continuum manipulator which resembles a snake. Compared to the other actuation mechanisms, tendon-based actuation has advantages of supplying consistent input to the grasping system with the ease of control strategy.

Borrowed from the ancient Japanese art of science, the origami inspires researchers to create numerous origami patterns that can be transformed from a planar sheet into a complex 3D stereo morphology when actuated actively or passively based on the built-in compliance of geometry of folds and creases [8], [9]. Encouraged from these patterns, roboticists have developed origami robots whose functions automatically derive from the folding mechanisms on geometry [10], [11]. In the evolution of pattern design, it is discovered that some specific patterns [12], [13] hold a universality property, that is, starting from a single piece of paper sheet, any 3D silhouette, like the connected polygonal frame in [12], can be sculpted via folding, although the results indicate to be inefficient if utilized in practical applications [11]. Another interesting category called active origami patterns can generate motions based on the built structure [14]. These remarkable properties of computational geometry give a wide range of applications for origami structure including monolithic self-folding gripper. Several monolithic fingers [15], [16] and grippers [17]–[19] composed of flexible beams generated by computational methods based on buckling of structures are proved to be effective for handling diverse objects, although the buckling behavior is not incorporated into the optimization models [15].

Most previous grippers based on origami structures are initially designed as an integration of origami fingers with rigid base [20], [21]. The combination of flexible parts with rigid components suffers from the following weaknesses. First, the rigid parts may damage fragile objects with which contact is made; Second, folding regions of fingers tend to fatigue with repeated folding [20]; Third, the complex structures make the fabrication process and control strategy more complicated [21]. Although the origami pattern is innovative and comparable with that in our work, the magnetically-actuated origami gripper, Oriceps, created by Edmondson et al. [22]–[24] has several drawbacks. The limitation on the flexure geometry induces unnecessary deflection and thus unsatisfactory force transfer. In addition, driven by magnetic-active material, the output traction force is shown to be obviously smaller compared with other actuation mechanisms,

*Research is supported by the Hong Kong Innovation and Technology Fund (ITF) ITS-018-17FP.

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e.g. tendon and fluid. Thus to generate larger deflection on the fingertips, a larger-sized permanent magnet or a longer moment arm length for rotating torque is inevitable, any of which would result in an increase on inertia of fingers and not be appropriate for real implementations of grasping. Meanwhile, the C-magnets for generation of magnet field in [23], [24] are bulky, immobile and not easy to be shrunk on volume when a large magnet field is still necessary. As for manufacturing method, although currently multiple origami printing methods have been developed, e.g. lithography [25], ink writing [26] and 4D printing [27], etc., direct 3D printing via commercially-available printers provides a more convenient and mature technique with a lower cost and faster iteration speed for practical prototyping.

In this study, based on the previous researches, we develop a monolithic soft gripper (depicted in Fig. 1) combining a novel active origami pattern with tendon-based actuator. This soft origami gripper can transit self-shape between two configurations depending on geometric constraints to accomplish the opposite grasping motions of two fingers with a large ratio of output displacement to input movement distance. The crease pattern provides the geometrically-constrained motion trajectory while the tendon-based actuator can afford directional movement at specific input points (e.g. point P_2 in Fig. 2), endowing the whole system with grasping capability. Powered by tendon-based actuator, the gripper subject to geometric constraints with a certain degree of elastic deformation can be effectively switched between a flat-sheet mode and a gripping mode in which a wide range of daily objects can be stably held with a controllable blocking force.

The rest of the paper is organized as follows. Section II illustrates the design principle of the origami pattern, presents the kinematic mechanism of the monolithic gripper. Modelling of the geometric structure is proposed with a semi-rigid origami model in Section III. Section IV conducts the characteristic tests for the grasping performance, followed with a demonstration of real grasping application. Finally, in Section V, a conclusion is summarized and some future works are discussed. The main contributions of our work are concluded as follows.

- Taking advantages of the idea of synergies, combining the origami structure with 3D-printed soft robotics which holds the properties of ease of fabrication without postprocessing and simple control of the stiffness of the soft gripper.
- Design of a monolithic gripper based on a novel and simple origami pattern, with the capability of displacement amplification from input to output and the ease of controlling output force.
- Proposal of a geometric design method to model the trajectory of the fingertip by an approximately elastic deformation of joints using optimization algorithm.

II. Origami Folding Design

Origami is an art of folding flat sheets into 3D structures that can be implemented for shape morphing transformation, locomotion and manipulation [11]. For the convenience of folding, it is essential to design a pattern on the paper sheet which consequently consists of separated tiles with compliant creases connecting. Due to the stiffness variation between tiling blocks and joint creases, the plane sheet can be transformed toward target spatial configuration with little difficulty.

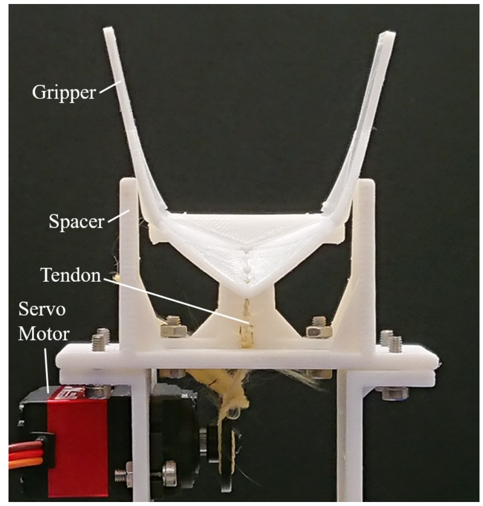


Fig. 1: Proposed soft gripper prototype with motor actuation and boundary condition of spacer.

A. Origami pattern

In this study, the pattern designed is analogous to the well-known diamond Yoshimura pattern [8]. However, unlike the translational motion under axial compression of Yoshimura buckle pattern [28], we subdivide the structure into smaller identical triangular element units (see red unit inset in Fig. 2(a)). With more units to be manipulated, more joints and DoFs can be acquired. Although a basic set of single and uniform element units can be used to produce a variety of shapes or motions, a particular set of various element units placed locally at a portion of the design integrated with a corresponding action set can provide a level of abstraction, further optimizing the design [29]. Thus for the convenience of manipulation control, some redundant DoFs should be eliminated through combination of neighbor tiles of creases. Consequently, the reconstructed structure is illustrated in Fig. 2(a). The whole pattern (solid black pattern in Fig. 2(a)) is composed of multiple uniform right triangular units (red-dotted pattern in Fig. 2(a)) and a combination of these triangles in the forms of larger triangular and diamond shapes. In practice, triangles and diamonds represent the tiles while the connecting edges denote the compliant joints.

B. Geometric transformation

Realization of gripping pose transition using geometric structure constraints stems from the inspiration of natural principle of folding paper. As stated in [9], the membrane film folded in two orthogonal directions can generate a vertex and the latter crease will make the former bent. Therefore, the two tiles connected by the former crease would be tightened

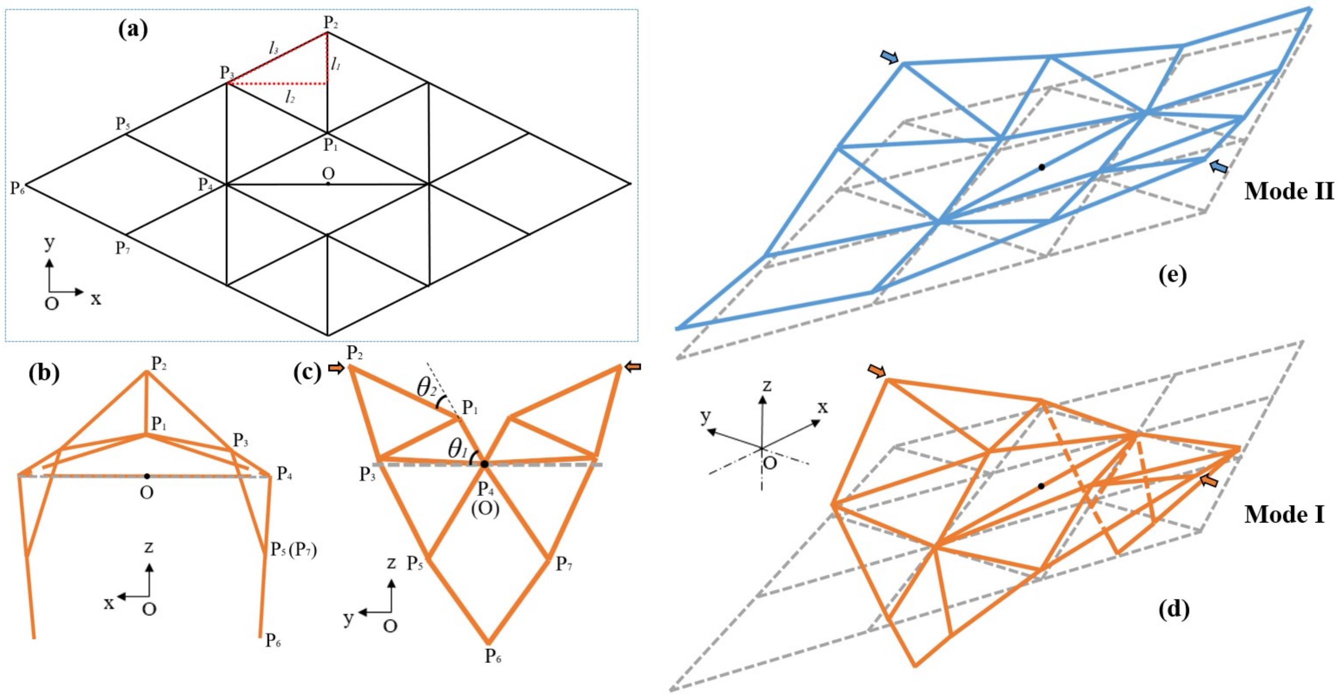


Fig. 2: Truss model for the designed origami pattern; (a) Crease pattern of folding elements that are validated to be suitable for monolith grippers (inset with red-dotted basic element unit), (b-d) Various perspectives of gripper during pose transition under Mode I, (d-e) Two modes of the origami pattern from the same initial pose (a) for the identical actuation under different initial boundary conditions.

and clung mutually, owing to the internal tensile stress in the crease. Similarly, from empirical perspective, a piece of non-stretchable paper separated by a crease into two segments, when encountered with an opposite and upward input displacement at the ends of the crease, due to the inherent stiffness and internal tensile force, would show a highly unstable response in the transient state that the linear crease would bend into a polyline and the two half sheets move closer towards each other, followed by a re-stabilization till a complete contact when the pattern settles to another localized energy minimum point.

In the design, it is assumed that the tiles are rigid with stretchable but unbendable edges in this pattern. Planar coordinate system with the origin O is inset in Fig. 2(a). Since the pattern, loading method and boundary conditions are bi-symmetrical about two diagonals, it is sufficient to analyze a quarter of the geometric configuration. Initially, the input actuation is set on two vertex points on the short diagonal of the whole diamond pattern, whose directions are opposite and upward on both points in the yOz plane (see Fig. 2(d)). When actuated, points on the short diagonal are above the xOy plane according to the rigid body transformation (see Fig. 2(c)). Meanwhile, with the origin fixed, bi-symmetry property induces the point P_4 to be consistently affixed. Because of the continuum identity of the monolithic body, point P_3 is stretched upwards for a certain distance, whose position is of ease to be acquired by combination of the known position of point P_1, P_2 and P_4 with the corresponding segment length. In fact, there are two stationary modes under the claimed actuation input, achieved with various boundary conditions (see Fig. 2(d-e)). If an appropriate initial pose is selected, rigid solid $P_4P_5P_6P_7$ can be restricted downwards into negative z region (shown in Fig. 2(b-d)), under the upward stress of point P_3 and fixed point P_4, the downward movement magnitude of rigid body $P_4P_5P_6P_7$ can be leveraged, which drives point P_6 to approximately rotate along axis of edge P_3P_4 at a specific rotating speed. In summary, this pattern can transfer the opposite-directional input at two diagonal vertices into a rotational trajectory at the end vertices of another diagonal.

III. Kinematic Modelling

As Balkcom et al. stated in [30], although the paper bending is essential for the mechanics of paper-folding, it is applicable and helpful to simplify the model of origami structure as rigid polygonal facets linked with revolute crease joints. Considering the property of soft material utilized in our study, a tolerance on the length of crease joints is applied while the polygonal tiles are assumed to be rigid and unbendable. Therefore, in this letter, we propose a geometric design method to model the trajectory of the fingertip by an approximated elastic deformation of joints using minimization algorithm in which a tolerance and weight on the edge deformation are adopted to achieve a reasonable set of point positions and make the structure self-consistent. In this paper, positions of each point P_i $(i = 1, 2, ..., 6)$ were iteratively optimized by a customized Python algorithm to describe the configuration of the folded origami pattern. Bi-symmetrical structure and external load simplify the analysis in the dynamic state, for which only a quarter part needs to be investigated.

Suppose the rotating angles of point P_1 and P_2 to be θ_1 and θ_2 respectively, the positions after rotation can be achieved via affine transformations by

$$P_O^{'}P_1^{'} = R(\theta_1) \cdot P_O P_1 \tag{1}$$

$$P_1^{'}P_2^{'} = R(\theta_1) \cdot (R(\theta_2) \cdot (P_1P_2 - P_OP_1) + P_OP_1) \tag{2}$$

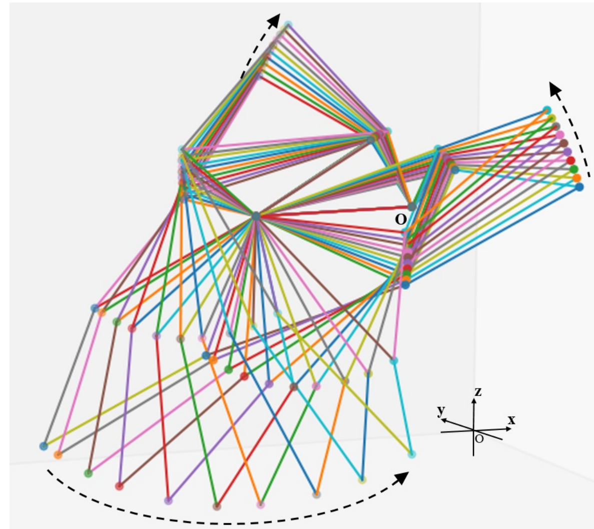
in which P_iP_j ($i = O, 1$ and $j = 1, 2$) denotes the original position of the corresponding segment vector, e.g. $P_OP_1 = [x_1\ y_1\ z_1]^T - [x_O\ y_O\ z_O]^T$; $P_i^{'}P_j^{'}$ ($i = O, 1$ and $j = 1, 2$) denotes the position of edge vector after motion; and $R(\theta_i)$ ($i = 1, 2$) denotes the corresponding rotation matrix.

To acquire the folded positions of point P_3 and P_5, due to the elasticity phenomenon on the edge of P_2P_3 and P_3P_5, when calculating the coordinate values of these points using geometric relationship, a tolerance tol (set to be 10 in this study after some numerical experiments) and a weight value w (set to be $[1, 1, 1, 1, 1, 1000]$ for F_i ($i = 1, 2, ..., 6$) in the optimization functions) are considered in the distribution of length variations based on the following minimization equation set. The optimization objective is to minimize the sum of the elastic deformation magnitude in the relative edges that interact with point P_3 and P_5. Let optimization domain $\Omega \subseteq \mathbb{R}^3$,

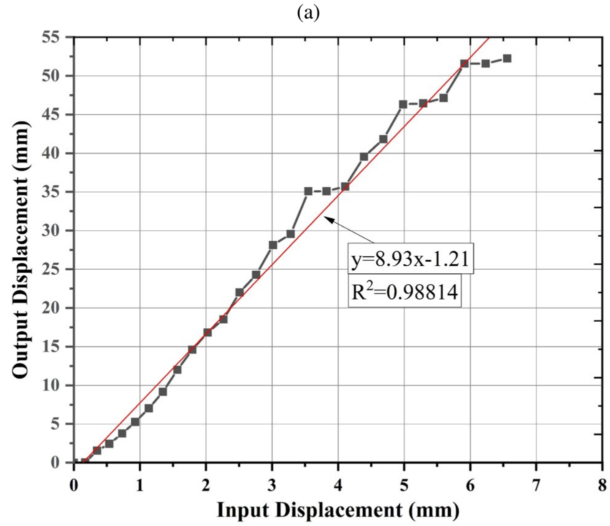
$$\begin{aligned} \underset{\Omega}{\text{minimize}} \quad & F = (||P_2P_3|| - l_3) \cdot w[0] \\ & + (||P_1P_3|| - l_3) \cdot w[1] \\ & + (||P_3P_4|| - 2l_1) \cdot w[2] \\ & + (||P_3P_5|| - l_3) \cdot w[3] \\ & + (||P_4P_5|| - l_3) \cdot w[4] \\ & + (y_5 - l_1) \cdot w[5] \\ \text{subject to} \quad & z_5 \leqslant 0 \ , \\ & P_4 = C \end{aligned} \tag{3}$$

where $||P_iP_j||$ ($i = 1, 2, 3, 4$ and $j = 3, 4, 5$) denotes the l^2-norm of the corresponding edge vector; l_i ($i = 1, 2, 3$) denotes the length of basic triangular unit (see Fig. 2(a)); y_5 and z_5 are the coordinate values of point P_5 on y and z axes respectively; and C denotes a specific constant value, representing that the point P_4 is affixed. Using an algorithm with Newton's methods, the minimization equations can be numerically solved by systematically seeking a stationary point of the functions, with coefficient tol acting as the termination criteria of the minimization iteration.

With the coordinate values of point P_5, the position of point P_6 on the rigid solid $P_4P_5P_6P_7$ is determined by principle of rigid body rotation and symmetry property of the structure. Fig. 3 presents the simulated pose transformation process of a half part of the soft gripper and the fitted relationship between input and output displacements.



(a)



(b)

Fig. 3: Simulated results of the proposed model; (a) Procedure diagram of pose transition for half side of the origami structure, (b) Fitted relationship curve between the variation of input distance and fingertip displacement.

IV. Experiments and Results

In this section, two performance tests and grasping demonstration are conducted to characterize the gripper designed and modelled in the previous sections. First, the dimension and fabrication details of the gripper are included. Next, the experiment platform layout is also clearly stated. Afterwards, two characterizing experiments are operated which contain actuation stroke test and grasping force test to validate the design proposal and disclose its grasping capability. Finally, a demonstration of grasping daily objects is proceeded to show the practical performance of the soft gripper.

A. Gripper prototype

Although nowadays casting and moulding have been widely used in soft body robotics field [31], direct 3D printing technology has offered a powerful tool for soft robotics,

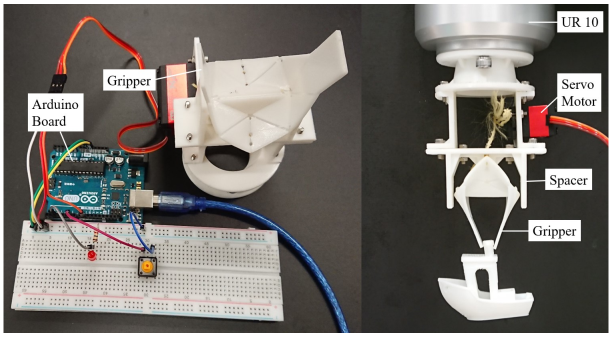


Fig. 4: An illustration of experimental setup. The gripper system is affixed on the UR10 manipulator, with motor connected with Arduino control board for switch.

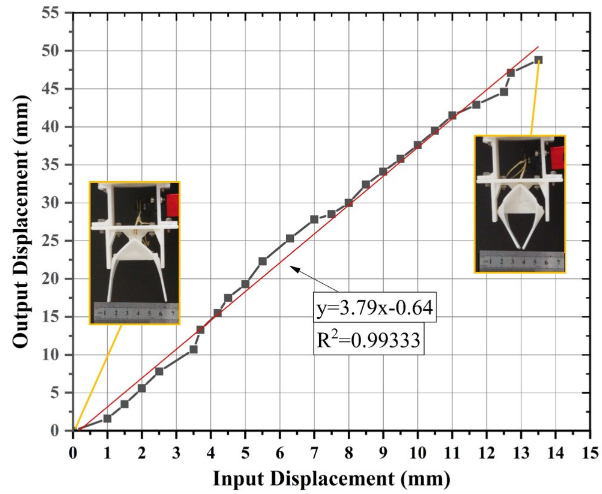


Fig. 5: Curve of fingertip gap displacement vs. actuation pulling distance during sequential steps and relationship with linear fitting (insets of measurement states at the start and end points).

especially with complex geometry shapes, to shorten the iteration period between modelling and prototyping [4]. In this work, the origami structure for soft gripper (as shown in Fig. 1) is monolithically printed by a commercially-available fused-deposition-modeling (FDM) 3D printer (Ultimaker 2+, Ultimaker) with parameters customized. With various hardness of thermoplastic polyurethane (TPU) filament and diverse infill percentage, the stiffness of soft gripper can be tuned. Here, we use a TPU with shore harness of 95 A and the infill percentage is set to be 100%, considering the presumed assumptions in the modelling and the requirements for practical grasping manipulation. The dimension of basic element triangle in Fig. 2(a) is 10×20mm on l_1 and l_2 respectively. Diamonds and larger triangles are the combination of the elements, which can be further calculated individually, connected with crease width of 1.2 mm. The thickness of tiles and creases are set to be 1.8 mm and 0.6 mm correspondingly based on empirical experience after some experimental tests. For a better interaction with target objects, the fingertip tiles are revised to be rectangular with a larger contacting area. The spacer and fixtures are 3D-printed by the same machine with different parameters using rigid PLA filament.

B. Experimental setup

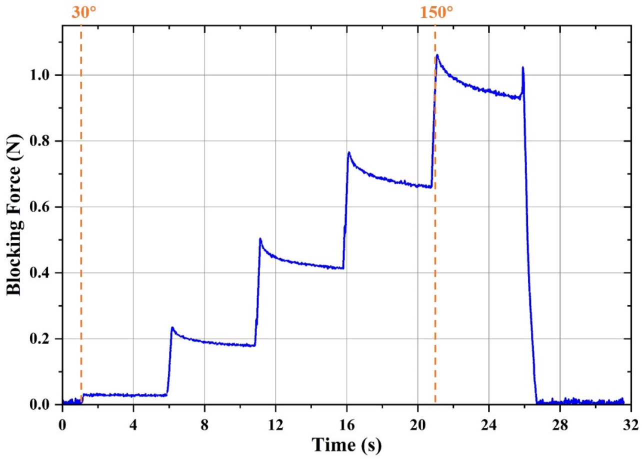
An illustration of experimental setup is presented in Fig. 4. A universal robot arm (UR10, Universal Robots) acts as a manipulator to localize target objects, with a control accuracy of 0.1mm. The origami gripper prototype is driven by a servo motor (PDI-HV5932MG, JX Servo) through cable tension. For the cable, it is attached from the ends of the short diagonal of the pattern (e.g. point P_2 in Fig. 2) to the roller mounted on the servo motor. The servo motor is connected to a controller board (Arduino UNO microcontroller) to switch the input signal manually. A spacer is also arranged for the initial boundary condition of pose transition. For the blocking force test, a force/torque sensor (ATI mini 27 Force/Torque sensor, ATI Industrial Automation, with measurement resolution of 0.015 N on F_y and 0.03 N on F_z) is installed on the base platform.

C. Characterization of gripping performance

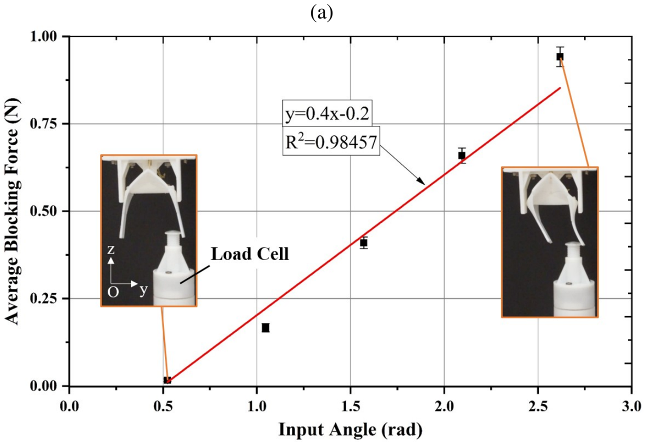
1) Gripping stroke test: In this test, the position shift of fingertips is investigated upon cable driving with discrete increasing magnitude of rotating angles which correspond to different cable pulling distances. The actuation procedure is separated into 30 sequential steps, each of which is a five-degree rotational input, with 5-second delay during intervals for measurement in stationary state. For the versatility of the test results, in this study, the measured pulling distance is designated as the input variable. The gripper is actuated by a cable attached on the ends of a diagonal as an input, while the output is measured at the tips of another diagonal (e.g. point P_6 in Fig. 2). A scale factor is calculated as the ratio of output contraction distance to input pulling distance. A camera is placed in front to record the position change of markers attached to the fingertips in the procedure and the test results are shown in Fig. 5.

In Fig. 5, a curve of fingertip gap distance vs. displacement on input points is presented with insets of gripping states at the start and end points. At the start point, the fingers are out of cable tension and blocked by the spacer. Afterwards it shows that under the actuation of servo motor, the fingertips move closer. Starting from the 5 th to the 30 th step, the servo motor rotates 26 times and the data indicate the fingertip gap is linearly correlated with the input displacement, which can be fitted with linear least square method. The scale factor is easily acquired to be 3.79 which means the output contraction distance is augmented by 3.79 times, comparing with the input pulling distance of the servo motor.

2) Blocking force test: To evaluate the maximum normal force that the finger can generate on the target objects, blocking force test is carried out with the setup layout exhibited in Fig. 4. The gripper is also hung on the fixture and bounded by the spacer. With the fixed force/torque sensor, the produced normal force on the contacting area is explicitly measured. Considering the contacting point when



(a)



(b)

Fig. 6: Output force test results; (a) Force vs. time curve for 5 steps in series, (b) Relationship between average force in each step and rotational angle of motor (insets of measurement scenarios at the stationary states).

interacting with real objects, the protruder on the force/torque sensor is placed above the fingertip with a distance of 4 mm. Similar to the stroke test, the procedure of blocking force test is separated into 5 continual steps with a five-second interval. At the starting point, the pulling cable is free of tension and the fingers are restricted by the spacer. The force/torque sensor is attached to the finger surface without interaction force. During the actuating procedure, the finger deforms to an irregular curve, owing to the compliant nature of the soft material. Thus the surface normal of the gripper is not a static vector, which leads the target grasping force to be the resultant force on both y axis (F_y) and z axis (F_z). The output force on the fingertip is explicitly measured and analyzed subsequently presented in Fig. 6(a). It indicates that the output force has a consistent increasing tendency with the rotating angle which is set to be a step function. At each pulse, there is a peak generated on the output force, which generally lowers down afterwards. This is probably a phenomenon that due to the visco-elasticity and hysteresis properties of the soft material, the input pulses during dynamic states need intervals to transit to quasi-static states and final stationary states. To quantitatively evaluate the relationship between output force and input rotating angle, the average force values as well as standard deviations in each step have been evaluated based on five repetitions on the measurement process and the results are plotted in Fig. 6(b). The output force reaches 1.06 N when the servo motor rotates to 150°. Data drawn shows a highly positive linear correlation between the two variables.

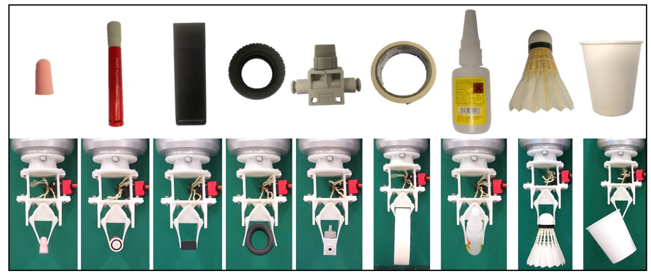


Fig. 7: Daily objects that can be grasped, lifted to show the success. Target objects includes an earplug, a marker pen, a USB, a rubber tire, a pneumatic adaptor, a tape, a bottle with fluid, a badminton and a paper cup.

3) Grasping demonstration: To explore the potential of the soft gripper, a wide range of objects are selected for handling as summarized in Fig. 7. When grasping target objects, soft gripper may change self-mode to satisfy the grasping scenario, i.e. power grasp mode, precision grasp mode or the combination of both modes [15]. Power grasp mode is applied when the target object is harder than the gripper, e.g. in this study, when grasping a marker pen, a USB and a badminton, the gripper will deform and try to conform to the objects. When the object is softer than the gripper, the precision mode works, e.g. in our work, an earplug and a rubber tire are gripped, embraced with an amount of passive deformation. Although the fingertip is not ideally optimized, the gripper still has the capability to stably grasp a variety of objects based on the geometric advantage of origami complaint structures.

V. Conclusion

In this letter, we have developed a monolithic soft gripper based on a novel origami pattern. The gripper can generate fingertip motions depending on the geometric constraints of the origami structure. A semi-rigid model is proposed with a geometric design method using minimization algorithm for the hyperelastic deformation of elastomer material. A soft origami pattern has been prototyped through 3D printing technology with soft elastomer. Through experiments, the gripper is validated with properties of amplification mechanism and ease of linear control. In this study, we take advantage of synergies by combination of origami spring structure with 3D-printed soft robotics. This letter shows the potential to apply the origami field with the 3D printing technique of soft matters, the combination of which has the restorable motion instead of buckling mechanism in the conventional paper-origami gripper that are sensitive to the fatigue of repetitive folding and unfolding [20], [28].

However, some limitations and challenges in the modelling of soft origami structure to simulate the motion still remains to be a problem. In this letter, comparing the modelling simulation and experimental results (Fig. 3(b) and Fig. 5 respectively), the tendency of the grasping trajectory with a specific amplification mechanism has been correctly simulated, while the approximate geometric model is a little imprecise on the scale factor of amplifying mechanism because of the simplification of the assumptions and a lack of material properties.

The future of soft origami actuators is promising due to their superior characteristics. In the next step, bar-and-hinge models [32] with material properties shall be involved in the modelling to computationally set the weight values and decrease the discrepancy between the practical and simulated scale factors. Miniaturization of the structure of origami actuator can be further achieved by substituting the electromagnetic motor with more compact actuators, e.g. smart materials [11]. In the future research, we intend to employ shape memory polymer actuator, like super-coiled nylon thread, with the origami structure to further compress the size of the gripper without affecting its mobility property.

REFERENCES

[1] G. M. Whitesides, "Soft robotics," *Angewandte Chemie International Edition*, vol. 57, no. 16, pp. 4258–4273, 2018.

[2] C. Majidi, "Soft robotics: a perspective—current trends and prospects for the future," *Soft Robotics*, vol. 1, no. 1, pp. 5–11, 2014.

[3] C. Laschi, B. Mazzolai, and M. Cianchetti, "Soft robotics: Technologies and systems pushing the boundaries of robot abilities," *Sci. Robot.*, vol. 1, no. 1, p. eaah3690, 2016.

[4] H. K. Yap, H. Y. Ng, and C.-H. Yeow, "High-force soft printable pneumatics for soft robotic applications," *Soft Robotics*, vol. 3, no. 3, pp. 144–158, 2016.

[5] J. Shintake, V. Cacucciolo, D. Floreano, and H. Shea, "Soft robotic grippers," *Advanced Materials*, p. 1707035, 2018.

[6] D. B. Camarillo, C. F. Milne, C. R. Carlson, M. R. Zinn, and J. K. Salisbury, "Mechanics modeling of tendon-driven continuum manipulators," *IEEE Transactions on Robotics*, vol. 24, no. 6, pp. 1262–1273, 2008.

[7] S. Hirose and Y. Umetani, "The development of soft gripper for the versatile robot hand," *Mechanism and machine theory*, vol. 13, no. 3, pp. 351–359, 1978.

[8] Y. Yoshimura, "On the mechanism of buckling of a circular cylindrical shell under axial compression," 1955.

[9] K. Miura, "Method of packaging and deployment of large membranes in space," *Title The Institute of Space and Astronautical Science Report*, vol. 618, p. 1, 1985.

[10] C. D. Onal, R. J. Wood, and D. Rus, "An origami-inspired approach to worm robots," *IEEE/ASME Transactions on Mechatronics*, vol. 18, no. 2, pp. 430–438, 2013.

[11] D. Rus and M. T. Tolley, "Design, fabrication and control of origami robots," *Nature Reviews Materials*, p. 1, 2018.

[12] E. D. Demaine, M. L. Demaine, and J. S. Mitchell, "Folding flat silhouettes and wrapping polyhedral packages: New results in computational origami," *Computational Geometry*, vol. 16, no. 1, pp. 3–21, 2000.

[13] D.-Y. Lee, S.-R. Kim, J.-S. Kim, J.-J. Park, and K.-J. Cho, "Origami wheel transformer: A variable-diameter wheel drive robot using an origami structure," *Soft robotics*, vol. 4, no. 2, pp. 163–180, 2017.

[14] C. C. Min and H. Suzuki, "Geometrical properties of paper spring," in *Manufacturing Systems and Technologies for the New Frontier*. Springer, 2008, pp. 159–162.

[15] F. Chen, W. Xu, H. Zhang, Y. Wang, J. Cao, M. Y. Wang, H. Ren, J. Zhu, and Y. Zhang, "Topology optimized design, fabrication, and characterization of a soft cable-driven gripper," *IEEE Robotics and Automation Letters*, vol. 3, no. 3, pp. 2463–2470, 2018.

[16] C.-H. Liu, T.-L. Chen, C.-H. Chiu, M.-C. Hsu, Y. Chen, T.-Y. Pai, W.-G. Peng, and Y.-P. Chiang, "Optimal design of a soft robotic gripper for grasping unknown objects," *Soft robotics*, 2018.

[17] Y. Liu and M. Y. Wang, "Topology design of a conforming gripper with distributed compliance via a level set method," in *Robotics and Biomimetics (ROBIO), 2014 IEEE International Conference on*. IEEE, 2014, pp. 2191–2196.

[18] C.-H. Liu and C.-H. Chiu, "Optimal design of a soft robotic gripper with high mechanical advantage for grasping irregular objects," in *Robotics and Automation (ICRA), 2017 IEEE International Conference on*. IEEE, 2017, pp. 2846–2851.

[19] B. Zhu, M. Skouras, D. Chen, and W. Matusik, "Two-scale topology optimization with microstructures," *ACM Transactions on Graphics (TOG)*, vol. 36, no. 5, p. 164, 2017.

[20] D. Jeong and K. Lee, "Design and analysis of an origami-based three-finger manipulator," *Robotica*, vol. 36, no. 2, pp. 261–274, 2018.

[21] R. Niiyama, X. Sun, C. Sung, B. An, D. Rus, and S. Kim, "Pouch motors: Printable soft actuators integrated with computational design," *Soft Robotics*, vol. 2, no. 2, pp. 59–70, 2015.

[22] B. J. Edmondson, L. A. Bowen, C. L. Grames, S. P. Magleby, L. L. Howell, and T. C. Bateman, "Oriceps: Origami-inspired forceps," in *ASME 2013 conference on smart materials, adaptive structures and intelligent systems*. American Society of Mechanical Engineers, 2013, pp. V001T01A027–V001T01A027.

[23] E. W. Wilcox, A. Shrager, L. Bowen, M. Frecker, P. Von Lockette, T. Simpson, S. Magleby, R. J. Lang, and L. L. Howell, "Considering mechanical advantage in the design and actuation of an origami-based mechanism," in *ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers, 2015, pp. V05BT08A055–V05BT08A055.

[24] J. Butler, L. Bowen, E. Wilcox, A. Shrager, M. I. Frecker, P. von Lockette, T. W. Simpson, R. J. Lang, L. L. Howell, and S. P. Magleby, "A model for multi-input mechanical advantage in origami-based mechanisms," *Journal of Mechanisms and Robotics*, vol. 10, no. 6, p. 061007, 2018.

[25] D. Deng and Y. Chen, "Origami-based self-folding structure design and fabrication using projection based stereolithography," *Journal of Mechanical Design*, vol. 137, no. 2, p. 021701, 2015.

[26] B. Y. Ahn, D. Shoji, C. J. Hansen, E. Hong, D. C. Dunand, and J. A. Lewis, "Printed origami structures," *Advanced Materials*, vol. 22, no. 20, pp. 2251–2254, 2010.

[27] Q. Ge, C. K. Dunn, H. J. Qi, and M. L. Dunn, "Active origami by 4d printing," *Smart Materials and Structures*, vol. 23, no. 9, p. 094007, 2014.

[28] G. W. Hunt and I. Ario, "Twist buckling and the foldable cylinder: an exercise in origami," *International Journal of Non-Linear Mechanics*, vol. 40, no. 6, pp. 833–843, 2005.

[29] C. D. Onal, R. J. Wood, and D. Rus, "Towards printable robotics: Origami-inspired planar fabrication of three-dimensional mechanisms," in *Robotics and Automation (ICRA), 2011 IEEE International Conference on*. IEEE, 2011, pp. 4608–4613.

[30] D. J. Balkcom and M. T. Mason, "Robotic origami folding," *The International Journal of Robotics Research*, vol. 27, no. 5, pp. 613–627, 2008.

[31] D. Rus and M. T. Tolley, "Design, fabrication and control of soft robots," *Nature*, vol. 521, no. 7553, p. 467, 2015.

[32] E. Filipov, K. Liu, T. Tachi, M. Schenk, and G. Paulino, "Bar and hinge models for scalable analysis of origami," *International Journal of Solids and Structures*, vol. 124, pp. 26–45, 2017.