2019

Fully 3D printed monolithic soft gripper with high conformal grasping capability

Charbel Tawk
University of Wollongong, charbel@uow.edu.au

Yuan Gao
University of Wollongong, yg984@uow.edu.au

Rahim Mutlu
University of Wollongong, rmutlu@uow.edu.au

Gursel Alici
University of Wollongong, gursel@uow.edu.au

Fully 3D printed monolithic soft gripper with high conformal grasping capability

Abstract

The recent advances in material science and engineering disciplines have had a significant impact on the robotics field where numerous bioinspired soft robots have been developed. Roboticists can now develop and fabricate soft robotic systems made of materials with low elasticity using additive manufacturing technologies. One of the most studied classes of soft robotic systems is soft adaptive grippers. In this work, we present a novel fully 3D printed soft pneumatic gripper that incorporates a novel design of soft pneumatic chambers and a bioinspired fin-ray structure for conformal grasping. The soft gripper was printed in a single step using a low-cost and open-source fused deposition modeling (FDM) 3D printer and a commercially available thermoplastic poly(urethane) (TPU). A soft pneumatic actuator representing each finger of the gripper was optimized using finite element modeling (FEM). The FEM simulations predicted accurately the performance of the actuator in terms of deformation and blocked force. The high conformability of the proposed soft gripper was validated experimentally. The soft gripper was demonstrated lifting a heavy load and grasping a wide variety of objects with different weights, shapes, textures and stiffnesses.

Disciplines

Engineering | Science and Technology Studies

Publication Details

Tawk, C., Gao, Y., Mutlu, R. & Alici, G. (2019). Fully 3D printed monolithic soft gripper with high conformal grasping capability. IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM (pp. 1139-1144). United States: IEEE.

C. Tawk, Y. Gao, R. Mutlu and G. Alici, "Fully 3D Printed Monolithic Soft Gripper with High Conformal Grasping Capability," *2019 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, Hong Kong, China, 2019, pp. 1139-1144.

Fully 3D Printed Monolithic Soft Gripper with High Conformal Grasping Capability

Charbel Tawk, Yuan Gao, Rahim Mutlu and Gursel Alici

Abstract— **The recent advances in material science and engineering disciplines have had a significant impact on the robotics field where numerous bioinspired soft robots have been developed. Roboticists can now develop and fabricate soft robotic systems made of materials with low elasticity using additive manufacturing technologies. One of the most studied classes of soft robotic systems is soft adaptive grippers. In this work, we present a novel fully 3D printed soft pneumatic gripper that incorporates a novel design of soft pneumatic chambers and a bioinspired fin-ray structure for conformal grasping. The soft gripper was printed in a single step using a low-cost and open-source fused deposition modeling (FDM) 3D printer and a commercially available thermoplastic poly(urethane) (TPU). A soft pneumatic actuator representing each finger of the gripper was optimized using finite element modeling (FEM). The FEM simulations predicted accurately the performance of the actuator in terms of deformation and blocked force. The high conformability of the proposed soft gripper was validated experimentally. The soft gripper was demonstrated lifting a heavy load and grasping a wide variety of objects with different weights, shapes, textures and stiffnesses.**

I. Introduction

The recent advances in science and engineering disciplines have enabled roboticists to develop bioinspired soft robots that mimic their biological counterparts. Soft robotics is a multi-disciplinary research field that focuses on developing soft actuators, soft and stretchable sensors, soft power sources and soft active structures for a wide variety of soft robotic applications. Soft robots are made of highly deformable and compliant materials that can sustain large deformations repeatably. Bioinspired soft robots were developed to mimic soft biological bodies such as elephant trunks [1, 2], octopus' arms [3], snakes [4], fish [5], worms [6] and caterpillars [7]. Soft robots have many advantages compared to conventional robots such as adaptability, conformability, agility and durability [8]. Due to these advantages, several applications based on soft robotic concepts were developed including soft grippers [9, 10], locomotion robots [11, 12], medical devices [13] and many others [14].

Conventional robotic grippers have been extensively studied for tasks involving picking and placing a wide variety of objects. However, these conventional robotic systems are made of rigid and stiff materials which make them unsuitable to operate in dynamic environments. Also, they require complex machining, laborious assembly processes and multiple sensors onboard [15]. Due to the high Young's modulus of the components used in conventional robotic grippers, control algorithms are needed to ensure that a sufficient but not excessive grasping force is applied without damaging the objects being handled. Grasping delicate objects using these systems require sophisticated control methods with additional sensory feedback. Soft grippers that are made of highly deformable and compliant materials can be an uncomplicated alternative. First, these soft grippers can be manufactured rapidly using low-cost and off-the-shelf soft materials. Second, they can grasp and interact with a wide variety of objects without requiring any sensors and complex control methods. Third, they are safe to operate alongside humans due to their inherent softness. Finally, they can be customized and tailored to different applications easily by employing various manufacturing techniques that include molding and 3D printing. Developing universal grippers that can pick and place any arbitrary object is still a challenge for both soft and rigid grippers. The realization of a stable and firm grip requires an adequate contact area between the object being handled and the gripper. Generally, rigid and soft robotic grippers adopt a multi-finger design that is inspired by the human hand which has been accepted as a perfect model for grippers [16].

Several types of soft grippers have been proposed in the literature. Although these grippers can accomplish conformal grasping tasks, they require complicated and laborious fabrication methods involving multiple manufacturing steps [17]. Due to the intrinsic compliance and adaptability of soft robotic systems [18], a soft robotic gripper can generate highly passive deformations and adapt itself compliantly to the shape of an object being handled.

Pneumatic soft actuators are one of the most used actuators for soft robotic applications since they can be easily and rapidly manufactured using different techniques. Also, complex topologies can be achieved using soft pneumatic actuators and 3D printing to generate various modes of deformations for soft grippers. The main types of soft pneumatic actuators used to drive soft grippers are PneuNets [19-24] and fiber-reinforced actuators [25-28]. Recent manufacturing techniques proposed to fabricate soft grippers using additive manufacturing methods include FDM 3D

*This study was partly supported by the Startup Grant and Global Challenges Program Seed Grant from the University of Wollongong, Australia.

R. Mutlu (*corresponding author, rmutlu@uow.edu.au), C. Tawk (ct887@uowmail.edu.au) and G. Alici (gursel@uow.edu.au) are with Applied Mechatronics and Biomedical Engineering Research (AMBER) Group, School of Mechanical, Materials, Mechatronic and Biomedical Engineering, and ARC Centre of Excellence for Electromaterials Science, University of Wollongong, NSW, 2522, Australia.

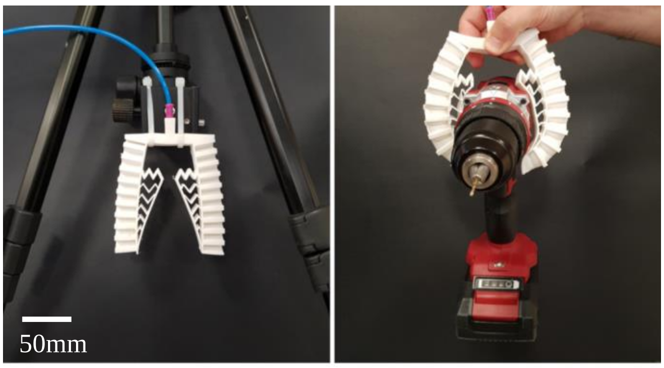
Y. Gao (yg384@uowmail.edu.au) is with School of Mechanical, Materials, Mechatronic and Biomedical Engineering, University of Wollongong, NSW, 2522, Australia.

C. Tawk, Y. Gao, R. Mutlu and G. Alici, "Fully 3D Printed Monolithic Soft Gripper with High Conformal Grasping Capability," *2019 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, Hong Kong, China, 2019, pp. 1139-1144.

printing [29-31], multi-material 3D printing [32-33] and silicone 3D printing [34].

The major contributions of this study are to develop a novel soft actuator (i.e. soft and 3D printed soft finger for a soft gripper) which eliminates contact friction between inflating chambers as in PneuNet actuators and to use a modified fin-ray structure to enhance the grasping capability of the soft gripper and achieve a highly conformable soft grip.

In this study, we developed a fully 3D printed soft pneumatic gripper with conformal capability using a low-cost and open-source FDM 3D printer and a commercially available thermoplastic poly(urethane) (Fig. 1). The gripper was printed in a single step without requiring any support material and post-processing. A soft pneumatic actuator involving a novel design of pneumatic chambers was developed and characterized. The performance of the soft actuator was optimized using FEM in terms of deformation and blocked force. The FEM simulations predicted the behavior of the actuator accurately. A single actuator generates a tip blocked force of 4.26N. Two actuators coupled with a bioinspired fin-ray structure that enhances the gripping capabilities of the gripper were designed and 3D printed to realize the soft gripper as shown in Fig. 2. The soft gripper was demonstrated lifting a load of 1.60kg. Also, we demonstrated that the gripper can grasp a wide variety of objects with different weights, shapes, textures and stiffnesses.



(a) (b)

Fig. 1. (a) The fully 3D printed soft monolithic gripper with conformal capability. (b) The soft gripper lifting a 1.60kg electric screwdriver.

II. Materials And Methods

In this work, we used a low-cost and open-source FDM 3D printer (FlashForge Creator Pro, FlashForge Corporation) to fabricate the soft gripper in one manufacturing step without requiring any support material and post-processing. The main advantage of using such a 3D printer is the ability to manufacture monolithic soft structures in one manufacturing step using commercially available soft materials. A commercially available thermoplastic poly(urethane) (TPU) known commercially as NinjaFlex (NinjaTek, USA) was used to 3D print the soft gripper. The computer-aided-design (CAD) models were designed and modeled in Autodesk Fusion 360 (Autodesk Inc.). The CAD models were sliced using a commercially available slicer (Simplify3D LLC, OH) where the printing parameters were set and adjusted based on recent studies on 3D printing soft pneumatic actuators and sensors using FDM 3D printing [31,35]. The soft pneumatic actuators and the full soft gripper were printed along their width (W) (Fig. 2.) to ensure that no support material is required during the 3D printing process. The printing parameters were optimized and adjusted to obtain airtight soft pneumatic actuators. The 3D printing parameters are listed in Table I.

The 3D printed prototypes were activated using a positive-pressure pneumatic pump (AEG Mini Wheelbarrow Compressor, 19L, 10Bar, Australia). The pressure was directly controlled from Matlab (The MathWorks, Inc.) using a pressure regulator and pneumatic controllers.

TABLE I. TPU Printing parameters

Parameter	*Value*	*Unit*
Resolution Settings		
Primary Layer Height	0.1	mm
First Layer Height	0.09	mm
First Layer Width	0.125	mm
Extrusion Width	0.4	mm
Retraction Settings		
Retraction Length	4	mm
Retraction Speed	40	mm/s
Speed Settings		
Default Printing Speed	10	mm/s
Outline Printing Speed	8	mm/s
Solid Infill Speed	8	mm/s
First Layer Speed	8	mm/s
Temperature Settings		
Printing Temperature	240	°C
Heat Bed Temperature	32	°C
Infill Settings		
Infill Percentage	100	%
Infill/Perimeter Overlap	30	%
Thin Wall and Movements Behavior		
Allowed Perimeter Overlap	25	%
External Thin Wall Type	Perimeter Only	-
Internal Thin Wall Type	Single Extrusion	-
Avoid Crossing Outline	ENABLED	-
Detour Factor	100	-
Additional Settings		
Extrusion Multiplier	1.15	-
Outline/Perimeter Shells	3	-
Support Material	DISABLED	-

C. Tawk, Y. Gao, R. Mutlu and G. Alici, "Fully 3D Printed Monolithic Soft Gripper with High Conformal Grasping Capability," *2019 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, Hong Kong, China, 2019, pp. 1139-1144.

III. Design of the Monolithic Soft Gripper

The primary objective of this study was to develop a fully 3D printed, low-cost and soft monolithic [36] gripper with high conformal capabilities. To achieve this aim, soft pneumatic bending actuators were coupled with bioinspired and modified fin-ray structures as shown in Fig. 2. The fin-ray structure was also studied and optimized using FEM modeling to assess its behavior in terms of deformation. Several designs were considered and simulated to enhance the bending motion of the rays and to ensure that the overall gripper is conformal. The soft pneumatic positive-pressure actuators were designed to provide the bending motion required to drive the soft gripper and to generate the necessary grip forces required for grasping different objects. A Zig-Zag design was chosen for the soft pneumatic chambers to avoid any contact between the walls of the adjacent chambers when the actuator is inflated. The bottom layer of the actuator is a strain-limiting layer that prevents the actuator from elongating. This Zig-Zag design prevents any energy losses due to the contact between adjacent pneumatic chambers as in conventional PneuNets soft actuators. These soft actuators are the active component of the gripper. The incorporated fin-ray structures on both sides are the passive component of the soft gripper. The main function of these bioinspired structures is to enhance the conformability of the soft gripper. When the gripper comes in contact with an arbitrary object, the structure will adapt to the shape of the object which will result in a higher contact area between the soft gripper and the object being grasped. We used a modified fin-ray structure with compliant ribs to enhance the grasping capability of the soft gripper as shown in Fig. 2.

IV. Finite Element Modeling

Finite element modeling simulations were performed on a single actuator to optimize its topology and to predict its performance in terms of deformation and blocked force. The TPU was modeled as a hyperelastic material based on its experimental stress-strain data where a 5-parameter Mooney-Rivlin material model was implemented in ANSYS [31,35]. The FEM simulations were performed in ANSYS Workbench. The CAD models of the actuators were directly imported to ANSYS design modeler. The CAD models were meshed using higher order tetrahedral elements where the mesh was studied to ensure that the results are mesh-independent. A fixed support boundary condition was imposed to fix the actuator on one side where the pressure input is located. A pressure normal to the internal walls was imposed to simulate the pneumatic air pressure. Also, contact pairs were defined between adjacent walls since they come into contact when the actuator is partially fixed on its tip in the blocked force simulations. The FEM simulations predicted the bending behavior of the actuator and its blocked force accurately. Fig. 3. shows the experimental and FEM bending positions of the actuator at different input pressures. Also, the FEM simulations of the full soft gripper proved that the gripper can achieve a conformal grip due to the fin-ray structure as shown in Fig. 4. Fig. 5. shows the experimental and FEM blocked forces. The FEM blocked force was higher than the experimental one at higher pressures. The main reason is that the actuator slides over the force sensor during the experiment by moving from the center of the force sensor to its edge which reduced the output force (Fig. 6.)

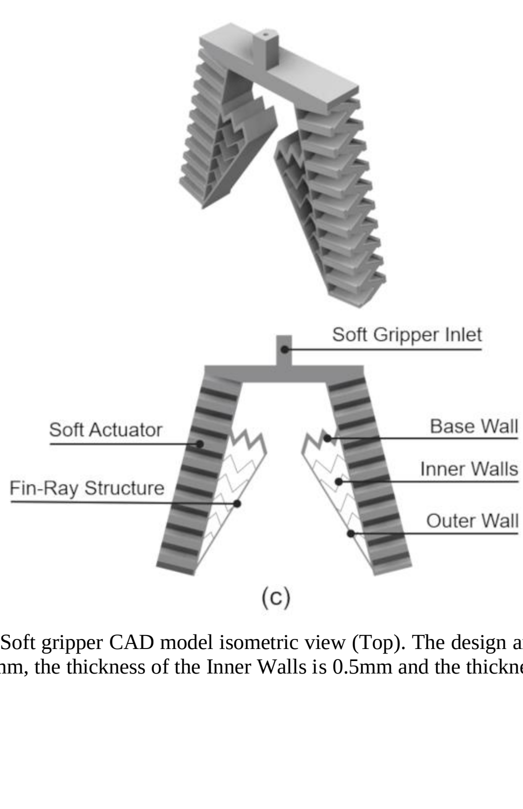


Fig. 2. (a) The CAD model of the soft pneumatic actuator and its dimensions. L: 108mm, W: 20mm, H: 20mm. (b) A cross-sectional view of the soft pneumatic actuator. The thickness of the walls of the actuator is 1.0mm (c) Soft gripper CAD model isometric view (Top). The design and dimensions of the walls of the fin-ray structure (Bottom). The thickness of the Base Wall is 2mm, the thickness of the Inner Walls is 0.5mm and the thickness of the Outer Wall is 1.0mm.

C. Tawk, Y. Gao, R. Mutlu and G. Alici, "Fully 3D Printed Monolithic Soft Gripper with High Conformal Grasping Capability," *2019 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, Hong Kong, China, 2019, pp. 1139-1144.

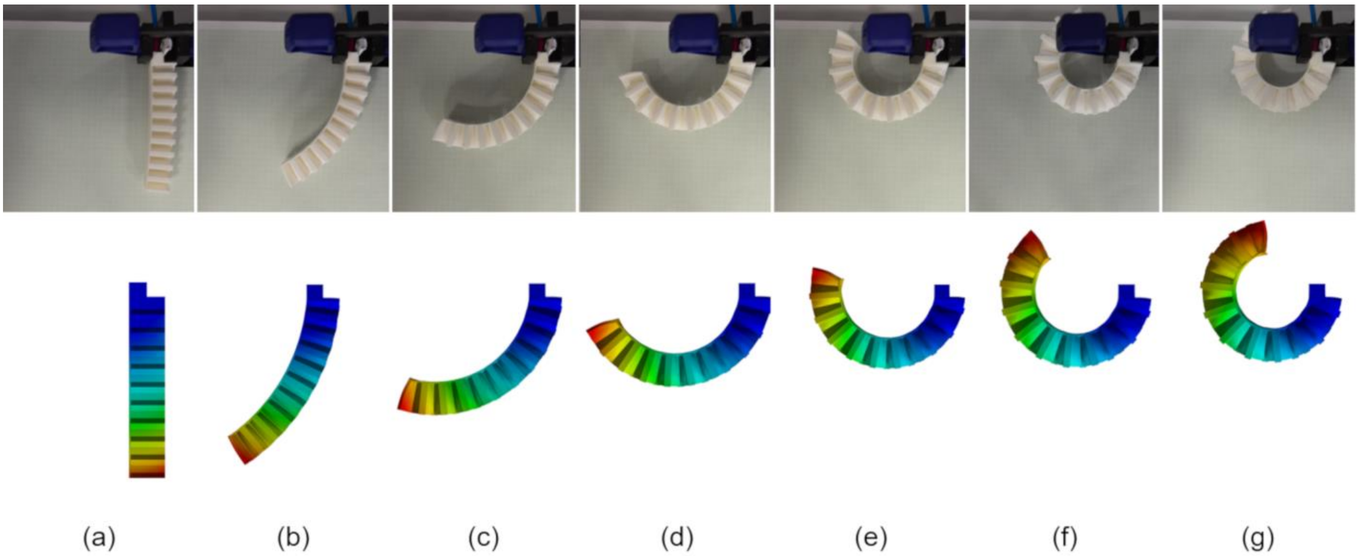


Fig. 3. The top figures correspond to the experimental bending motion of the single soft actuator of the gripper at different input pressures and the bottom figures correspond to the finite element simulations at the same input pressures. The input pressures applied are (a) 0kPa, (b) 50kPa, (c) 100kPa, (d) 150kPa, (e) 200kPa, (f) 250kPa and (g) 300kPa.

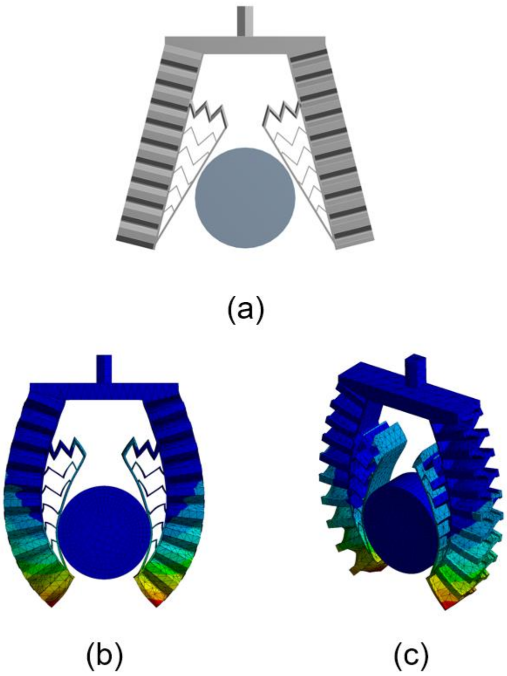


Fig. 4. (a) The Soft gripper and the cylindrical object grasped CAD models. (b) Front view and (c) isometric view of the soft gripper grasping a cylindrical object in the FEM simulation. The FEM simulations demonstrated the conformal grasping capability of the gripper using the soft positive-pressure actuators and the fin-ray structure.

V. Experimental Results

The experimental setup used consisted of a computer equipped with Simulink (The MathWorks, Inc.), Humusoft DAQ board, and a pressure regulator (VPPM-6L, FESTO) for air pressure control. Experiments were conducted to test the bending capability of a single soft actuator (Fig. 3.) and its output blocked force (Fig. 6.). Also, the performance of the 3D printed monolithic soft gripper was evaluated experimentally.

A. Blocked Force Measurement

The tip blocked force of a single actuator was measured using a 6-axis force sensor (K6D27, ME-Meßsysteme GmbH). One end of the actuator was fixed where the input pressure tube is located. The tip of the actuator was laid on the center of the force sensor as shown in Fig. 5. The pressure was ramped up by a step of 50kPa when the force was recorded. The maximum pressure applied was 300kPa. Although the actuator can sustain higher pressures and consequently generate higher forces, this value of 300kPa was chosen to ensure that safety requirements were met. The maximum experimental tip blocked force generated by the actuator is 4.26N.

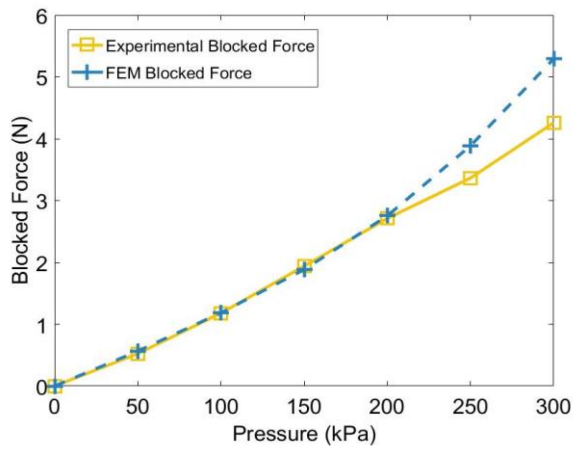
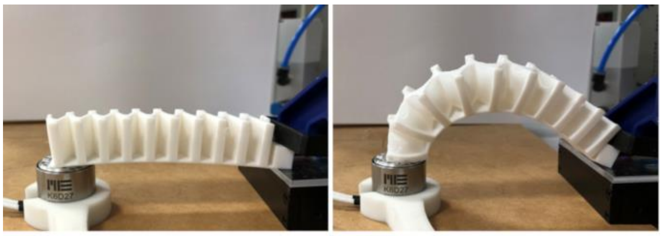


Fig. 5. Experimental and FEM tip blocked forces for a single pneumatic actuator.

C. Tawk, Y. Gao, R. Mutlu and G. Alici, "Fully 3D Printed Monolithic Soft Gripper with High Conformal Grasping Capability," *2019 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, Hong Kong, China, 2019, pp. 1139-1144.



(a) (b)

Fig. 6. Blocked force experimental setup. The position of the actuator when a pressure of (a) 0kPa is applied and (b) when a pressure of 300kPa is applied. The actuator tip slid to the edge of the force sensor at higher pressures.

B. *Grasped Objects*

The soft gripper can grasp different objects with different weights, shapes, textures and stiffnesses as shown in Fig 7. The gripper conforms to the shape of the objects it grasps due to the modified fin-ray structure involved. The gripper proved its versatility by grasping a wide variety of objects and its conformability by adapting to the shape of the objects.

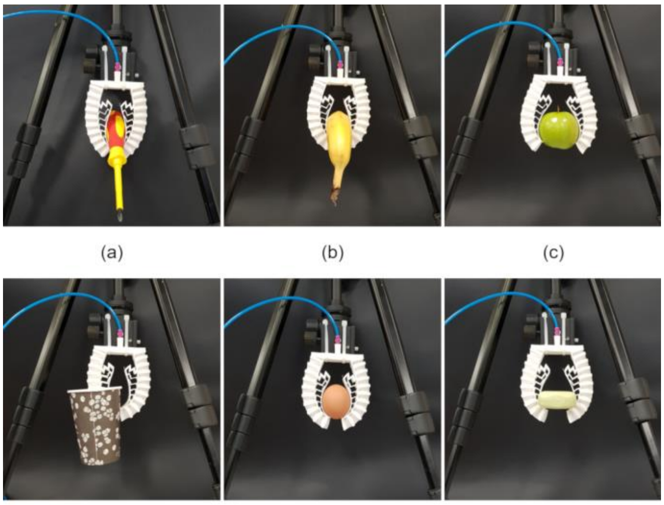


Fig. 7. The soft monolithic gripper grasping (a) a screwdriver, (b) a banana, (c) an apple, (d) a cup, (e) an egg and (f) a soap.

VI. CONCLUSIONS AND FUTURE WORK

We have developed a fully 3D printed soft monolithic pneumatic gripper with conformal capability that can grasp a wide variety of objects with different weights, shapes, texture and stiffnesses. The gripper was 3D printed using a low-cost and open-source fused deposition modeling 3D printer and an off-the-shelf soft material. The design of the gripper incorporates active and passive components. The active component consists of positive-pressure soft pneumatic actuators that generate a bending motion upon activation based on a novel Zig-Zag topology while the passive component is a bioinspired fin-ray structure that is responsible for enhancing the gripping capabilities of the gripper and its conformability. This coupled design proved its significance for developing soft and 3D printed versatile soft grippers. Also, a single actuator was optimized and its performance in terms of deformation and blocked force was predicted with reasonable accuracy using finite element modeling. In addition, the topology of the fin-ray structure was optimized based on FEM simulations to enhance their bending behavior and conformability. In future work, the overall performance of the gripper will be enhanced based on finite element modeling and experimental evaluation.

ACKNOWLEDGMENT

This study was partly supported by the Start-Up Grant and Global Challenges Program Seed Grant at the University of Wollongong, Australia. The authors acknowledge the use of the facilities in the Intelligent Nano-Tera Research Systems Laboratory at UOW and acknowledge the assistance of Dr. Emre Sariyildiz, Mr. Stefan Wessels and Mr. Evan Dunwoodie with using the pneumatic control equipment.

REFERENCES

[1] M. W. Hannan and I. D. Walker, "Kinematics and the Implementation of an Elephant's Trunk Manipulator and Other Continuum Style Robots," *Journal of Robotic Systems,* vol. 20, no. 2, pp. 45-63, 2003.

[2] O. Salomon and A. Wolf, "Inclined Links Hyper-Redundant Elephant Trunk-Like Robot," *ASME J. Mechanisms Robotics,* vol. 4, no. 4, p. 045001-6, 2012.

[3] C. Laschi, B. Mazzolai, V. Mattoli, M. Cianchetti, and P. Dario, "Design of a biomimetic robotic octopus arm," *Bioinspir. Biomim.,* vol. 4, no. 1, p. 015006, 2009.

[4] C. D. Onal and D. Rus, "A modular approach to soft robots," in *Proc. 4th IEEE RAS & EMBS Int. Conf. Biomed. Robot. Biomech. (BioRob)*, 2012, pp. 1038-1045.

[5] A. D. Marchese, C. D. Onal, and D. Rus, "Autonomous Soft Robotic Fish Capable of Escape Maneuvers Using Fluidic Elastomer Actuators," *Soft Robot.*, vol. 1, no. 1, pp. 75-87, 2014.

[6] S. Sangok, C. D. Onal, C. Kyu-Jin, R. J. Wood, D. Rus, and K. Sangbae, "Meshworm: A Peristaltic Soft Robot With Antagonistic Nickel Titanium Coil Actuators," *IEEE/ASME Trans. Mech.*, vol. 18, no. 18, pp. 1485-1497, 2013.

[7] L. Huai-Ti, G. L. Gary, and T. Barry, "GoQBot: a caterpillar-inspired soft-bodied rolling robot," *Bioinspir. Biomim.*, vol. 6, no. 2, p. 026007, 2011.

[8] G. M. Whitesides, "Soft Robotics," *Angewandte Chemie International Edition*, vol. 57, no. 16, pp. 4258-4273, 2018.

[9] K. C. Galloway *et al.*, "Soft Robotic Grippers for Biological Sampling on Deep Reefs," *Soft Robot.*, vol. 3, no. 1, pp. 23-33, 2016.

[10] E. Brown *et al.*, "Universal robotic gripper based on the jamming of granular material," *Proc. Natl. Acad. Sci. U.S.A*, vol. 107, no. 44, pp. 18809-18814, 2010.

[11] R. F. Shepherd *et al.*, "Multigait soft robot," *Proc. Natl. Acad. Sci. U.S.A*, vol. 108, no. 51, pp. 20400-20403, 2011.

[12] N. W. Bartlett *et al.*, "A 3D-printed, functionally graded soft robot powered by combustion," *Sci.*, vol. 349, no. 6244, pp. 161-165, 2015.

[13] P. Yong-Lae *et al.*, "Design and control of a bio-inspired soft wearable robotic device for ankle–foot rehabilitation," *Bioinspir. Biomim.*, vol. 9, no. 1, p. 016007, 2014.

[14] C. Majidi, "Soft Robotics: A Perspective—Current Trends and Prospects for the Future," *Soft Robot.*, vol. 1, no. 1, pp. 5-11, 2014.

[15] D. T. Pham and S. H. Yeo, "Strategies for gripper design and selection in robotic assembly," *Int. J. Prod. Res.*, vol. 29, pp. 303-316, 1991.

[16] A. Bicchi, "Hands for dexterous manipulation and robust grasping: a difficult road toward simplicity," *IEEE Trans. Robot. Autom.*, vol. 16, pp. 652-662, 2000.

[17] A. D. Marchese, R. K. Katzschmann, and D. Rus, "A Recipe for Soft Fluidic Elastomer Robots," *Soft Robot.*, vol. 2, no. 1, pp. 7-25, 2015.

[18] C. Laschi and M. Cianchetti, "Soft Robotics: New Perspectives for Robot Bodyware and Control," *Front. Bioeng. Biotechnol.*, vol. 2, no. 3, 2014.

[19] B. Mosadegh *et. al*., "Pneumatic Networks for Soft Robotics that Actuate Rapidly," *Adv. Funct. Mater.*, vol. 24, pp. 2163-2170, 2014.
[20] T. Wang, L. Ge, and G. Gu, "Programmable design of soft pneu-net actuators with oblique chambers can generate coupled bending and twisting motions," *Sens. Actuators, A,* vol. 271, pp. 131-138, 2018.
[21] W. Hu, W. Li, and G. Alici, "3D Printed Helical Soft Pneumatic Actuators," in *Proc. IEEE/ASME Int. Conf. Adv. Intel. Mech.*, 2018, pp. 950-955.
[22] G. Alici, T. Canty, R. Mutlu, W. Hu and V. Sencadas, "Modeling and Experimental Evaluation of Bending Behavior of Soft Pneumatic Actuators Made of Discrete Actuation Chambers*", Soft Robot.*, vol. 5, no. 1, pp. 24-35, 2018.
[23] P. Glick, S. A. Suresh, D. Ruffatto, M. Cutkosky, M. T. Tolley, and A. Parness, "A Soft Robotic Gripper with Gecko-Inspired Adhesive," *IEEE Robot. Autom. Lett.,* vol. 3, no. 2, pp. 903-910, 2018.
[24] Y. Hao, Z. Gong, Z. Xie, S. Guan, X. Yang, Z. Ren, T. Wang, and L. Wen, "Universal soft pneumatic robotic gripper with variable effective length." in *Proc. 2016 35th Chinese Control Conf.*, 2016, pp. 6109-6114. pp. 6109-6114.
[25] R. Deimel, and O. Brock, "A novel type of compliant and underactuated robotic hand for dexterous grasping," *Int. J. Robot. Res.,* vol. 35, no. 1-3, pp. 161-185, 2016.
[26] J. Fraś, M. Maciaś, F. Czubaczyński, P. Sałek, and J. Główka, "Soft Flexible Gripper Design, Characterization and Application," in *Proc. of the International Conference SCIT,* 2016, pp. 368-377.
[27] J. Zhou, S. Chen, and Z. Wang, "A Soft-Robotic Gripper With Enhanced Object Adaptation and Grasping Reliability," *IEEE Robot. Autom. Lett.*, vol. 2, no. 4, pp. 2287-2293, 2017
[28] H. Zhang, A. S. Kumar, J. Y. H. Fuh, and M. Y. Wang, "Topology optimized design, fabrication and evaluation of a multimaterial soft gripper," in *Proc. IEEE Int. Conf. Soft Robot*., 2018, pp. 424-430.
[29] H. K. Yap, H. Y. Ng, and C.-H. Yeow, "High-Force Soft Printable Pneumatics for Soft Robotic Applications," *Soft Robot.,* vol. 3, no. 3, pp. 144-158, 2016.
[30] B. A. W. Keong and R. Y. C. Hua, "A Novel Fold-Based Design Approach toward Printable Soft Robotics Using Flexible 3D Printing Materials," *Adv. Mater. Technol.,* vol. 3, no. 2, p. 1700172, 2018.
[31] C. Tawk, M. in het Panhuis, G.M, Spinks, and G. Alici, "Bioinspired 3D Printable Soft Vacuum Actuators (SOVA) for Locomotion Robots, Grippers and Artificial Muscles", *Soft Robot*., vol. 5, no. 6, pp. 685-694, 2018.
[32] R. MacCurdy, R. Katzschmann, K. Youbin, and D. Rus, "Printable hydraulics: A method for fabricating robots by 3D co-printing solids and liquids," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2016, pp. 3878-3885.
[33] Z. Wang, and S. Hirai, "Soft Gripper Dynamics Using a Line-Segment Model with an Optimization-Based Parameter Identification Method," *IEEE Robot. Autom. Lett.,* vol. 2, no. 2, pp. 624-631, 2017.
[34] O. D. Yirmibesoglu *et al.*, "Direct 3D printing of silicone elastomer soft robots and their performance comparison with molded counterparts," in *Proc. IEEE Int. Conf. Soft Robot.*, 2018, pp. 295-302.
[35] C. Tawk, M. in het Panhuis, G. M. Spinks, and G. Alici, "Soft Pneumatic Sensing Chambers for Generic and Interactive Human–Machine Interfaces". *Adv. Intell. Syst*. doi:10.1002/aisy.201900002.
[36] R. Mutlu, G. Alici, M. in het Panhuis, and G. M. Spinks, "3D Printed Flexure Hinges for Soft Monolithic Prosthetic Fingers," *Soft Robot.*, vol. 3, pp. 1-14, 2016.