A Soft Gripping Robot System with Graphene-based Piezoelectric Sensor (GPS)

Cheng-Hsiu Chuang, Wei-Song Hung, Ching-Yuan Chang, and Po Ting Lin

***Abstract*—Soft robots have been known for safer than rigid robots and being able to work closer with human and other surrounding objects, especially for having contact with delicate objects. One solution for delicate manipulation is to design flexible soft grippers with sensing capability and proper controllability. Adaptive control of soft gripping could be achieved with the sensing information between the gripper and the object. This paper presented a soft gripping robot system incorporate with Graphene-based Piezoelectric Sensor (GPS). The soft gripper was made of 3D printing (3DP) with the material of thermoplastic polyurethane (TPU). Six air chambers were made inside the soft gripper. The soft gripper was to be actuated by the inflation of these air chambers by pressurized air. The GPS was made of graphene and polyvinylidene fluoride (PVDF), which were initially well mixed in a solution and applied at the tip of the soft gripper. The layered structure of graphene allowed PVDF to have piezoelectric effect without the need of polarization. As the gripper tip had tactile contact with an object, the graphene/PVDF membrane slightly deformed and produced electricity. A mechatronic system was built to collect the piezoelectric signal. As a result, the gripping response was found to be linearly proportional to the applied pressure for pneumatic actuation. Furthermore, GPS was found to have around 6 times more sensitive than commercial PVDF sensor. The signal-to-noise (SNR) of GPS was around twice greater than commercial PVDF sensor. Therefore, the proposed soft gripper with GPS was suitable for gripping delicate objects and detection of small gripping responses at the gripper tip.**

Index Terms*—Soft Gripper, Pneumatic Actuation, Mechatronics, Graphene/PVDF Piezoelectric Membrane.

This paper was first submitted in June 21, 2021. Part of this paper was presented at 2020 International Conference on Advanced Robotics and Intelligent Systems (ARIS 2020) [1]. This work was supported by Ministry of Science and Technology (MOST), Taiwan (grant numbers MOST 108-2221-E-011-129-MY3, MOST 109-2218-E-011-003, MOST 108-2218-E-011-010 and MOST 107-2218-E-011-021) and Center for Cyber-Physical System Innovation, which is a Featured Areas Research Center in Higher Education Sprout Project of Ministry of Education (MOE), Taiwan (since 2018).

Cheng-Hsiu Chuang was a MS student in the Department of Mechanical Engineering at NTUST, Taipei 10607, Taiwan and graduated in July 2020 (e-mail: scsh10211paul@gmail.com).

Wei-Song Hung is a Professor in the Graduate Institute of Applied Science and Technology at National Taiwan University of Science and Technology (NTUST), Taipei 10609, Taiwan (e-mail: wshung@mail.ntust.edu.tw)

Ching-Yuan Chang is an Associate Professor in the Department of Mechanical Engineering at National Taipei University of Technology (NTUT), Taipei 10608, Taiwan (e-mail: chang@mail.ntut.edu.tw)

Po Ting Lin is the corresponding author of this paper. Dr. Lin is an Associate Professor in the Department of Mechanical Engineering at National Taiwan University of Science and Technology (NTUST), Taipei 10607, Taiwan (e-mail: potinglin@mail.ntust.edu.tw).

I. Introduction

SOFT robots have drawn great attentions to the field of robotics and automation. Various soft robotic applications have been developed, such as soft grippers [2, 3], bio-inspired robotics [4-6], soft wearable robots [7], artificial muscles [8, 9], medical devices [10], rehabilitation and surgical devices [10-15], and human-machine interaction (HMI) [16], etc. Soft robotics had the advantages of being able to work with human with greater safety and less probabilities of causing damages to human or other surrounding objects. Researchers have spent efforts on developing the methods to manufacture soft robots [17-19], and how to control them [20-23]. Polydimethylsiloxane (PDMS) has been used to make soft grippers [24, 25], which had rigid bone structures made of polylactic acid (PLA). PLA bone structures were manufactured by 3D printing and inserted into the soft PDMS fingers. The soft gripper was actuated by utilizing cables to pull the bone structures and bend the soft fingers. On the other hand, pneumatic actuations were used in some 3D-printed soft grippers [26, 27], which were made of thermoplastic polyurethane (TPU).

Proper control of soft grippers could be done as appropriate analyses of their kinematics motions and the responses of the contact with other objects. Variable Denavit-Hartenberg (DH) parameters [28-30] have been utilized to parametrically model the kinematics motions of soft grippers with respect to different levels of actuations. The experimental results showed that the kinematics motions of soft grippers were nonlinear due to flexibility of the elastomeric materials, which was challenging for the prediction of interactive responses between the soft gripper and the grasped objects. A mixture of polyvinylidene fluoride (PVDF) and graphene (Gr) was used to design a piezoelectric sensor [31]. Since the PVDF and Gr were well mixed in the solution and could be applied to the surface in any shapes, the PVDF/Gr mixture was directly applied at the tip of the soft finger [1, 32]. Once it was cured, the piezoelectric effort of the PVDF/Gr membrane could detect the instantaneous tactile responses of grasping. This paper presented a pneumatically actuated soft gripper that integrated with the graphene-based piezoelectric sensor (GPS), as well as the details about the soft gripper design, the mechatronic system, the measurement system, and the experimental setup.

II. Design of a Pneumatic Soft Gripper with Graphene-based Piezoelectric Sensor (GPS)

Fig. 1 showed the design of a pneumatically actuated soft finger, which was general for soft gripper designs with different numbers of fingers. In this paper, a two-finger soft gripper was presented. Each soft finger was made by a 3D printer (i.e. FlashForge 3D Printer Creator Pro). The soft material was TPU (i.e. Flex mark 8) with the Shore hardness of 80A. Table I showed more details about the 3D printing parameters.

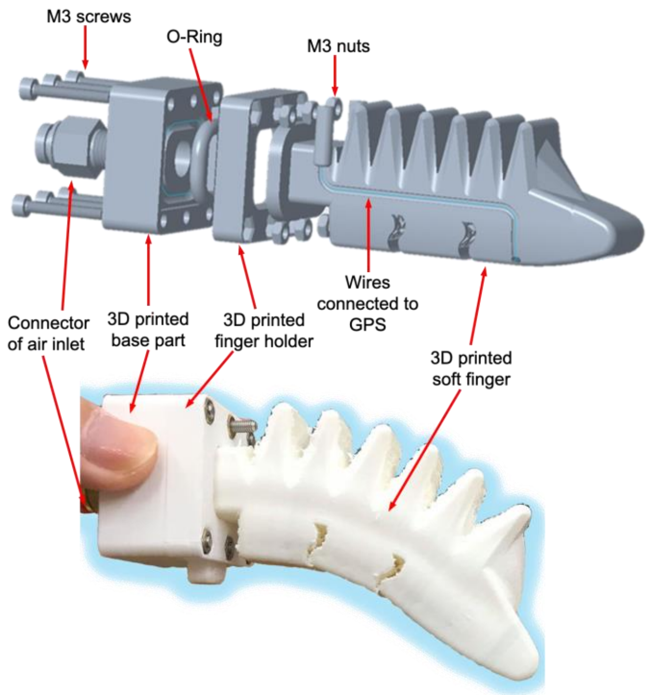


Fig. 1. Assembly design of the pneumatic soft finger with GPS.

TABLE I
3D PRINTING PARAMETERS FOR MANUFACTURING THE SOFT FINGERS

Parameters	Values	Units
Layer height	0.12	mm
First layer height	0.15	mm
Perimeter shells	3	layers
Top solid layers	4	layers
Bottom solid layers	4	layers
Infill fill density	100	%
Print speed	15	mm/s
Travel speed	20	mm/s
Extrude temperature	215	℃
Platform temperature	50	℃

The length of the soft finger was 92 mm as the width and thickness were 20 mm and 35.8 mm, respectively. Fig. 2 showed the cross-section view of the soft finger. An air flow channel was made inside the soft finger with wall thickness of 2 mm. As pressured air was pumped into the air channel and inflated the air chambers, the deformations of the air chambers bended the soft finger to actuate the grasping motion. The soft finger was installed in a finger holder, that was 3D printed with PLA. The air channel was sealed with the use of an O-ring and tightened by M3 screws and nuts. On the opposite side of the air chambers, some cellular structures were 3D printed to provide greater flexibility of the soft finger. The GPS was applied at the finger tip for detection of tactile responses during the grasping motions. The flexible foundation at the finger tip not only prevented damages to the grasped objects, but also enlarged the deformation of the GPS leading to greater sensitivity of the tactile responses of grasping. Two notches were made at the bottom of the soft finger to allow greater bending so that the pneumatic actuation of the soft finger was close to human finger's bending motion.

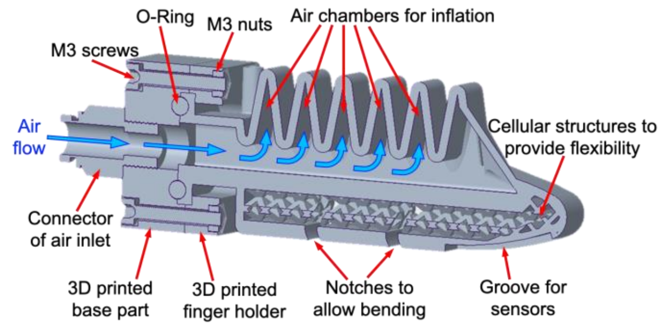


Fig. 2. Cross-section view of the pneumatic soft finger design.

The preparation of GPS started with proper stirring and mixing of PVDF and Gr in a solution of N-methyl-2-pyrrolidone (NMP). The stirring condition was 10,000 RPM for 2 hours in an ice bath. Once a complete homogenization of the PVDF/Gr mixture was achieved, it was degassed at 90°C for 24 hours. The PVDF/Gr mixture could then be applied at the tip of the soft finger and a PVDF/Gr membrane was obtained as the solution completely vaporized. The piezoelectric effect (i.e. β-phase of the material) was induced by the properly mixed Gr inside PVDF without the need of polarization. Metal wires were connected to the PVDF/Gr membrane to detect the potential difference as the deformation occurred.

III. EXPERIMENTAL SETUP FOR PNEUMATIC ACTUATIONS AND IN-SITU SENSING MEASUREMENTS

To verify the performance of the proposed soft gripper design with GPS, it was compared with commercial PVDF sensors, as shown in Fig. 3. The experimental setup of the pneumatic actuations of the soft grippers with two different kinds of sensors was presented in this section. The tactile responses of grasping were measured and analyzed.

(a) (b)

Fig. 3. Two kinds of sensors that have been used in this paper: (a) proposed GPS, (b) commercial PVDF sensor.

Fig. 4 showed the mechatronic system for the pneumatic actuations of the soft grippers. The red lines provided the 24V powers as the black lines were connected to the ground. A current controller was powered and connected to a computer via via USB-RTU Modbus (thick black line). The current controller sent signals to a proportional value via a light blue line. The value controlled the pressure of the output air (thick blue line).

A transducer was used to measure the pressure of the output air and send a feedback signal to the proportional value (via the green line). The experimental setup allowed proper control of the pressured air flow applied to the air channels of the soft gripper. The maximum pressure that was applied to the soft gripper was 40 psi in this paper.

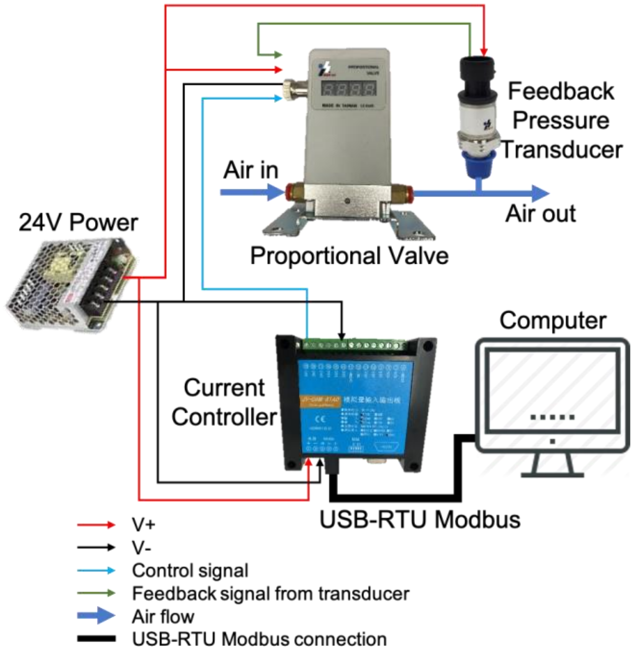


Fig. 4. Experimental setup for the pneumatic control.

The in-situ measurement setup for analyzing the tactile responses of the soft gripper was shown in Fig. 5. A charge amplifier was used to enlarge the sensor signals. A convertor was used to transform the analog signals to digital signals. The voltage of the in-situ response due to grasping was analyzed. The motion of grasping a soft paper cut was studied in this paper. The pressure of the pressured air for actuating the soft gripping was properly controlled to perform stable grasping without damaging the objects.

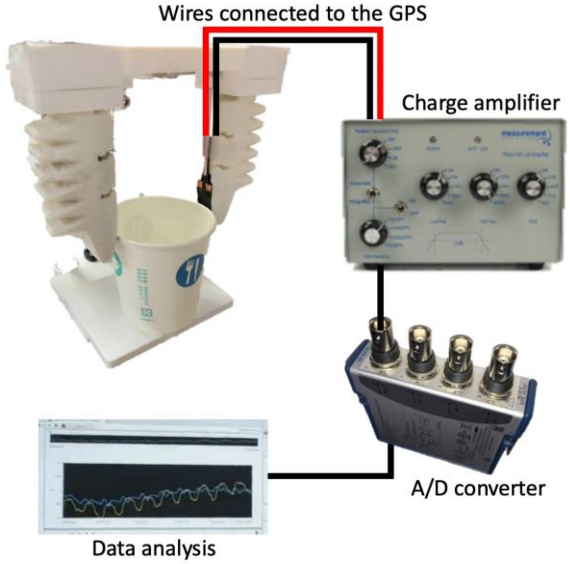


Fig. 5. In-situ measurement of the soft gripping signal.

A low-pass filter was used to remove the noises in the acquired signals. Fig. 6 showed the typical responses of the in-situ measurements of repetitive grasping the cup in a frequency of 2 Hz. Fig. 6 (a) showed the raw data of the repetitive responses directly obtained from the setup in Fig. 5. The low-pass filtered data was shown in Fig. 6 (b). As the soft gripper was actuated and tactile contact occurred between the GPS and the cup, GPS deformed and generated a positive signal. On the other hand, GPS recovered back to its original shape and released a negative signal as the gripper released the cup. The positive peak values were recorded for the later analysis.

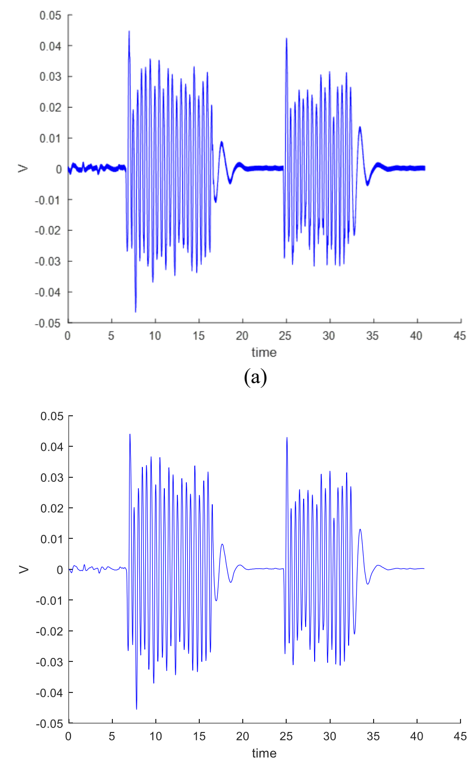
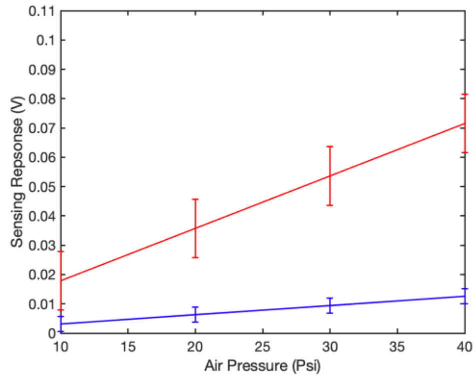


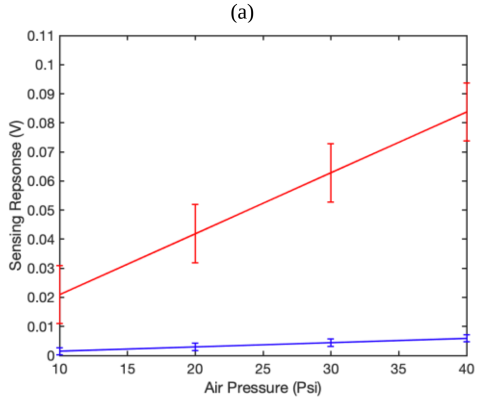
Fig. 6. Signal responses of the GPS from a repetitive gripping test: (a) raw data, (b) processed data by low-pass filtering.

IV. Experimental Results and Discussions

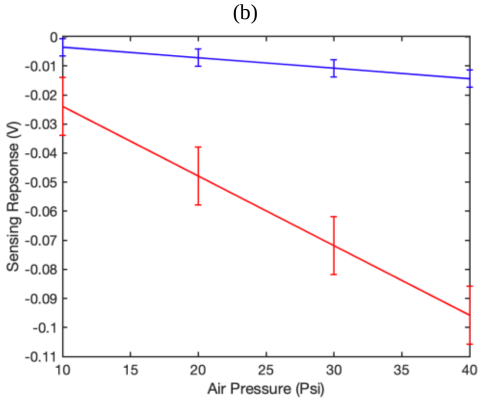
Fig. 7 showed the responses of grasping the cup using the soft gripper with two different kinds of sensors. The red lines presented the responses based on the proposed GPS as the blue ones indicated the signals from the commercial PVDF sensor. Various pressure levels (i.e. 10, 20, 30 and 40 psi) were applied to actuate the soft gripper and the corresponding tactile responses of grasping the soft cup were analyzed. The error bar was based on the statistical analysis of 70 repetitive grasping motions. The relationship between the voltage response and the applied air pressure was modeled by Least Square Approximations (LSA). Fig. 7 (a) and (b) showed the responses of grasping motions of the left and right fingers, respectively. Fig. 7 (c) and (d) showed the responses of releasing motions of the left and right fingers, respectively.



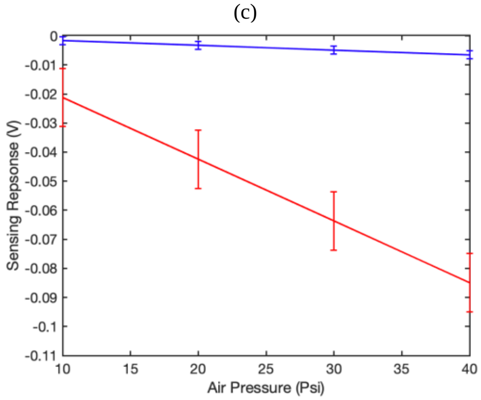
(a)



(b)



(c)



(d)

Fig. 7. Sensing responses based on the proposed GPS (red lines) and commercial PVDF sensors (blue lines): (a) signals from left finger while grasping a paper cup, (b) signals from right finger while grasping a paper cup, (c) signals from left finger while releasing a paper cup, (d) signals from right finger while releasing a paper cup.

The experimental results showed that the signals from the proposed GPS was around 6 times stronger than the commercial PVDF sensor. The signal-to-noise ratio (SNR) of the proposed GPS (i.e. mean over standard deviation ranged from 2 to 8) was also greater than the commercial sensor (i.e. ranged from 1 to 5). The consistency between both sides of the gripper was good as the variance was less than 0.01 V. A greater sensitivity of the tactile responses between the proposed GPS and the grasped objects allowed better control of applied air pressure for the pneumatic actuations of the soft gripper.

In practical robot manipulation with the proposed soft gripper and GPS, the system could be built based on the structure shown in Fig. 8. A two-finger soft gripper with GPS was installed at the end of a 6R robot arm, as shown in Fig. 9. As the gripper started to execute the grasping motion, the in-situ measurements of the GPS signals were collected and enhanced by the charge amplifier. The analog signal was then converted to digital and the positive peak value of grasping motion was recorded. The acquired signal, which represented the interfacial response between the GPS and the object, could then be used as feedback information for the control of robot motion and applied air pressure. The feedback signal was sent to the current controller and used to adjust the air pressure provided by the proportional value. On the other hand, robot motions could be adjusted based on the feedback signal as well. The propose system would be useful for customized object manipulation with uncertain information of the objects. Soft manipulation with tactile sensing could ensure appropriate grasping without damaging the objects.

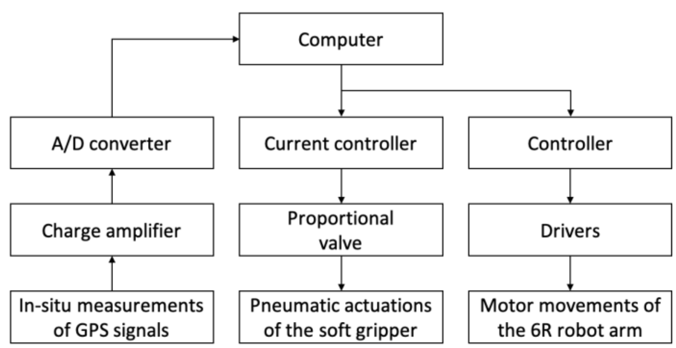


Fig. 8. Architecture of the controls of the 6R robot arm and pneumatic soft gripper, and the in-situ measurements of the GPS signals.

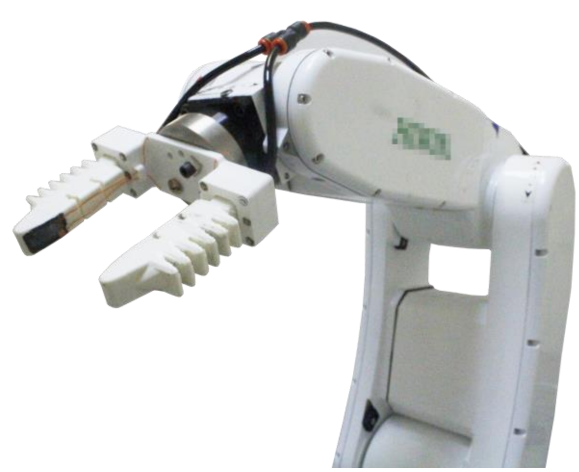


Fig. 9. Integration of a pneumatic soft gripper and GPS with a 6R industrial robot arm.

V. Conclusions

In this paper, a pneumatic soft gripper design was proposed and integrated with Graphene-based Piezoelectric Sensor (GPS). The soft gripper was made of elastomeric TPU material and manufactured by 3D printing. An air channel and several air chambers were made in the pneumatically actuated soft gripper. GPS, that was made by the mixture of PVDF and Gr, was applied at the tip of the soft fingers. As pressured air was applied to the air channel and inflated the air chambers, the soft fingers bended to grasp. As the GPS had contact with an object, the PVDF/Gr membrane deformed and generated a positive signal. The peak value of the signal was recorded to analyze the interfacial tactile response between the GPS and the object. The mechatronic system, in-situ measurement system and their application to a 6R robot manipulation were also presented in this paper. The experimental results showed that the proposed soft gripping system could deliver a more sensitive sensing signal than the usage of commercial PVDF sensors. The responses of the proposed GPS could be used to adjust the applied air pressure and robot motion.

VI. References

[1] C.-H. Chuang, W.-S. Hung, C.-Y. Chang, and P. T. Lin, "A Pneumatic Soft Gripper Design with Graphene-based Piezoelectric Sensors (GPS)," presented at the 2020 International Conference on Advanced Robotics and Intelligent Systems (ARIS 2020), Taipei, Taiwan, 1144, 2020.

[2] S. Shian, K. Bertoldi, and D. R. Clarke, "Dielectric elastomer based “grippers” for soft robotics," *Advanced Materials*, vol. 27, no. 43, pp. 6814-6819, 2015, DOI. 10.1002/adma.201503078.

[3] J. Shintake, S. Rosset, B. Schubert, D. Floreano, and H. Shea, "Versatile soft grippers with intrinsic electroadhesion based on multifunctional polymer actuators," *Advanced materials*, vol. 28, no. 2, pp. 231-238, 2016, DOI. 10.1002/adma.201504264.

[4] R. F. Shepherd, F. Ilievski, W. Choi, S. A. Morin, A. A. Stokes, A. D. Mazzeo, X. Chen, M. Wang, and G. M. Whitesides, "Multigait soft robot," *Proceedings of the National Academy of Sciences*, vol. 108, no. 51, pp. 20400-20403, 2011.

[5] M. Calisti, M. Giorelli, G. Levy, B. Mazzolai, B. Hochner, C. Laschi, and P. Dario, "An octopus-bioinspired solution to movement and manipulation for soft robots," *Bioinspiration & Biomimetics*, vol. 6, no. 3, 2011.

[6] C. D. Onal and D. Rus, "Autonomous undulatory serpentine locomotion utilizing body dynamics of a fluidic soft robot," *Bioinspiration & Biomimetics*, vol. 8, no. 2, 2013.

[7] C. Walsh, "Human-in-the-loop development of soft wearable robots," *Nature Reviews Materials*, vol. 3, no. 6, p. 78, 2018, DOI. 10.1038/s41578-018-0011-1.

[8] R. Mutlu, G. Alici, M. in het Panhuis, and G. M. Spinks, "3D printed flexure hinges for soft monolithic prosthetic fingers," *Soft Robotics*, vol. 3, no. 3, pp. 120-133, 2016.

[9] M. A. Delph, S. A. Fischer, P. W. Gauthier, C. H. M. Luna, E. A. Clancy, and G. S. Fischer, "A soft robotic exomusculature glove with integrated sEMG sensing for hand rehabilitation," in *2013 IEEE 13th International Conference on Rehabilitation Robotics (ICORR)*, pp. 1-7, 2013.

[10] M. Cianchetti, T. Ranzani, G. Gerboni, T. Nanayakkara, K. Althoefer, P. Dasgupta, and A. Menciassi, "Soft robotics technologies to address shortcomings in today's minimally invasive surgery: the STIFF-FLOP approach," *Soft robotics*, vol. 1, no. 2, pp. 122-131, 2014, DOI. 10.1089/soro.2014.0001.

[11] Y.-L. Park, B.-r. Chen, N. O. Pérez-Arancibia, D. Young, L. Stirling, R. J. Wood, E. C. Goldfield, and R. Nagpal, "Design and control of a bio-inspired soft wearable robotic device for ankle–foot rehabilitation," *Bioinspiration & Biomimetics*, vol. 9, no. 1, 2014.

[12] Y.-L. Park, B.-r. Chen, N. O. Pérez-Arancibia, D. Young, L. Stirling, R. J. Wood, E. C. Goldfield, and R. Nagpal, "Design and control of a bio-inspired soft wearable robotic device for ankle–foot rehabilitation," *Bioinspiration & biomimetics*, vol. 9, no. 1, p. 016007, 2014.

[13] Y. Ding, I. Galiana, A. Asbeck, B. Quinlivan, S. M. M. De Rossi, and C. Walsh, "Multi-joint actuation platform for lower extremity soft exosuits," in *2014 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 1327-1334, 2014.

[14] P. Polygerinos, Z. Wang, K. C. Galloway, R. J. Wood, and C. J. Walsh, "Soft robotic glove for combined assistance and at-home rehabilitation," *Robotics and Autonomous Systems*, vol. 73, pp. 135-143, 2015, DOI. 10.1016/j.robot.2014.08.014.

[15] G. Agarwal, N. Besuchet, B. Audergon, and J. Paik, "Stretchable materials for robust soft actuators towards assistive wearable devices," *Scientific Reports*, vol. 6, 2016.

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

[17] P. Polygerinos, N. Correll, S. A. Morin, B. Mosadegh, C. D. Onal, K. Petersen, M. Cianchetti, M. T. Tolley, and R. F. Shepherd, "Soft robotics: Review of fluid-driven intrinsically soft devices; manufacturing, sensing, control, and applications in human-robot interaction," *Advanced Engineering Materials*, vol. 19, no. 12, p. 1700016, 2017, DOI. 10.1002/adem.201700016.

[18] J. F. Morrow, "Direct 3D Printing of Silicone Elastomer Soft Robots without Support," Thesis, Department of Mechanical, Industrial, and Manufacturing Engineering, Oregon State University, 2017.

[19] J. Paik, "Soft robot design methodology for ‘push-button’ manufacturing," *Nature Reviews Materials*, vol. 3, no. 6, p. 81, 2018, DOI. 10.1038/s41578-018-0014-y.

[20] G. Gerboni, A. Diodato, G. Ciuti, M. Cianchetti, and A. Menciassi, "Feedback control of soft robot actuators via commercial flex bend sensors," *IEEE/ASME Transactions on Mechatronics*, vol. 22, no. 4, pp. 1881-1888, 2017, DOI. 10.1109/TMECH.2017.2699677.

[21] H. Zhang, R. Cao, S. Zilberstein, F. Wu, and X. Chen, "Toward effective soft robot control via reinforcement learning," presented at the International Conference on Intelligent Robotics and Applications, 2017, DOI. 10.1007/978-3-319-65289-4_17.

[22] H. Wang, B. Yang, Y. Liu, W. Chen, X. Liang, and R. Pfeifer, "Visual servoing of soft robot manipulator in constrained environments with an adaptive controller," *IEEE/ASME Transactions on Mechatronics*, vol. 22, no. 1, pp. 41-50, 2017, DOI. 10.1109/TMECH.2016.2613410.

[23] Y. Ansari, M. Manti, E. Falotico, M. Cianchetti, and C. Laschi, "Multiobjective optimization for stiffness and position control in a soft robot arm module," *IEEE Robotics and Automation Letters*, vol. 3, no. 1, pp. 108-115, 2018, DOI. 10.1109/LRA.2017.2734247.

[24] W.-Y. Tan, K.-A. Yang, Y.-J. Chen, L.-Y. Huang, L.-M. Yan, C.-Y. Chang, C.-H. Kuo, and P. T. Lin, "Soft Gripper Design Based on Embedded Molding and Cable Actuation," presented at the The 42nd National Conference on Theoretical and Applied Mechanics (CTAM 2018), Taipei, Taiwan, 2018.

[25] K.-A. Yang, C.-H. Chuang, Y.-T. Yao, W.-Y. Tan, and P. T. Lin, "Design and Force Estimation of a Cable-Driven Soft Finger," presented at the The 16th International Conference on Automation Technology (Automation 2019), Taipei, Taiwan, 1101, 2019.

[26] E. Shahabi, Y.-T. Yao, C.-H. Chuang, P. T. Lin, and C.-H. Kuo, "Design and Testing of 2-Degree-of-Freedom (DOF) Printable Pneumatic Soft Finger," presented at the The 6th IFToMM International Symposium on Robotics and Mechatronics (ISRM 2019), Taipei, Taiwan, 047, 2019, DOI. 10.1007/978-3-030-30036-4_27.

[27] E. Shababi, W.-H. Lu, P. T. Lin, and C.-H. Kuo, "Computer Vision-Based Object Recognition and Automatic Pneumatic Soft Gripping," presented at the ASME 2019 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE 2019), Anaheim, CA, USA, DETC2019-97976, 2019.

[28] K.-A. Yang, Y.-T. Yao, W.-Y. Tan, and P. T. Lin, "Investigation of Soft Actuator Kinematics Based on Parametric DH Functions," presented at the International Conference on Advanced Technology Innovation 2019 (ICATI2019), Sapporo, Hokkaido, Japan, SCG9003, 2019.

[29] P. T. Lin, E. Shahabi, K.-A. Yang, Y.-T. Yao, and C.-H. Kuo, "Parametrically Modeled DH Table for Soft Robot Kinematics: Case Study for A Soft Gripper," presented at the The 15th IFToMM World Congress, Krakow, Poland, 453, 2019, DOI. 10.1007/978-3-030-20131-9_62.

[30] P. T. Lin, K.-A. Yang, C.-H. Chuang, and Y.-T. Yao, "Nonlinear Kinematics and Force Analyses of A Cable-Driven Soft Finger," *Journal of Robot Society of Taiwan (iRobotics)*, vol. 3, no. 4, pp. 1-8, 2020.

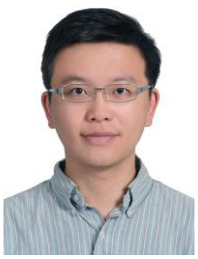
[31] W.-S. Hung, S.-Y. Ho, Y.-H. Chiao, C.-C. Chan, W.-Y. Woon, M.-J. Yin, C.-Y. Chang, Y. M. Lee, and Q.-F. An, "Electrical Tunable

PVDF/Graphene Membrane for Controlled Molecule Separation," *Chemistry of Materials*, 2020.
[32] C.-H. Chuang, "A Pneumatic Soft Gripper Design with Graphene-Based Piezoelectric Sensors," MS Thesis, Mechanical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan, 2020.

Cheng-Hsiu Chuang received the M.S. degree in the Department of Mechanical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan in July 2020.

Wei-Song Hung is currently a Professor in the Graduate Institute of Applied Science and Technology at National Taiwan University of Science and Technology, Taipei, Taiwan. His research interests include synthesis and preparation of graphene quantum dots, positron annihilation lifetime for microstructure analysis, and membrane separation technology.

Ching Yuan Chang is currently an Associate Professor in the Department of Mechanical Engineering at National Taipei University of Technology, Taipei, Taiwan. His research interests include in-situ measurement, signal analysis, machine vision, experimental mechanics and industrial applications.



Po Ting Lin received the M.S. and Ph.D. degrees in the Department of Mechanical and Aerospace Engineering from Rutgers University, New Brunswick, New Jersey, USA in 2007 and 2010, respectively. He is currently an Associate Professor in the Department of Mechanical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan. His current research interests and publications are in the areas of Machine Vision, Robotics, Machine Learning, Reliability-Based Design Optimization, and Multidisciplinary Design Optimization