Vision-Based Proprioception and Tactile Sensing for Soft Pneumatic Robots

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***Abstract*—Soft pneumatic robot manipulators are popular in industrial and human-interactive applications due to their compliance and flexibility. However, deploying them in real-world scenarios requires advanced sensing for tactile feedback and proprioception. This work introduces a novel vision-based sensing approach for soft robots, demonstrated through PneuGelSight, a pioneering pneumatic manipulator equipped with an embedded camera for high-resolution proprioceptive and tactile sensing. Experimental evaluations validate the sensor's advanced sensing capabilities when integrated as an end effector for object manipulation.**

I. Introduction

Soft robots are increasingly recognized as the future of robotics due to their flexibility and intrinsic safety. Their compliance with external environments makes them ideal for applications in agriculture[1], [2], the food industry[3], assistive and rescue robotics[4], [5], and medical fields[6]–[8]. However, sensing remains a major challenge. Unlike rigid robots with discrete joints, soft robots exhibit continuous deformation, leading to a high-dimensional state space that complicates modeling and control.

This paper introduces PneuGelSight, a vision-based sensor for soft robotic fingers that integrates proprioception and tactile sensing. Embedded in a pneumatically actuated soft finger, it leverages high-dimensional visual input and deep learning to model nonlinear soft robot behavior. Experimental results demonstrate its ability to accurately capture large-scale deformations and fine surface details, enhancing both shape perception and contact sensing.

II. Related Works

A. Sensing for Soft Robot

Soft robotic sensing has traditionally relied on point-based and string-based sensor units utilizing resistive [9]–[11], capacitive [12], [13], magnetic [14], [15], optical waveguide [16], [17], and acoustic [18] mechanisms. These sensors estimate deformation and provide tactile information, such as contact location and force. However, point-based sensors face challenges in spatial resolution and scalability, while string-based sensors integrate signals along their length, reducing contact localization accuracy.

Vision-based sensing, originally developed for high-precision texture reconstruction, remains underutilized in soft robotics. For instance, [19] employs a bottom-mounted camera for high-resolution shape perception but lacks detailed contact information. These limitations underscore the need for advanced sensing techniques that achieve both high resolution and precise spatial localization in soft robotic applications.

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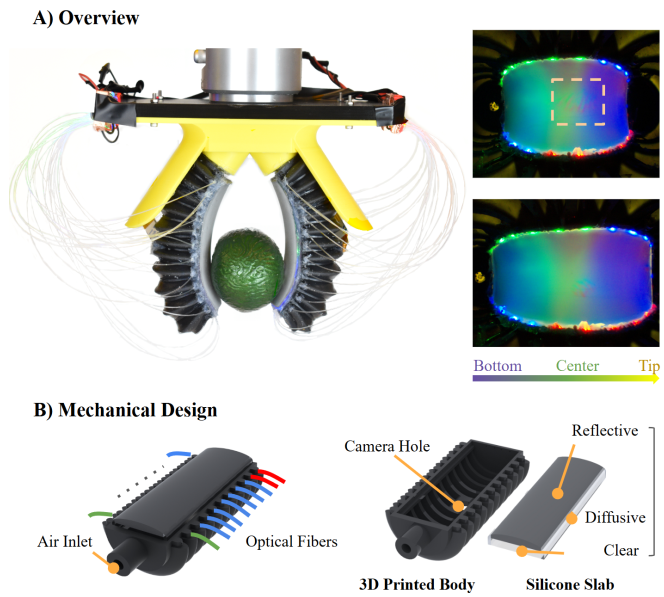

Fig. 1. (A) Overview of the proposed soft robotic tactile and proprioceptive system. (B) Mechanical design of the PneuGelSight sensor.

B. Vision-based Tactile Sensing

Vision-based sensing utilizes embedded cameras to detect optical signal changes linked to physical parameters. A key example is GelSight [20], [21], which captures high-resolution contact geometry. GelSight sensors use an embedded camera to analyze light reflections from a reflective surface, inferring surface normals through multiple colored light sources.

Various GelSight designs [22]–[24] have been developed for different robotic applications. However, they rely on a rigid base for housing electronic and optical components, restricting deformation to just a few millimeters. In contrast, our approach enables high-fidelity sensing in a compact, fully deformable design, seamlessly integrating proprioception and tactile perception in soft robotics.

III. Design and Fabrication

PneuGelSight is a pneumatic soft finger integrating an embedded camera and internal illumination for high-resolution proprioception and tactile sensing. It features a 3D-printed bellow-shaped back and a silicone slab that bends inward for grasping. The inner silicone surface is transparent and metallic-coated, allowing the camera to capture an unobstructed contact view for 3D shape reconstruction (Fig. 1). Optical fibers and diffusers ensure uniform illumination with color-coded lighting for precise control.

Inspired by the human palm, PneuGelSight measures 110 mm in length with a 55 mm semi-circular cross-section.

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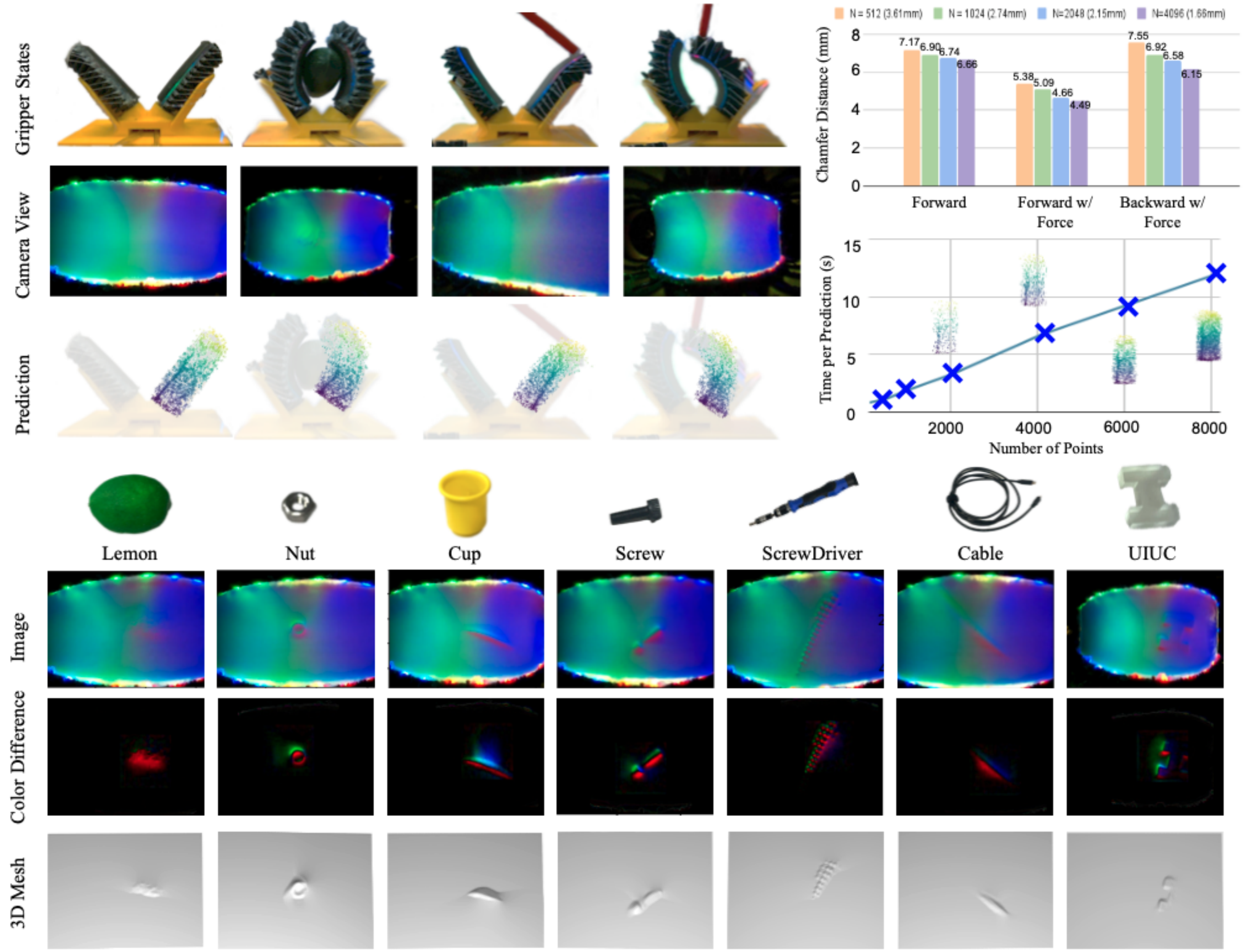

Fig. 2. Accuracy of proprioception and tactile sensing. We analyze the impact of sampled point cloud intensity on proprioception accuracy (top right) and qualitatively assess the sensor's texture reconstruction capability (bottom row)

The silicone slab is cast in three layers: an opaque diffuser, crystal-clear silicone (varying hardness), and a semi-specular aluminum-coated protective layer. The actuated body is 3D-printed using flexible silicone. The lighting system consists of 24 fibers (6 green, 7 blue, 7 red, 4 additional blue), secured with semi-cylindrical protrusions. A 160-degree FOV wide-angle Arducam is embedded and sealed with silicone for airtightness.

IV. Experiment

A. Proprioception

We trained a conditional auto-encoder for proprioceptive sensing (detailed structure in the main paper). Evaluation against RGBD ground truth data shows a mean distance of 4.24–7.10 mm across various bending scenarios, demonstrating robustness, including in backward bending cases. Higher point cloud densities improve accuracy but increase inference time, with $N = 512$ balancing speed and $N = 4096$ optimizing accuracy.

B. Tactile Sensing

We trained a MLP conditioned on proprioception result, with detailed structure in the main paper. Results demonstrate the system's ability to distinguish surface normals using optical signals, achieving reliable reconstruction across different bending angles. The sensor accurately captures fine textures, including those of nuts, screws, and lemons. While resolution decreases near the fingertip, the system effectively adapts, preserving detailed surface reconstruction while minimizing errors in less sensitive regions.

V. Conclusion

We introduce PneuGelSight, a vision-based sensing system for soft robots that integrates high-resolution proprioception and tactile sensing using a single embedded camera. By combining precise point cloud proprioception with detailed tactile feedback, PneuGelSight overcomes key challenges in soft robotic sensing. Compared to existing methods, it offers a simpler, more efficient implementation while achieving high-fidelity sensing.

References

[1] A. Qiu, C. Young, A. Gunderman, M. Azizkhani, Y. Chen, and A.-P. Hu, "Tendon-driven soft robotic gripper with integrated ripeness sensing for blackberry harvesting," 2023. [Online]. Available: https://arxiv.org/abs/2302.03099

[2] N. K. Uppalapati, B. Walt, A. J. Havens, A. Mahdian, G. Chowdhary, and G. Krishnan, "A berry picking robot with a hybrid soft-rigid arm: Design and task space control." in *Robotics: Science and Systems*, 2020, p. 95.

[3] Z. Wang, K. Or, and S. Hirai, "A dual-mode soft gripper for food packaging," *Robotics and Autonomous Systems*, vol. 125, p. 103427, 2020.

[4] Y. M. Zhou, C. J. Hohimer, H. T. Young, C. M. McCann, D. Pont-Esteban, U. S. Civici, Y. Jin, P. Murphy, D. Wagner, T. Cole, N. Phipps, H. Cho, F. Bertacchi, I. Pignataro, T. Proietti, and C. J. Walsh, "A portable inflatable soft wearable robot to assist the shoulder during industrial work," *Science Robotics*, vol. 9, no. 91, p. eadi2377, 2024. [Online]. Available: https://www.science.org/doi/abs/10.1126/scirobotics.adi2377

[5] E. W. Hawkes, L. H. Blumenschein, J. D. Greer, and A. M. Okamura, "A soft robot that navigates its environment through growth," *Science Robotics*, vol. 2, no. 8, p. eaan3028, 2017. [Online]. Available: https://www.science.org/doi/abs/10.1126/scirobotics.aan3028

[6] L. Rosalia, S. X. Wang, C. Ozturk, W. Huang, J. Bonnemain, R. Beatty, G. P. Duffy, C. T. Nguyen, and E. T. Roche, "Soft robotic platform for progressive and reversible aortic constriction in a small-animal model," *Science Robotics*, vol. 9, no. 91, p. eadj9769, 2024. [Online]. Available: https://www.science.org/doi/abs/10.1126/scirobotics.adj9769

[7] R. Beatty, K. L. Mendez, L. H. J. Schreiber, R. Tarpey, W. Whyte, Y. Fan, S. T. Robinson, J. O'Dwyer, A. J. Simpkin, J. Tannian, P. Dockery, E. B. Dolan, E. T. Roche, and G. P. Duffy, "Soft robot–mediated autonomous adaptation to fibrotic capsule formation for improved drug delivery," *Science Robotics*, vol. 8, no. 81, p. eabq4821, 2023. [Online]. Available: https://www.science.org/doi/abs/10.1126/scirobotics.abq4821

[8] L. Rosalia, C. Ozturk, D. Goswami, J. Bonnemain, S. X. Wang, B. Bonner, J. C. Weaver, R. Puri, S. Kapadia, C. T. Nguyen, and E. T. Roche, "Soft robotic patient-specific hydrodynamic model of aortic stenosis and ventricular remodeling," *Science Robotics*, vol. 8, no. 75, p. eade2184, 2023. [Online]. Available: https://www.science.org/doi/abs/10.1126/scirobotics.ade2184

[9] Z. Si, T. C. Yu, K. Morozov, J. McCann, and W. Yuan, "Robotsweater: Scalable, generalizable, and customizable machine-knitted tactile skins for robots," 2023. [Online]. Available: https://arxiv.org/abs/2303.02858

[10] B. Xu, L. Zhong, G. Zhang, X. Liang, D. Virtue, R. Madan, and T. Bhattacharjee, "Cushsense: Soft, stretchable, and comfortable tactile-sensing skin for physical human-robot interaction," 2024. [Online]. Available: https://arxiv.org/abs/2405.03155

[11] N. Farrow and N. Correll, "A soft pneumatic actuator that can sense grasp and touch," in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2015, pp. 2317–2323.

[12] C. Larson, B. Peele, S. Li, S. Robinson, M. Totaro, L. Beccai, B. Mazzolai, and R. Shepherd, "Highly stretchable electroluminescent skin for optical signaling and tactile sensing," *Science*, vol. 351, no. 6277, pp. 1071–1074, 2016. [Online]. Available: https://www.science.org/doi/abs/10.1126/science.aac5082

[13] S. S. Robinson, K. W. O'Brien, H. Zhao, B. N. Peele, C. M. Larson, B. C. Mac Murray, I. M. Van Meerbeek, S. N. Dunham, and R. F. Shepherd, "Integrated soft sensors and elastomeric actuators for tactile machines with kinesthetic sense," *Extreme Mechanics Letters*, vol. 5, pp. 47–53, 2015. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S235243161500108X

[14] A. Alfadhel and J. Kosel, "Magnetic nanocomposite cilia tactile sensor," *Advanced Materials*, vol. 27, 10 2015.

[15] Y. Yan, Z. Hu, Z. Yang, W. Yuan, C. Song, J. Pan, and Y. Shen, "Soft magnetic skin for super-resolution tactile sensing with force self-decoupling," *Science Robotics*, vol. 6, no. 51, p. eabc8801, 2021.

[16] P. Zhang, I. M. Lei, G. Chen, J. Lin, X. Chen, J. Zhang, C. Cai, X. Liang, and J. Liu, "Integrated 3d printing of flexible electroluminescent devices and soft robots," *Nature Communications*, vol. 13, no. 1, p. 4775, 2022. [Online]. Available: https://doi.org/10.1038/s41467-022-32126-1

[17] H. Zhao, R. Huang, and R. F. Shepherd, "Curvature control of soft orthotics via low cost solid-state optics," in *2016 IEEE International Conference on Robotics and Automation (ICRA)*, 2016, pp. 4008–4013.

[18] V. Wall, G. Zöller, and O. Brock, "Passive and active acoustic sensing for soft pneumatic actuators," *The International Journal of Robotics Research*, vol. 42, no. 3, pp. 108–122, 2023. [Online]. Available: https://doi.org/10.1177/02783649231168954

[19] U. Yoo, H. Zhao, A. Altamirano, W. Yuan, and C. Feng, "Toward zero-shot sim-to-real transfer learning for pneumatic soft robot 3d proprioceptive sensing," *arXiv preprint arXiv:2303.04307*, 2023.

[20] W. Yuan, S. Dong, and E. H. Adelson, "Gelsight: High-resolution robot tactile sensors for estimating geometry and force," *Sensors*, vol. 17, no. 12, p. 2762, 2017.

[21] M. K. Johnson, F. Cole, A. Raj, and E. H. Adelson, "Microgeometry capture using an elastomeric sensor," *ACM Transactions on Graphics (TOG)*, vol. 30, no. 4, pp. 1–8, 2011.

[22] J. Zhao and E. H. Adelson, "Gelsight svelte: A human finger-shaped single-camera tactile robot finger with large sensing coverage and proprioceptive sensing," 2023.

[23] I. H. Taylor, S. Dong, and A. Rodriguez, "Gelslim 3.0: High-resolution measurement of shape, force and slip in a compact tactile-sensing finger," in *2022 International Conference on Robotics and Automation (ICRA)*. IEEE, 2022, pp. 10 781–10 787.

[24] M. H. Tippur and E. H. Adelson, "Gelsight360: An omnidirectional camera-based tactile sensor for dexterous robotic manipulation," 2023.