Modularized Design Framework for Gelsight Family of Sensors

Arpit Agarwal[1,*], Mohammad Amin Mirzaee[2,*], Xiping Sun[2], Wenzhen Yuan[2]

***Abstract*— Customizing GelSight sensors for different robot hands is challenging due to the trial-and-error redesign process. This paper presents a systematic, objective-driven approach to optimizing GelSight sensor design using physically accurate optical simulations. By modularizing and parameterizing optical components, the method enables efficient evaluation through generalizable objective functions. This approach allows non-experts to optimize sensor designs interactively. The system is demonstrated by successfully refining example GelSight sensors in simulation.**

I. Introduction

Vision-based tactile sensors use an embedded camera to capture optical cues from the deformation of the sensor's soft surface, enabling the measurement of geometry and force at the contact interface. GelSight sensors employ a photometric stereo algorithm to measure the surface normal field, which is then used to reconstruct the 3D shape of the contact surface. This process relies on a meticulously designed illumination system that evenly lights the surface with multiple colored lights from different angles and controls reflectance properties through specific coatings. The design space of GelSight sensors includes various features, such as the illumination system [1]–[4], curvature [5]–[7], mirrors [8], and compliant grippers [9], with the optical system being the main factor influencing measurement quality.

A major challenge in developing vision-based tactile sensors (VBTS) is their lack of customizability, requiring a complete redesign of the optical system when integrated into new robots. The design process is heuristic, nonlinear, and lacks standardized components, making it time-consuming and complex.

To address this, we propose a systematic design approach for the GelSight sensor family, using parameterized optical modules and quantitative evaluation metrics. A physically-based simulator on top of the Blender [10] platform optimizes design parameters, simplifying the process. The Key Contributions are a formal, parameterized design framework for GelSight sensors, enabling sim-to-real transfer; new objective functions to quantify VBTS sensor performance; an interactive design tool using open-source libraries; and demonstration of optimization for VBTS sensor designs.

II. GelSight sensor modularization

We break down sensor modeling into five components: Soft elastomer, Support structure, Opaque coating, Light, and Camera. Each component has a corresponding design module for creation and optimization, which can either be modeled from scratch or initialized using our component library. This library, derived from vision-based sensor literature, allows novice users to design sensors without prior experience with VBTS sensors.

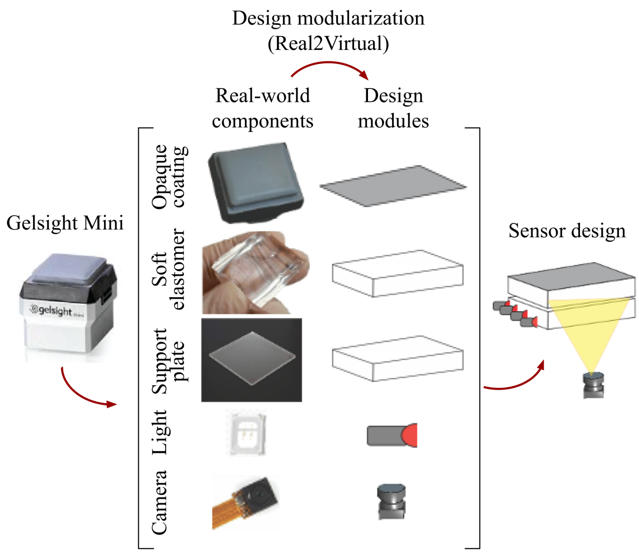

Fig. 1. This figure illustrates how a tactile sensor can be modularized into our proposed modules. These modules can then be used to create a digital design for further optimization.

Figure 1 illustrates how a GelSight Mini tactile sensor can be decomposed into real-world components, aligning with the modules in our framework. These modules enable the creation of a digital design that can be optimized efficiently.

III. Design Parameterization

We parameterize key sensor components to facilitate design modifications. The parameterization choices are based on expertise in VBTS tactile sensors.

Geometric Shape. All components are represented as triangle meshes, with a cage-based approach to reduce complexity, inspired by [11]. This enables efficient shape optimization while maintaining control over the design.

Optical Materials. Materials are assigned using analytic BSDF models [12], including RoughDielectric (for transparent surfaces like elastomers) and RoughConductor (for opaque coatings). These models are calibrated for real sensor materials.

Light Sources. Users can modify location, orientation, and type of lights using PointLight and AreaLight models. Light groups are optimized based on market-available LEDs with manufacturer-provided IES profiles.

Camera. A perspective camera model is used, with adjustable height, width, and field-of-view (FoV). Camera artifacts like saturation and exposure effects are simulated through post-processing.

This structured parameterization allows for efficient sensor design and optimization, making it accessible even to users without prior expertise.

*These authors contributed equally to this work.

[1]Arpit Agarwal is with Carnegie Mellon University, Pittsburgh, PA, USA {arpita1}@andrew.cmu.edu

[2]Mohammad Amin Mirzaee and Wenzhen Yuan are with University of Illinois at Urbana-Champaign, Champaign, IL, USA {mirzaee2,xipings2,yuanwz}@illinois.edu

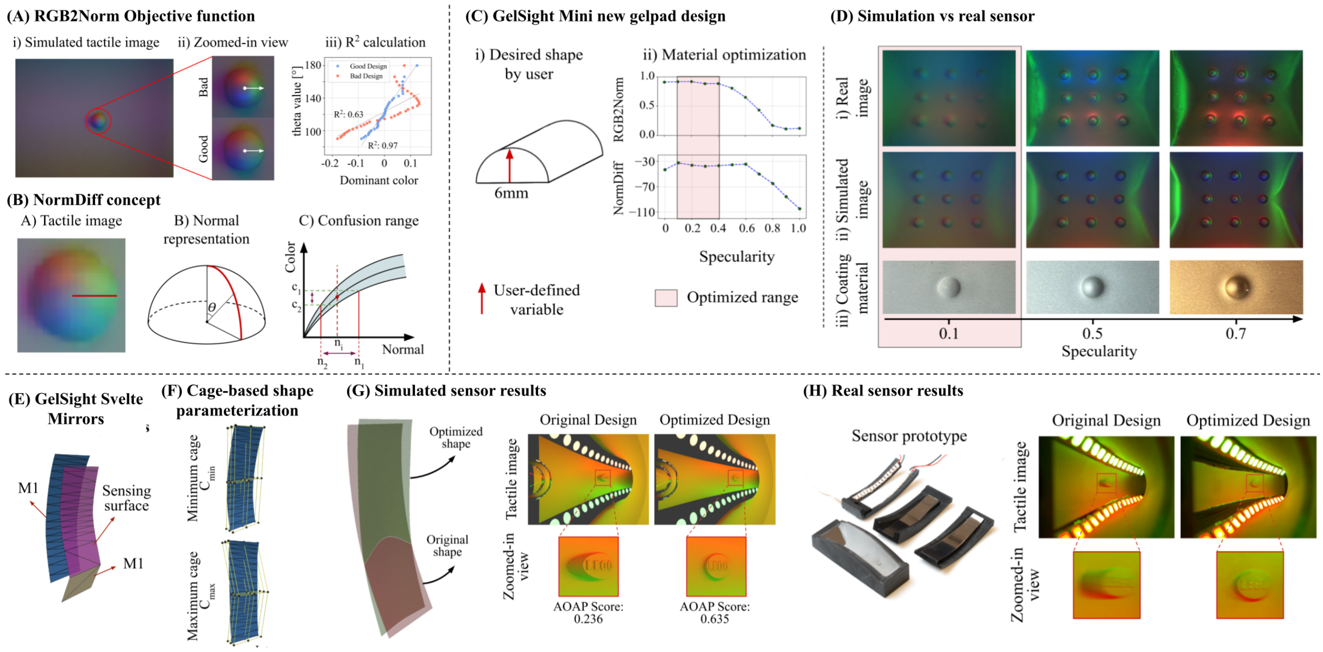

Fig. 2. (A) RGB2Norm function scores the correlation between the RGB value and normal vectors on multiple line segments. (B) NormDiff measures the uncertainty of noisy RGBs and normal vectors. (C) We use the RGB2nNorm and NormDiff to optimize the material of a new shape for Gelsight Mini. (D) Comparison between the simulations and experimental results. (E) we use cage-based representation to modify the geometries. (F) The user defines the range of deformation on the cage and we find the optimized shape in the range. (G) AOAP optimization could remove the distortion seen in the original sensor. (H) The experimental results match the simulation.

IV. Design Objective Functions

We introduce three objective function during the design optimization process. These functions highlight different aspects of sensor performance, enabling designers to choose based on specific goals.

The RGB2Normal Mapping Objective Function measures how accurately the sensor can recover surface normals from RGB colors. It uses spherical indenters to test the correlation between color and surface normals, with a strong, ideally linear correlation desired for high-quality 3D reconstruction, over line segments as shown in Figure 2 A.

The NormDiff Objective Function evaluates how distinct the RGB values are for different surface normals, without assuming linearity. This function uses a noise model to estimate confusion in normal estimation from RGB values, as described in Figure 2 B. The objective function value is the negative of the confusion range, meaning lower confusion leads to better sensor performance.

The As-Orthographic-As-Possible (AOAP) Objective Function measures geometric distortion caused by camera rays deviating from orthogonality. The goal is to optimize the design to make incident rays as perpendicular as possible to the sensing surface. This function includes a regularization term to encourage even surface coverage.

V. Experiments

Case Study I: GelSight Mini is a commercialized vision-based tactile sensor. Using our framework, we quickly generated the optical design and simulated tactile images, which closely matched real images. The sensing surface shape was modified to a cylindrical form by adjusting control points, demonstrating the flexibility of the design tool, as shown in Figure 2 Ci. For the coating material, the best results for the cylindrical surface were achieved with a specularity of around 0.2. We prototyped the real gelpads with different coating materials and compared the simulation and experiment results as shown in Figure 2 D.

Case Study II: GelSight Svelte [13] sensor utilizes multiple mirrors to direct the camera view to a human-finger-shaped sensing surface, allowing for sensing along the entire finger. During the investigation, we observed a "smearing" distortion when indenters were pressed on the sensing surface, as illustrated in Figure 2 H (Original Design). This distortion was due to the limitation in the design of the larger back mirror.

To alleviate this issue, we applied the *As-orthographic-as-possible* (AOAP) objective function and focused on improving perception at the center of the sensing surface. We used a cage-based parameterization of the larger mirror surface (M1) to optimize its shape. This reduced the search space significantly, and we initialized the cage with the original mirror shape. The optimization was performed using the CMA-ES algorithm, and the results showed that the AOAP score improved from 0.236 (initial design) to 0.635 (optimized design). As shown in the rendered tactile images, the smearing effect was almost entirely eliminated in the optimized design. This optimization approach can be applied to any optical surface design.

VI. Conclusion

In conclusion, this paper presents a framework for optimizing GelSight-based tactile sensors, introducing objective functions like RGB2Normal, NormDiff, and AOAP to improve shape measurement accuracy, reduce noise, and minimize optical distortion. We applied these methods to GelSight Mini and Svelte sensors, achieving enhanced performance in shape perception. Our approach demonstrates the potential for refining sensor geometry and materials. Future work will explore additional objective functions to further advance sensor design and optimization for a broader range of applications.

References

[1] R. Li, R. Platt, W. Yuan, A. Ten Pas, N. Roscup, M. A. Srinivasan, and E. Adelson, "Localization and manipulation of small parts using gelsight tactile sensing," in *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2014, pp. 3988–3993.

[2] 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)*. Philadelphia, PA, USA: IEEE, 2022, pp. 10 781–10 787.

[3] S. Q. Liu and E. H. Adelson, "Gelsight fin ray: Incorporating tactile sensing into a soft compliant robotic gripper," in *2022 IEEE 5th International Conference on Soft Robotics (RoboSoft)*. Edinburgh, United Kingdom: IEEE, 2022, pp. 925–931.

[4] M. A. Mirzaee, H.-J. Huang, and W. Yuan, "Gelbelt: A vision-based tactile sensor for continuous sensing of large surfaces," *IEEE Robotics and Automation Letters*, vol. 10, no. 2, pp. 2016–2023, 2025.

[5] B. Romero, F. Veiga, and E. Adelson, "Soft, round, high resolution tactile fingertip sensors for dexterous robotic manipulation," in *2020 IEEE International Conference on Robotics and Automation (ICRA)*. Paris, France: IEEE, 2020, pp. 4796–4802.

[6] Z. Lin, J. Zhuang, Y. Li, X. Wu, S. Luo, D. F. Gomes, F. Huang, and Z. Yang, "Gelfinger: A novel visual-tactile sensor with multi-angle tactile image stitching," *IEEE Robotics and Automation Letters*, vol. 8, no. 9, pp. 5982–5989, 2023.

[7] M. H. Tippur and E. H. Adelson, "Gelsight360: An omnidirectional camera-based tactile sensor for dexterous robotic manipulation," *arXiv preprint arXiv:2304.04268*, 2023.

[8] S. Wang, Y. She, B. Romero, and E. Adelson, "Gelsight wedge: Measuring high-resolution 3d contact geometry with a compact robot finger," in *2021 IEEE International Conference on Robotics and Automation (ICRA)*. Xi'an, China: IEEE, 2021, pp. 6468–6475.

[9] S. Q. Liu, Y. Ma, and E. H. Adelson, "Gelsight baby fin ray: A compact, compliant, flexible finger with high-resolution tactile sensing," in *2023 IEEE International Conference on Soft Robotics (RoboSoft)*, 2023, pp. 1–8.

[10] B. O. Community, *Blender - a 3D modelling and rendering package*, Blender Foundation, Stichting Blender Foundation, Amsterdam, 2018. [Online]. Available: http://www.blender.org

[11] J. Xu, T. Chen, L. Zlokapa, M. Foshey, W. Matusik, S. Sueda, and P. Agrawal, "An end-to-end differentiable framework for contact-aware robot design," *arXiv preprint arXiv:2107.07501*, 2021.

[12] W. Jakob *et al.*, "BSDFs - Mitsuba 3 — mitsuba.readthedocs.io," 2024. [Online]. Available: https://mitsuba.readthedocs.io/en/latest/src/generated/plugins_bsdfs.html

[13] J. Zhao and E. H. Adelson, "Gelsight svelte: A human finger-shaped single-camera tactile robot finger with large sensing coverage and proprioceptive sensing," in *2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2023, pp. 8979–8984.