Simulation-driven vision-based tactile sensor design

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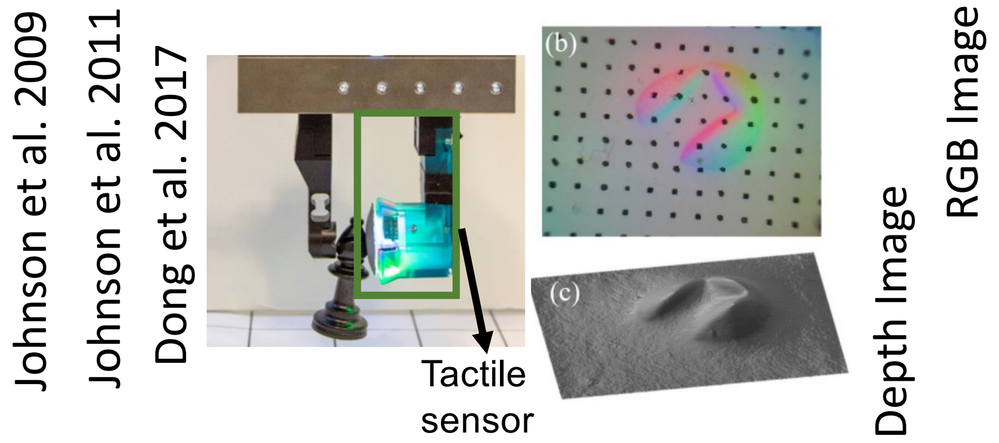
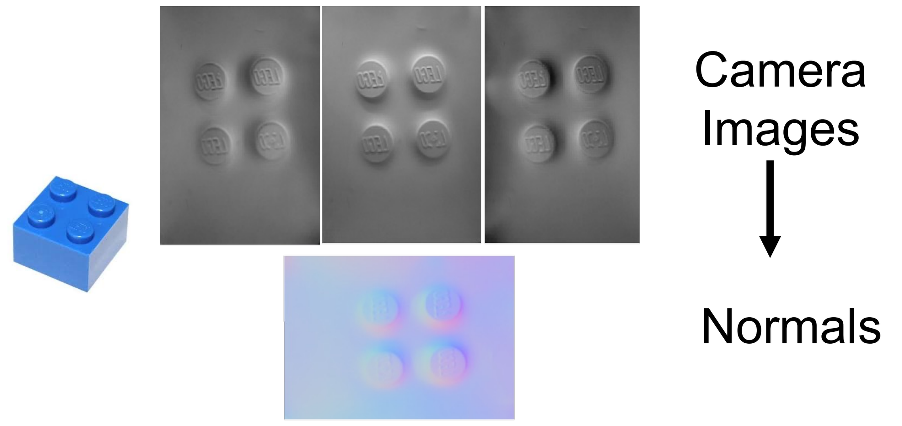
GelSight illustration



GelSight tactile sensor allows to capture dense tactile information which is essential for dexterous robot manipulation.

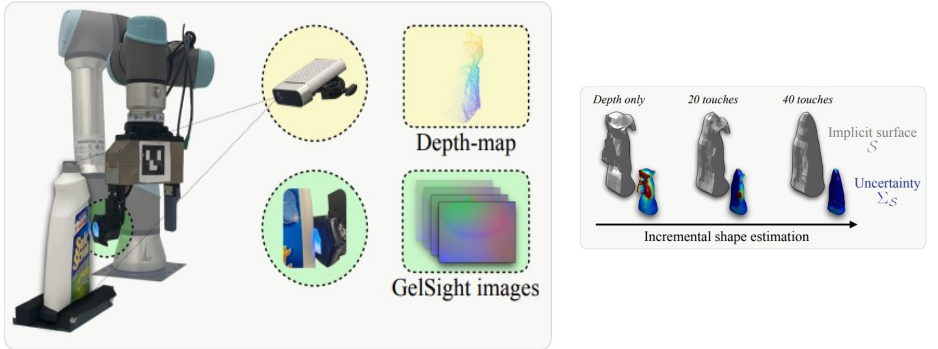
Photometric stereo



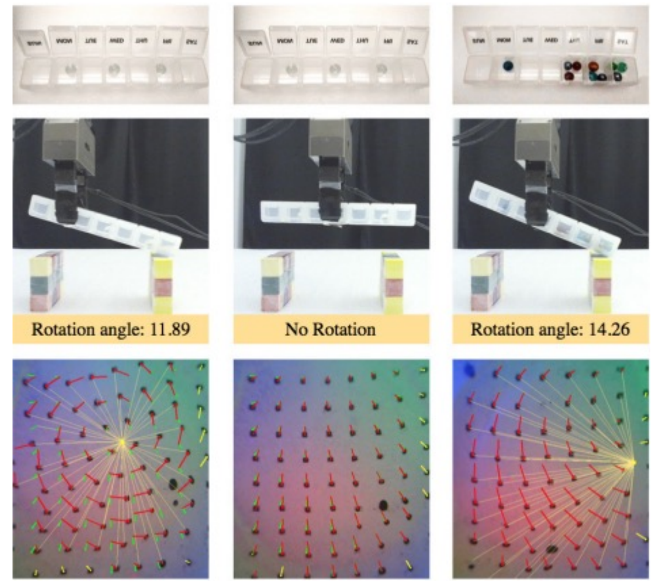
With photometric stereo, GelSight can encode surface normals as an RGB image.

Robotic applications

Object shape estimation: Suresh et al. 2022



Detecting grasp failure: Kolamuri et al. 2021



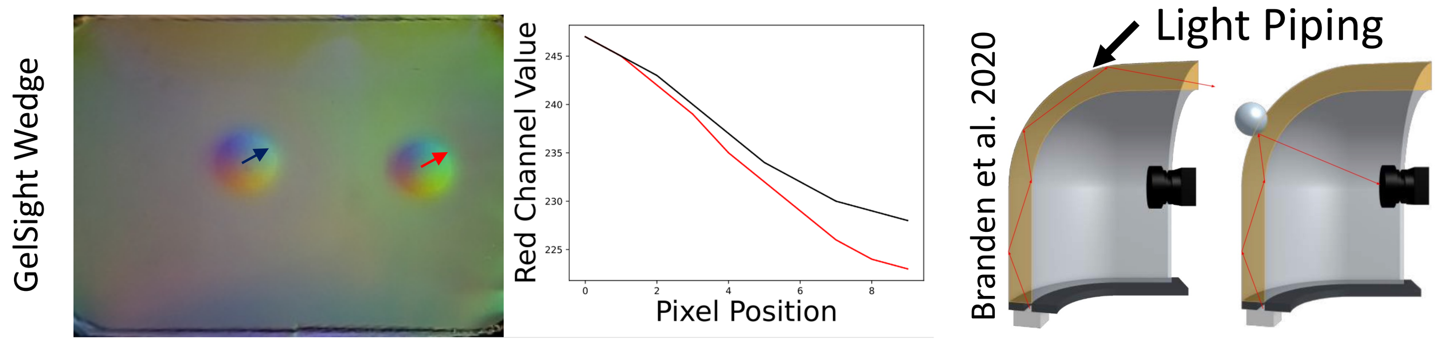
Sensor design challenges

Curved sensing surface: Improved contact area

Note: This is a new tactile sensor as compared to original GelSight

- First vision-based curved tactile sensor
- Uses light piping effect for illuminating all sensing surface
- Larger contact area
- Wider range of contact locations
- Big form factor
- No way to explore new sensor designs

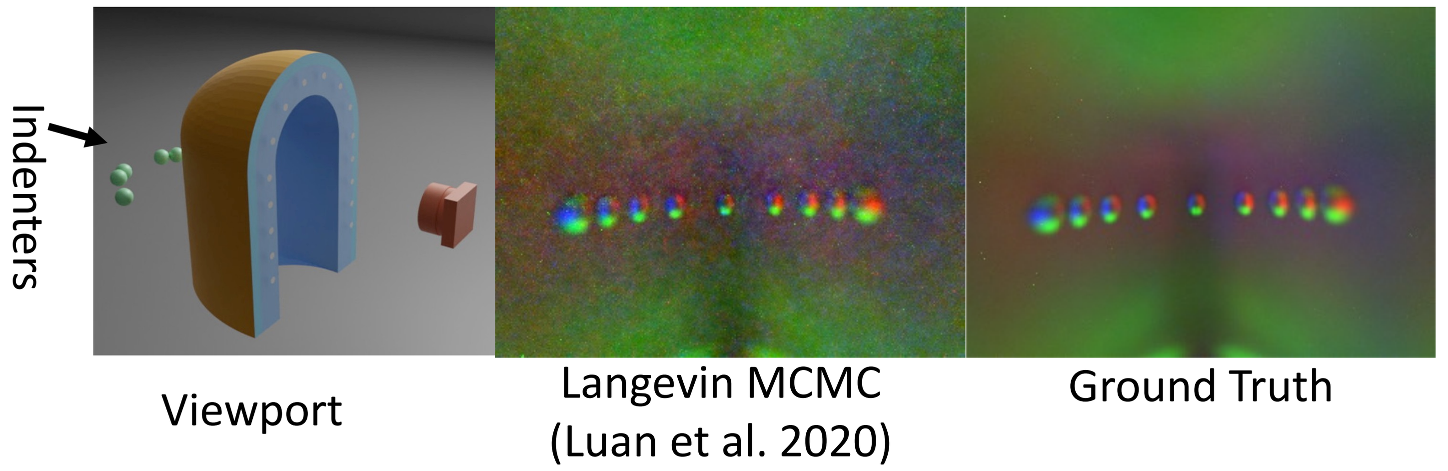
Uniform illumination: Improved surface reconstruction



- Spatial variation of color due to non-ideal illumination

Our approach: overview

Simulation: Use Markov Chain Monte Carlo rendering for physically accurate light transport simulation



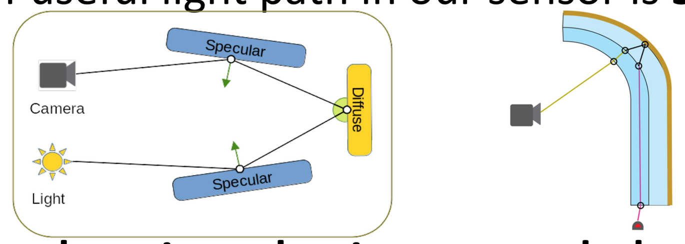
- Orders of magnitude faster than manufacturing the tactile sensor
- Measure sensor performance without expensive normal calibration

Calibration: Use fast and cheap methods to fit analytic simulation models for tactile sensor component (lights and coating material).

Design Space Exploration: Identify key parameters to use for tactile sensor design and analyze its impact on sensor's ability to reproduce normal.

Our approach: sensor simulation framework

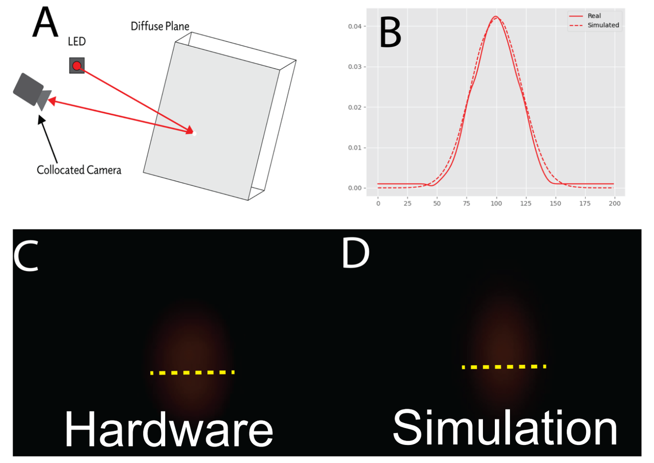
Challenge 1: Specular-Diffuse-Specular(SDS) paths
sampling SDS paths require MCMC techniques which exploit previously found paths to generate new paths
Challenge 2: Probability of sampling longer paths is low and **minimum** length of useful light path in our sensor is **5**



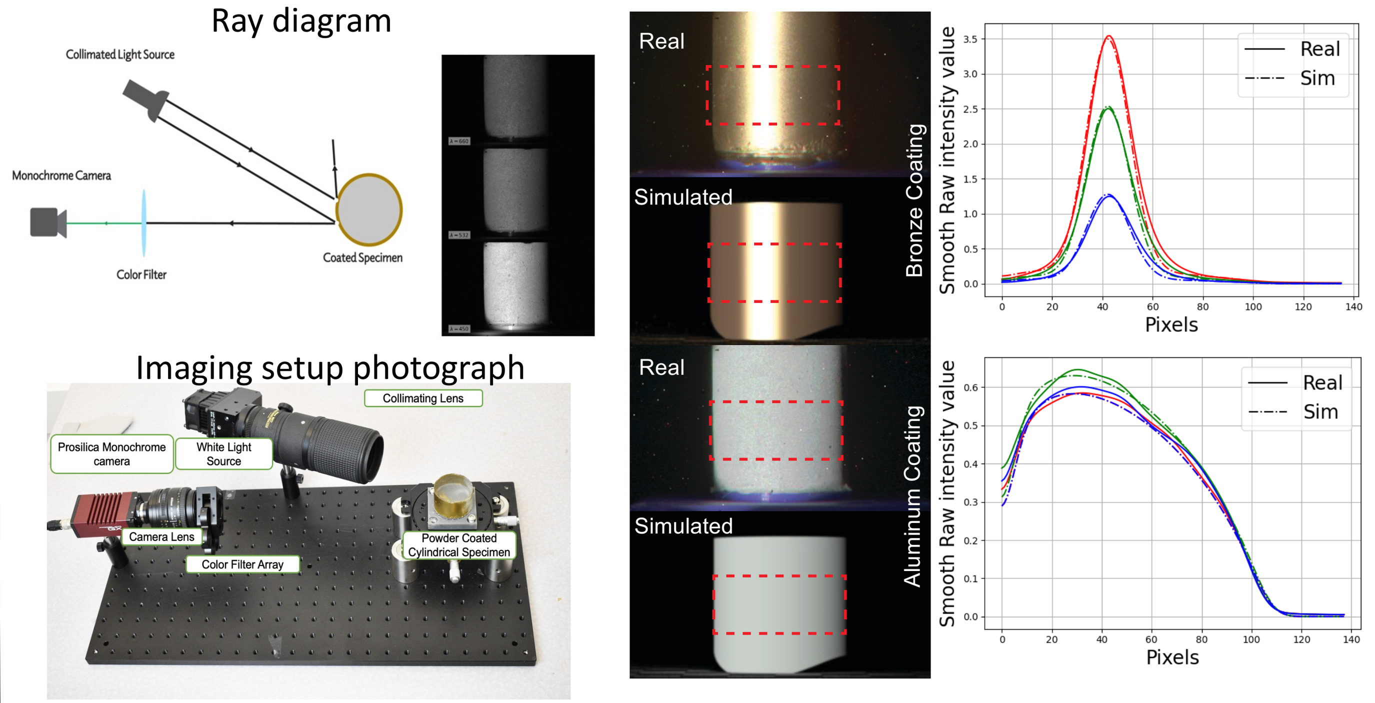
Our approach: simulation model calibration

High fidelity simulation requires accurate simulation model. Calibration of light model and coating material BRDF turned out to be critical models for simulation

Light profile characterization



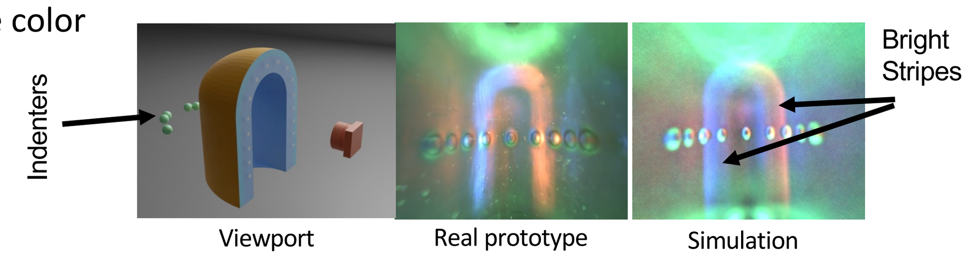
BRDF characterization



Tactile sensor hardware and simulation comparisons

Key Similarities

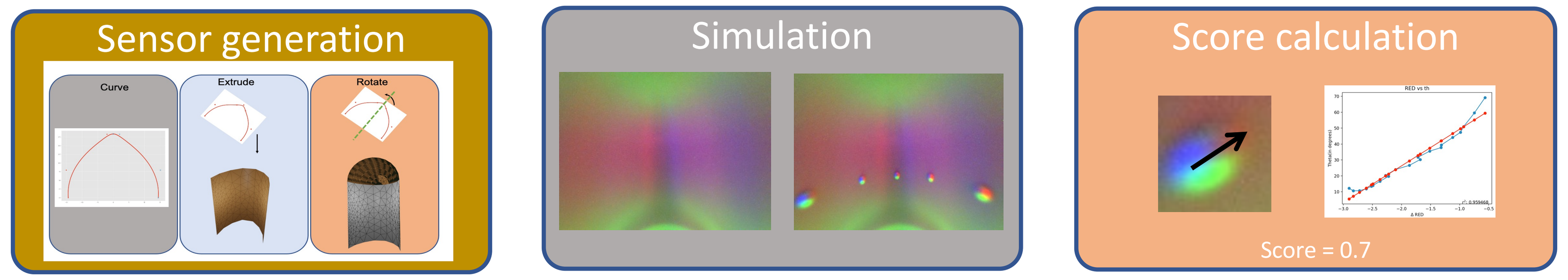
a) Bright stripes of LED light in simulation and physical tactile sensor prototype
b) Light piping of red color from right to illuminate the spheres on the left and similarly for blue color



Note: Multiple indentation allows to assess variation of sensor performance across the sensor surface

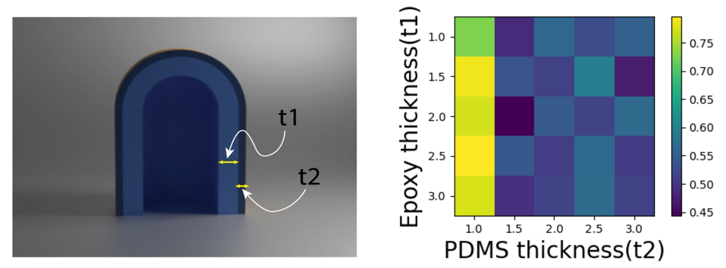
Results: Analysis of key design space choices on the sensor performance

Why - Provides high level intuitions on what are the key parameters to optimize and identify parameter ranges to set for optimization
What - Perturb parameter and perform design evaluation using *RGB2normal* score function



Effect of varying thickness of hard base (t1) and soft sensing volume (t2)

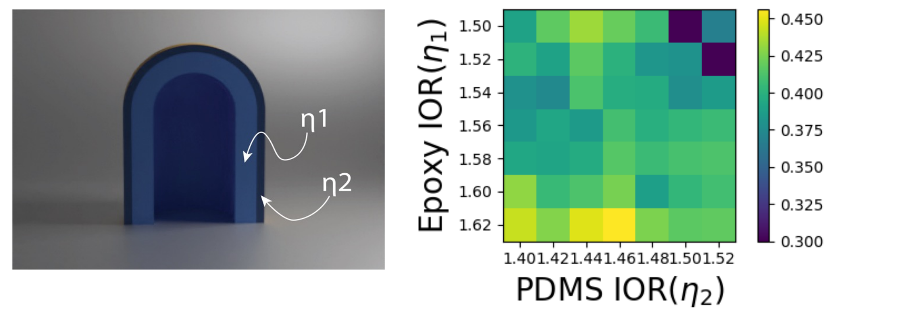
Thinner soft sensing (PDMS) volume leads to better sensing performance. It is due to light entering and leaving the region with minimum distortion.



Effect of index of refraction of hard base (η_1) and soft sensing volume (η_2)

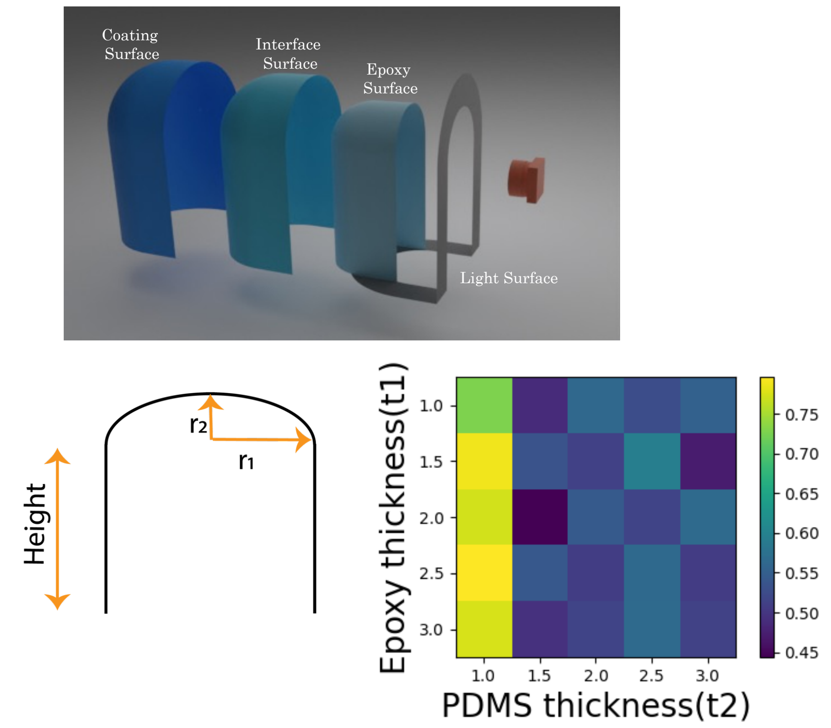
Higher contrast in IORs between 2 sensor materials (hard base and soft sensing volume) leads to better sensor performance.

Note: Matching IOR is a non-physical case and has been removed from the results



Effect of variation of innermost (Epoxy) sensor surface shape

Epoxy surface which is **flatter** at the top to have higher performance consistently and better illumination of indented sensor surface.



Conclusions

1. Physics-based and high-fidelity simulation framework for simulating vision-based tactile sensors
2. Low-dimensional tactile sensor parameterization and full sensor generation method
3. Interesting design parameter space exploration