Simulation of Curved GelSight Sensors for Sim2Real Learning

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Abstract— **Over the past years, several geometries have been proposed for the GelSight high-resolution tactile sensors. However, existing simulation methods are limited to flat-surface designs, which prevents their usage with the newer curved sensors. In this paper, we extend our previously proposed GelSight simulation method for flat-surface sensors, by considering that light rays travelling through a curved membrane follow geodesic paths [1]. The method is validated by simulating the finger-shaped GelTip sensor and comparing the generated synthetic tactile images against the corresponding real images. Combining the illumination generated from the geodesic paths, with a background image from the real sensor, produces the best results when compared to the lighting generated by direct linear paths in the same conditions. The proposed method not only unlocks simulating existing optical tactile sensors of curved geometries but also enables experimenting with sensors of novel geometries, before their fabrication.**
https://danfergo.github.io/geltip-sim.

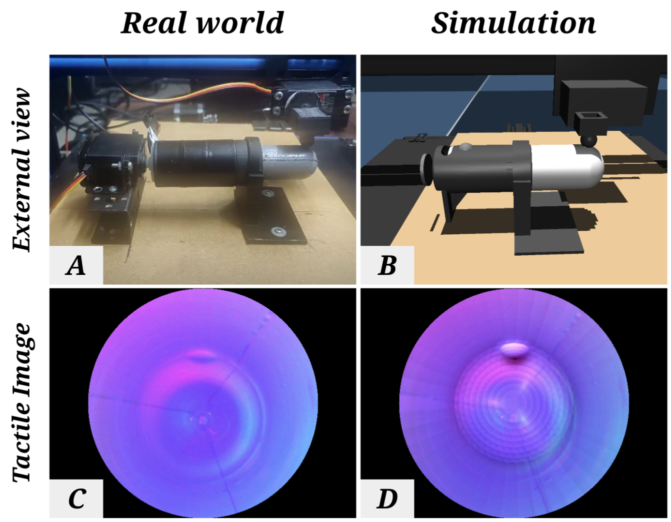

Fig. 1. **(A)** and **(B)**: The real and the simulated experimental setups respectively, in each a GelTip tactile sensor is mounted onto a 3D Printer and contacts a 3D printed object (here is a cube with a hollow cylinder in the centre). **(C)** and **(D)**: The corresponding tactile images captured from the GelTip sensor, real and simulated respectively.

I. INTRODUCTION

Touch sensing is an important sensing modality for robots interacting with objects in an unstructured way. With that, over the past years, the usage of cameras behind soft opaque membranes has emerged as a promising direction for developing tactile sensors [2], [3]. One family of such camera-based tactile sensors are the GelSight [3], wherein the entire raw image is for photometric analysis. However, carrying out experiments with tactile sensors is challenging as they are prone to damage and aren't easily commercially available. Therefore, the simulation of such sensors is important for robotics research. Firstly, it enables wider access to and sharing of experimental setups using the tactile sensors, as the simulation is cost-free, can be instantiated as many times as necessary, can be shared over the internet, etc. And, secondly, it accelerates the execution of experiments, as there are no hardware failures. In this context, simulation models have been proposed for flat GelSight sensors [4], [5], [6], [7], [8]. However, existing simulation methods are limited to flat-surface designs, which prevents their usage with the newer curved ones. In this paper, we extend our previously proposed GelSight simulation method [4], for flat-surface sensors, by considering that light rays travelling through a curved membrane, follow geodesic paths, and apply it to simulate a GelTip tactile sensor, as shown in Figure 1.

II. METHOD

Starting from our previous simulation method for flat GelSight sensors [4] additional steps are considered to address sensors of curved geometry, where the light travels through its curved membrane. Particularly, we address the sensor internal illumination, that for flat sensors [9], [10] is a constant vector field, starting on the LEDs / membrane edge and being tangent to the flat surface. For curved sensors, we consider the geodesic, i.e., the shortest path on a curved surface, as a reasonable path for the light to travel in the membrane. Four alternatives are considered for computing the light field: *Linear*, *Plane*, *Geodesic* and *Transport*. *Linear* is a baseline radial light field, originating from a point light source. *Plane* is a naïve approach for computing the geodesic path, based on the intersection of a plane that passes through the light source, with the sensor mesh. *Geodesic*[1] and *Transport*[2] are publicly available implementations for the computation of geodesic paths and vector transport, over meshes. Since the light within the entire sensor is constant, we can pre-compute it beforehand. This way, the method can be run online. The overall approach consists of two steps: light fields are firstly computed offline; then, using the computed light fields, the simulation model is run online for each frame of the sensor simulation. The online simulation

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[1]https://pypi.org/project/pygeodesic/
[2]https://pypi.org/project/potpourri3d/

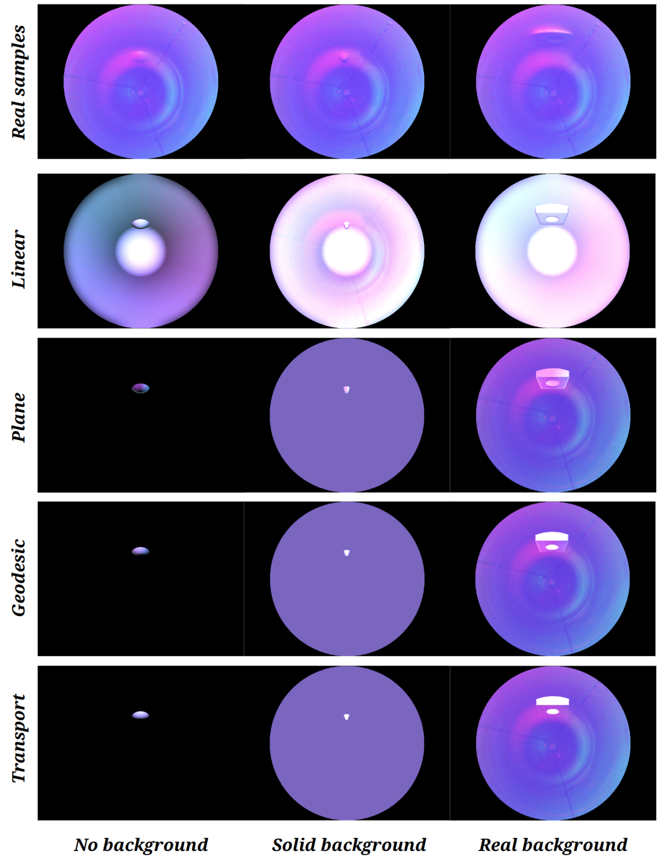

Fig. 2. Samples of tactile images extracted from the real (aligned) and synthetic datasets, for the 4 light fields considered: *Linear*, *Geodesic* and *Transport* light fields. With no ambient illumination, the *Geodesic*, *Linear* and *Transport* fields result in illumination only in the in-contact areas. Thus, these methods can successfully be combined with the real background image, to produce a realistic-looking simulated image.

model consists of three main steps: 1) smoothing of the raw depth map, captured from the simulation environment, to mimic the elastic deformation of the real sensor; 2) mapping of the smoothed depth map onto a point-cloud in the camera coordinates frame; 3) generation of the tactile image using Phong's reflection model and the pre-computed light fields.

III. EXPERIMENTS

For each light field, we generate the corresponding version of the dataset, from captured depth maps in simulation, and compare it against real aligned correspondences, as shown in Figure 2. We then compute the Structural Similarity (SSIM) over the entire dataset for the different scenarios, for quantitative analysis. As reported in Table I, the *Linear* light field results in a better SSIM of 0.84, when no ambient light is considered. However, if either a solid ambient illumination or the background image from the real sensor is used, then the *Plane*, *Geodesic* and *Transport* methods produce the best results, with a high SSIM of 0.93. This directly comes from the fact that the *Plane*, *Geodesic* and *Transport* methods do not produce any illumination in areas that are not being deformed by a contact, which contrasts with the *Linear* method that generates bright gradients throughout the entire sensor surface. This occurs because when no ambient light is considered, $k_a i_a = 0$, and where no contacts are happening, with the light travelling tangent through the surface, $\hat{L}_m \perp \hat{N} \implies \hat{L}_m \cdot \hat{N} = 0$, and the entire Phong's illumination expression is zero. This happens by design and follows directly from the GelSight working principle [11].

TABLE I
REAL AND GENERATED DATASETS COMPARISON (SSIM)

	None	Solid	Real
Linear	**0.84**	0.85	0.85
Plane	0.39	**0.93**	**0.94**
Geodesic	0.34	**0.93**	0.93
Transport	0.38	**0.93**	**0.94**

IV. CONCLUSIONS

We proposed a novel approach for simulating *GelSight* sensors of curved geometry, such as the *GelTip*. The specific considerations of the light trajectories within the tactile membrane help us in better verify whether our assumptions about the real sensor are true. For instance, with the analysis of different types of light fields, we verify that tactile images captured by the existing *GelTip* sensors contain a high degree of light that does not travel parallel to the sensor surface, as idealised by the early GelSight working principle [11]. In the future, we will compare the tactile images obtained from a real sensor fabricated using the morphology design optimised in the simulation, and also apply our proposed simulation model in Sim2Real learning for tasks like robot grasping and manipulation with optical tactile sensing.

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