

Automatic Physically-Based Sim2Real for Tactile Images through Differentiable Path-Tracing Rendering

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Introduction

High-fidelity simulation of vision-based tactile sensors is critical for robotic manipulation, but the sim-to-real gap persists due to complex refraction and unknown sensor parameters. We introduce a differentiable path tracer that optimizes camera pose, lighting, and object texture from just three real images—delivering realistic simulations with accurate light transport and glass refraction.

Background

High Data Dependency – The best-performing methods are data-driven and computationally expensive. [1]

Calibration Bottleneck – Current calibration procedures are fastidious and imprecise. [2]

No Full Image Differentiation – Existing tactile sensors lack end-to-end differentiable image formation. [3]

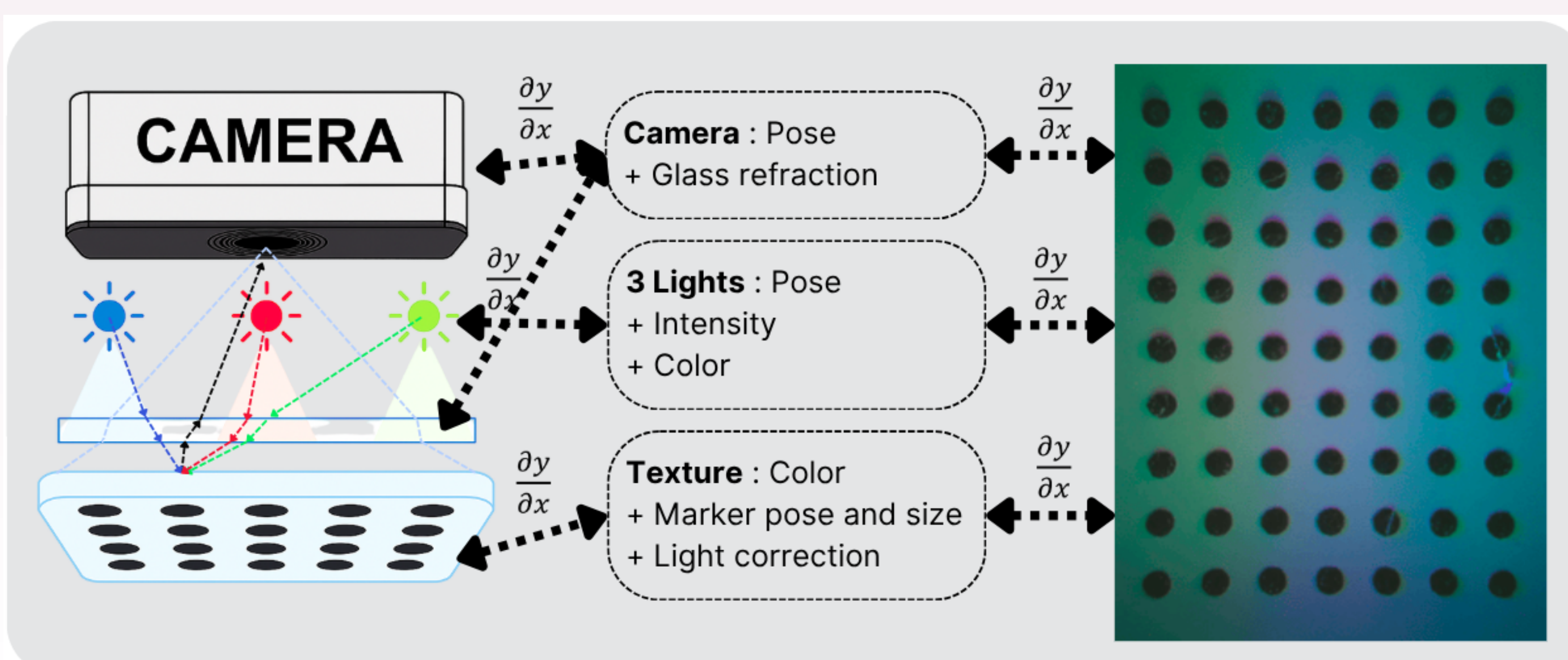
Contributions

Realistic Calibrated Rendering: Utilizes path tracing and optimized marker and light parameters.

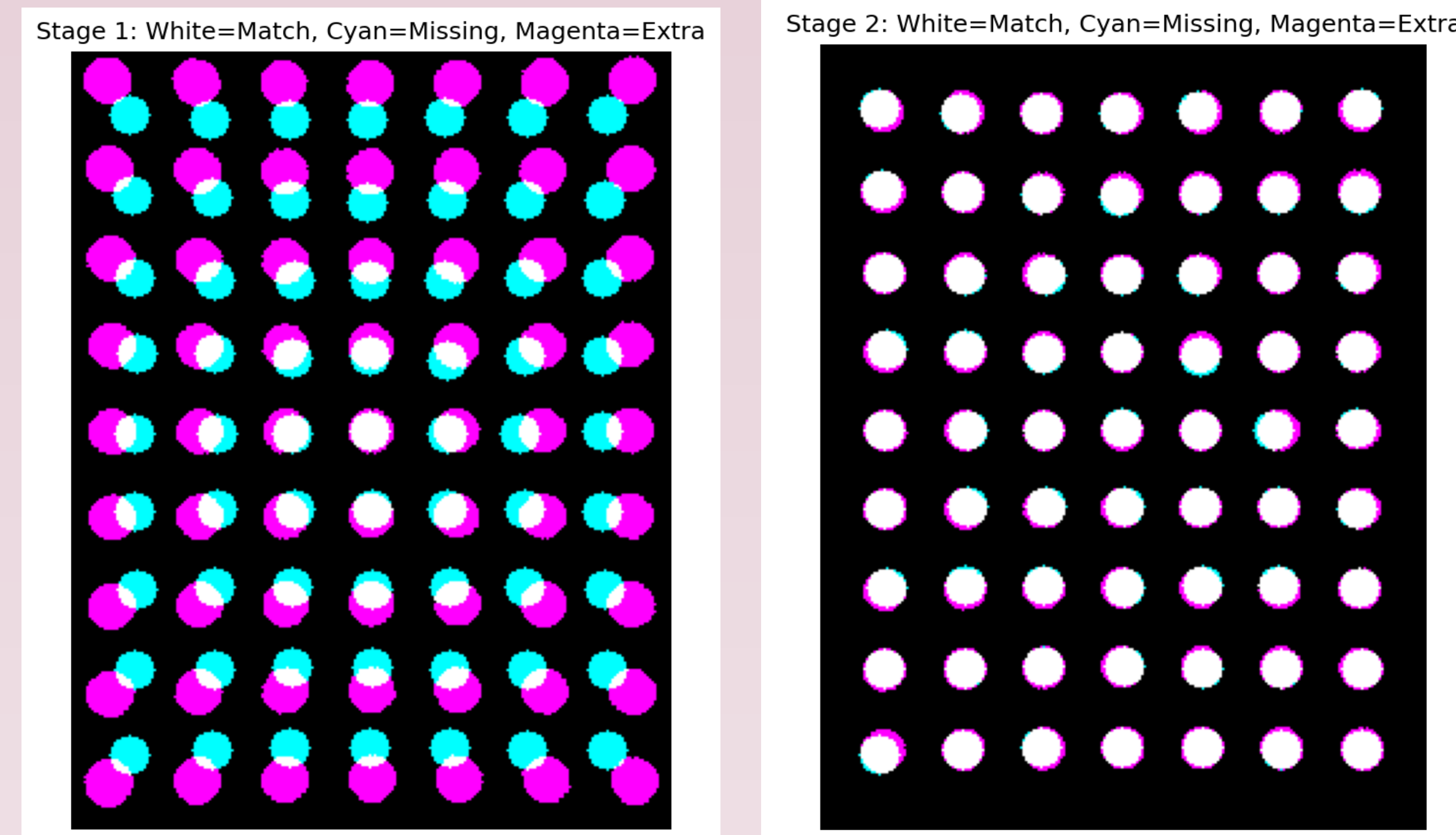
Differentiable Optimization: First use of differentiable rendering to streamline calibration and optimize synthetic rendering parameters (pose, light, markers).

Data Efficiency: Calibration performed using 3 images.

Overall pipeline

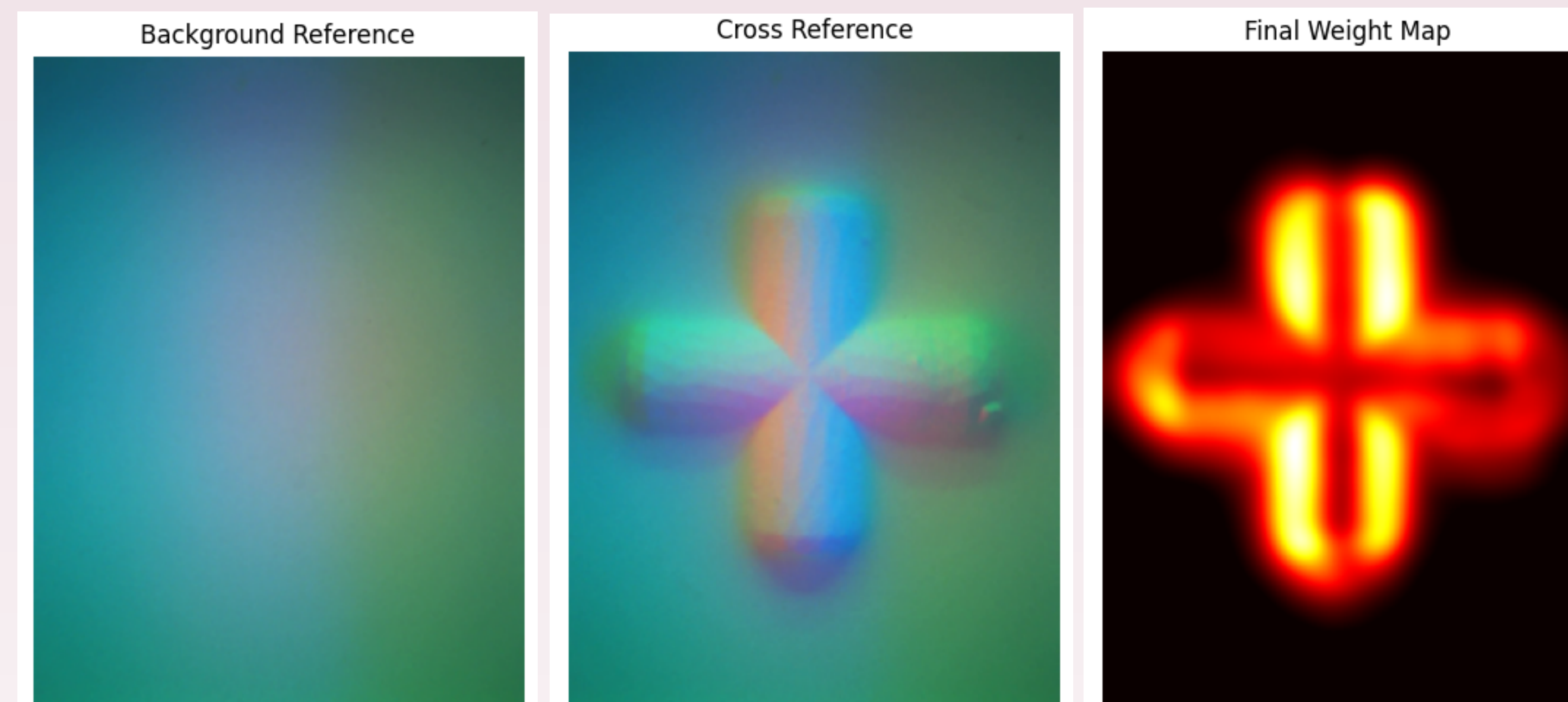


Pose Optimization with glass refraction

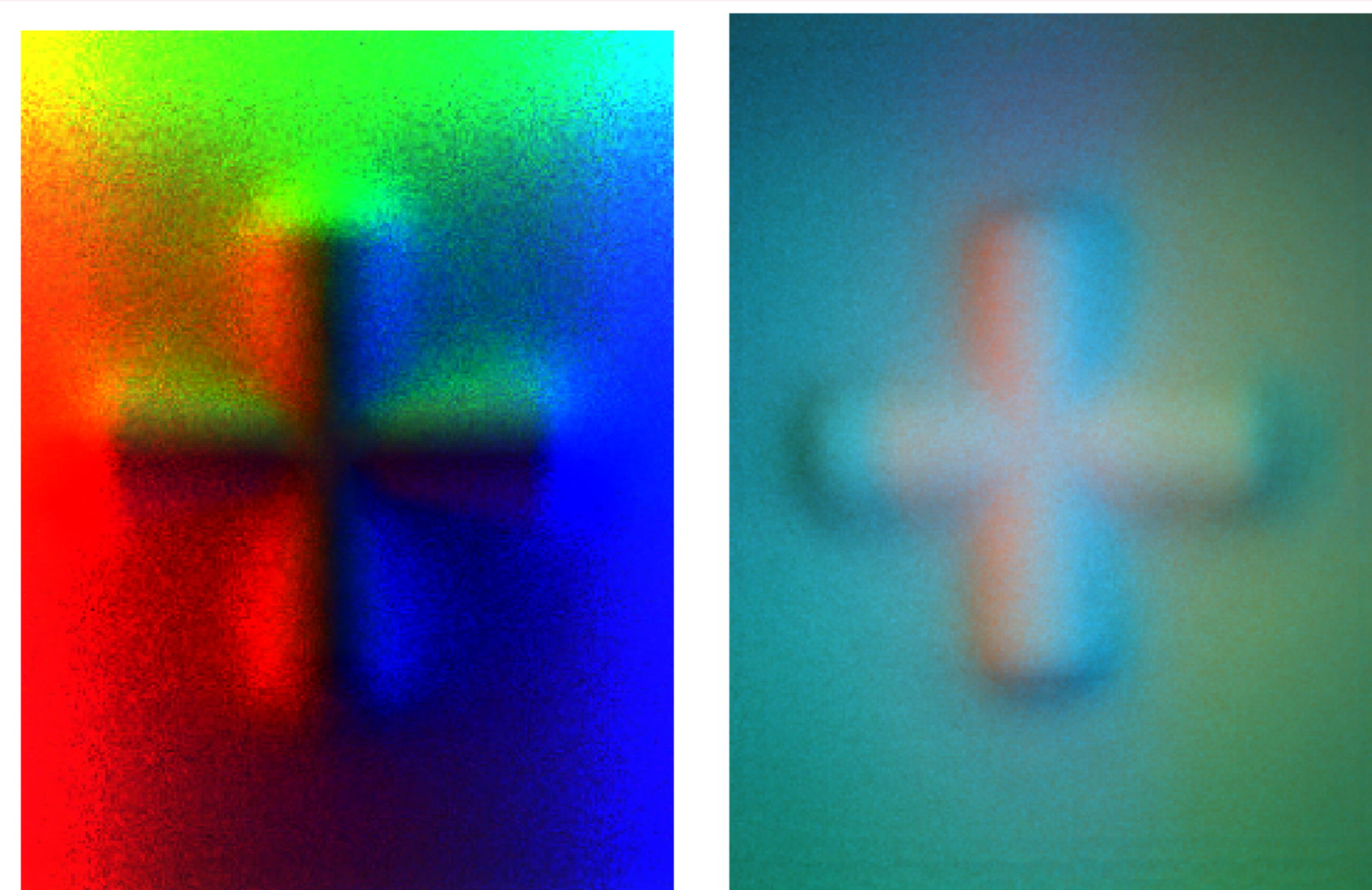


$$\mathcal{L}_{\text{pose}} = \sum_{j=1}^N ((u_j - u_j^{\text{ref}})^2 + (v_j - v_j^{\text{ref}})^2) \quad \mathcal{L}_{\text{stage2}} = \sum_{i=1}^N M_i \cdot (I_{\text{rendered},i} - I_{\text{ref},i})^2$$

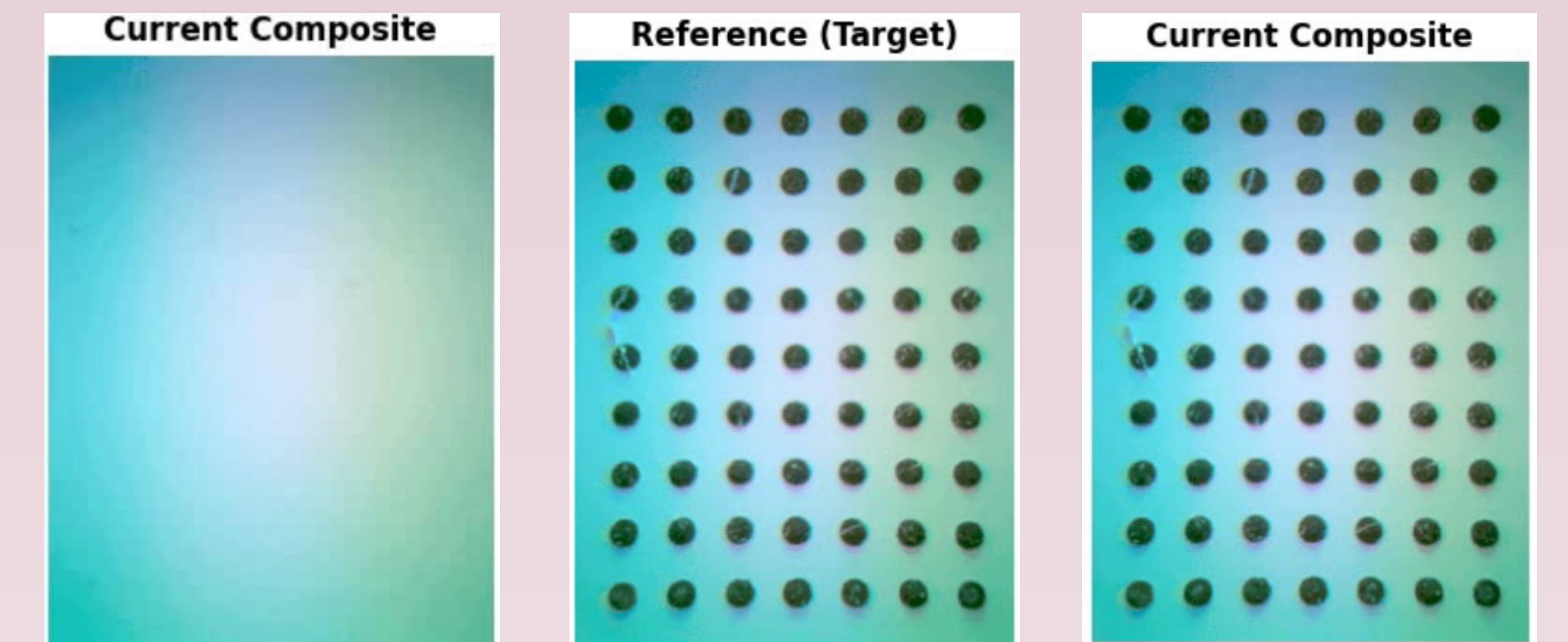
Light Optimization



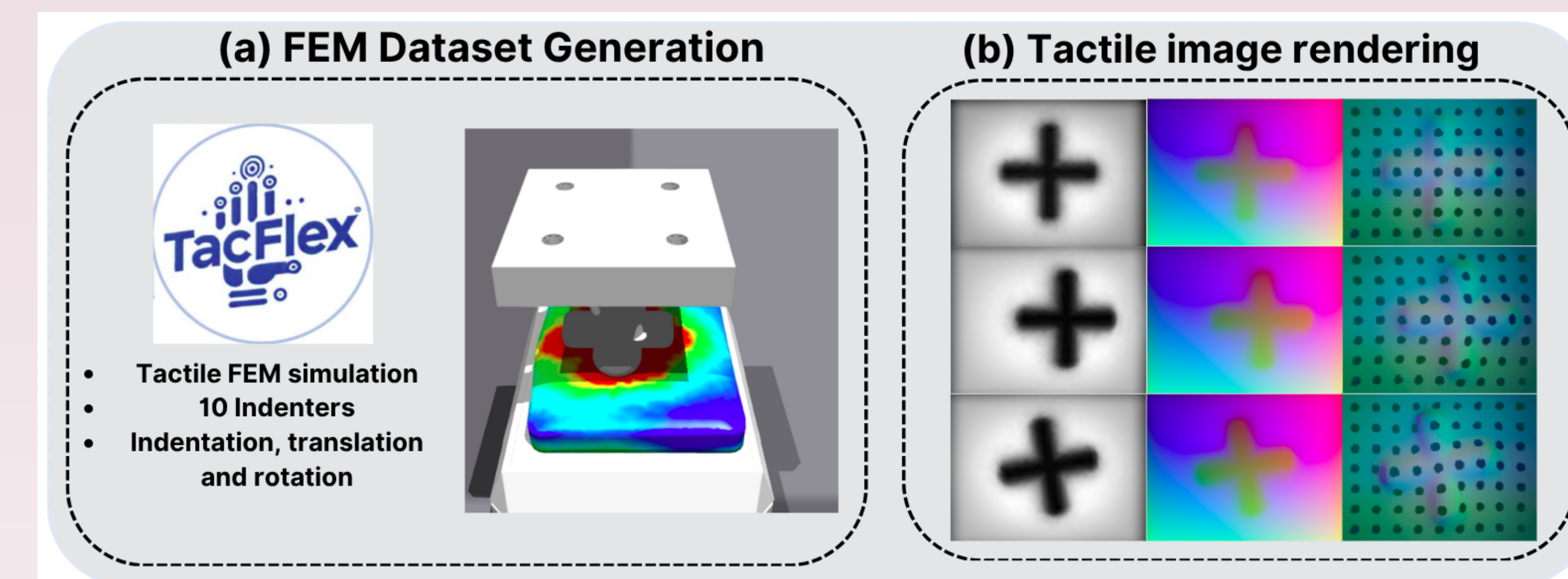
$$\mathcal{L}_{\text{light}} = \frac{1}{N} \sum_{i=1}^N W_i \cdot (T(I_{\text{rendered},i}) - T(I_{\text{ref-light},i}))^2 \quad \mathcal{L}_{\text{mesh}} = \frac{1}{N} \sum_{i=1}^N (T(I_{\text{rendered},i}) - T(I_{\text{ref-mesh},i}))^2$$



Marker optimization



Pix2pix domain adaptation



ID	SSIM ↑	PSNR (dB) ↑	MSE ↓
Depth	0.9543	38.45	9.36
NOCS	0.9609	38.74	8.69

Future works

- Extend the pipeline to other visual tactile sensors
- Integrate into physical tactile simulators
- End-to-end differentiable pipeline

Acknowledgements

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References

- [1] Lin, Yijiong, et al. "Tactile gym 2.0: Sim-to-real deep reinforcement learning for comparing low-cost high-resolution robot touch." IEEE Robotics and Automation Letters 7.4 (2022): 10754-10761.
- [2] Zhang, Chaofan, et al. "Tactflex: Multi-mode tactile imprints simulation for visuotactile sensors with coating patterns." IEEE Transactions on Robotics (2025).
- [3] Si, Zilin, et al. "DIFFTACTILE: A Physics-based Differentiable Tactile Simulator for Contact-rich Robotic Manipulation." The Twelfth International Conference on Learning Representations.