NFL-BA: Improving Endoscopic SLAM with Near-Field Light Bundle Adjustment

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

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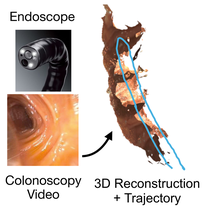
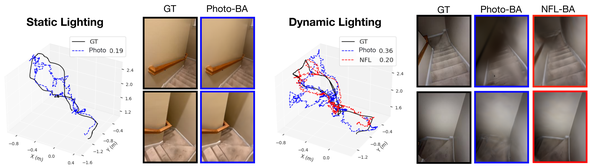
Motivation

SLAM in Endoscopy

- Endoscopic SLAM produces 3D maps and camera tracking of the colon, improving navigation safety, blind-spot detection, and polyp localization.
- **Applications:** surgical guidance, lesion mapping for re-inspection, and automated reporting of morphologies.



Challenges



- **Near-field lighting:** co-located LED cause large brightness swings, breaking photometric BA.
- **Specular & subsurface effects:** wet mucosa produces glare and sub-surface scattering
- **Low-texture scenes:** smooth colon walls lack geometry, leading to drift and "holes" in map.

Neural Gaussian SLAMS

At each camera pose $P_t = [R_t, T_t]$ at frame t, the renderer produces per-pixel color $\hat{C}(p)$ and depth $\hat{D}(p)$

$$\hat{C}(p) = \sum_{i \in \mathcal{N}} c_i \alpha_i \Pi_{j=1}^{i-1}(1-\alpha_j), \quad \hat{D}(p) = \sum_{i \in \mathcal{N}} z_i \alpha_i \Pi_{j=1}^{i-1}(1-\alpha_j)$$

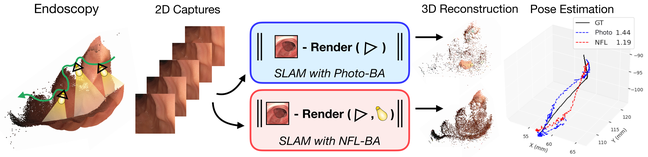
where α_i is occupancy, c_i is color, and z_i is depth.

Standard photometric BA optimizes poses and geometry assumes distant, uniform lighting, which fails under endoscopic illumination.

$$\text{Photo-BA:} \quad \min \sum_{t \in \mathcal{W}} \lambda_{ren} \mathcal{L}_{ren}(\hat{C}, C; M_t) + \lambda_{geo} \mathcal{L}_{geo}(\hat{D}, D; M_t)$$

Method

Near-Field Light Bundle Adjustment



We treat the endoscope's camera and light as co-locate, with each 3D point x_p receiving:

Lighting Direction

$$L^d(x_p) = \frac{x_p - x_L}{|x_p - x_L|}$$

Lighting Attenuation

$$L^a(x_p) = \frac{(L^d(x_p)^\top f)^\beta}{|x_p - x_L|^2}$$

$\beta = 0$ for simplicity

where x_L is the light source, f is the forward axis. Assuming diffuse reflectance where $PPS(\cdot)$ is a per-pixel shading term:

$$PPS(x_p) = L^a(x_p) \cdot (L^d(x_p)^\top n(x_p))$$

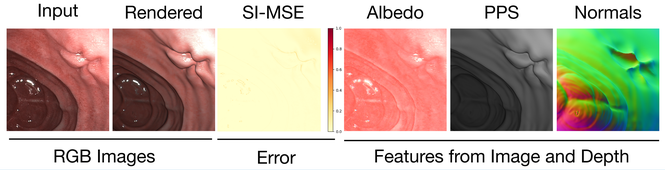
We reinterpret the direct color as the product of the albedo $\rho(\cdot)$ and the shading term $PPS(\cdot)$. This leads to the modified rendering equation under near-field lighting:

$$\hat{C}_{pps}(p) = \sum_{i \in \mathcal{N}} \rho(x_i) PPS(x_i) \alpha_i \Pi_{j=1}^{i-1}(1-\alpha_j)$$

With the new rendering equation, new bundle adjustment loss is

$$\text{NFL-BA:} \quad \min \sum_{t \in \mathcal{W}} \lambda_{ren} \mathcal{L}_{ren}(\hat{C}_{pps}, C; M_t) + \lambda_{geo} \mathcal{L}_{geo}(\hat{D}, D; M_t)$$

Our image formulation model matches real data with low error:



Evaluation

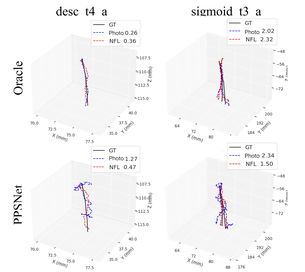
C3VD (Synthetic)

We evaluate both **MonoGS** [1] and **EndoGSLAM** [2] using ground truth and **PPSNet** [3] predicted depths.

Method	Depth	BA	Tracking ATE$_t$ (mm)↓	Tracking ATE$_r$ °↓	Mapping Chamfer (mm)↓	Rendering LPIPS↓
EndoGSLAM	Oracle	Photo	1.93	1.81	0.85	0.37
MICCAI'24	Oracle	NFL	2.04	**1.13**	0.97	0.40
MonoGS	Oracle	Photo	2.90	1.11	1.16	0.50
CVPR'24	Oracle	NFL	**1.60**	1.49	**0.79**	0.51
EndoGSLAM	PPSNet	Photo	3.03	1.73	1.23	0.39
MICCAI'24	PPSNet	NFL	**2.62**	**1.24**	1.25	0.39
MonoGS	PPSNet	Photo	3.48	1.70	1.59	0.56
CVPR'24	PPSNet	NFL	**2.18**	**1.65**	**0.99**	**0.53**

Table 1. Photo-BA vs. NFL-BA (ATE$_t$, Chamfer) across SLAM frameworks and depth sources.

EndoGSLAM Tracking



MonoGS

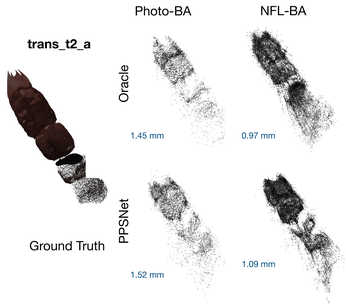
Predicted Depth

- ☑ 37% reduction in tracking errors
- ☑ 38% improved accuracy in mapping

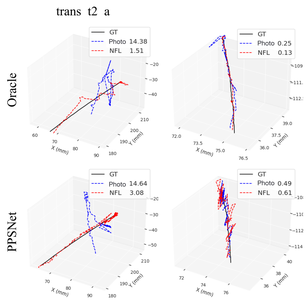
Oracle Depth

- ☑ SOTA Tracking and Mapping

MonoGS Mapping



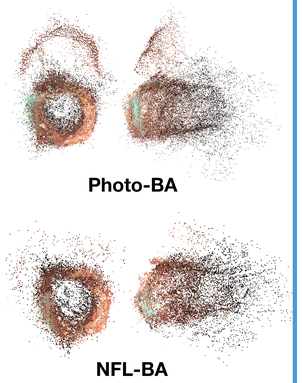
MonoGS Tracking



Colon10k (Real)

Qualitative results on real colonoscopy **Sequence 4** using predicted depth

Check out our website for videos!



- ☑ Less scatter
- ☑ Longer trajectory
- ☑ Fewer color artifacts

Limitations and Future

- Learn non-zero **angular attenuation** for different lights
- Normal calculation leads to a **~10% decrease in FPS**
- We omit **specular reflections and subsurface scattering** due to increased complexity
- Incorporate non-rigid BA with biomechanical priors for **deformable tissue**

Acknowledgments

[1] Matsuki et al. Gaussian Splatting SLAM. CVPR '24

[2] Wang et al. EndoGSLAM: Real-Time Dense Reconstruction and Tracking in Endoscopic Surgery. MICCAI '24

[3] Paruchuri et al. Leveraging Near-Field Lighting for Monocular Depth Estimation. ECCV '24

Please check out our website for interactive results!