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Endo-4DGX: Robust Endoscopic Scene Reconstruction and Illumination Correction with Gaussian Splatting

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Paper

Code & Dataset

Project Page

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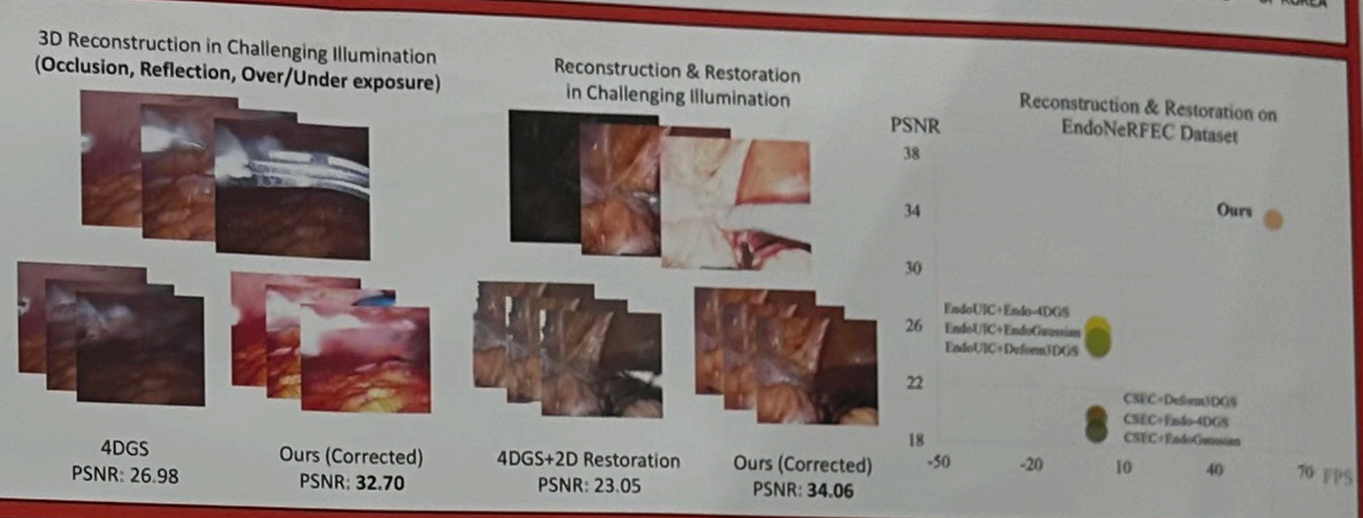
Motivations

- The endoscopic workspace is **dynamic** and **unpredictable**; **illumination changes** quickly due to factors such as the **occlusion**, **reflections**, **low-light** and **over-exposure**.
- Due to the rapid variation of the surgical environment, **2D restoration** methods **fail to produce consistent results** in real-time, leading to corrupted results.
- **Existing 3DGS**-based illumination correction solutions for general scenes, they are not applicable for surgical scenarios due to the **lack of ability** to model the **sub-area** and **spatial-level illumination changes** for deformable tissue.



Key Contributions

- Endo-4DGX, a novel endoscopic reconstruction method with illumination adaptive Gaussian Splatting. Endo-4DGX achieves illumination correction and reconstruction in challenging uneven illumination, providing robust reconstruction result that align-well with the need of challenging surgical environment.
- We introduce a **region-aware enhancement** module to resolve uneven lighting problems at the Gaussian level. Our region-aware module decodes the view specific embedding to model **the sub-area lightness changes**, refining the sub-area illumination changes for the small tissue areas.
- We design a **spatial-aware adjustment** module for spatial-level lightness adjustment, which focuses on the illumination refinement of the whole image. Our spatial-aware adjustment account for the rapid changes of the whole endoscope view, ensuring consistency for robust reconstruction.
- We provide **experiment results** on **three real surgical datasets** with Endo-4DGX for surgical scene reconstruction under challenging illumination, ensuring the robustness for robot-assisted surgery.

Methodology

4D Gaussians Representation: $\mathcal{G}' = \{\mu', r', s', o', c\}$

Appearance and Depth Rendering with Rasterization of 4DGS:

$$C(x) = \sum_i \alpha_i c_i \prod_{j=1}^{i-1}(1-\alpha_i),$$

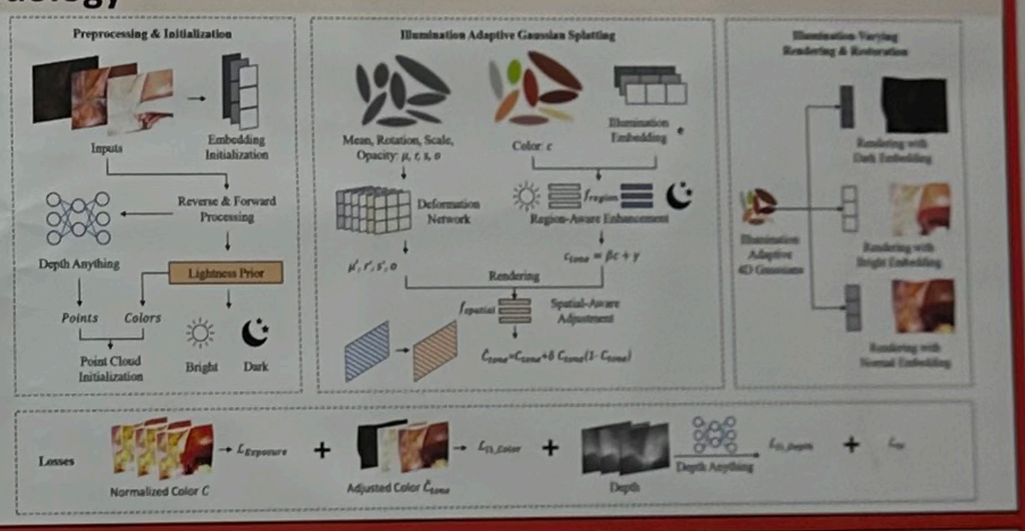
$$D(x) = \sum_i \alpha_i d_i \prod_{j=1}^{i-1}(1-\alpha_i),$$

Illumination Classification for Illumination Embedding Initialization:

$$IC(I) = \begin{cases} Bright, & if\ mean(I) > mean(\mathbf{p}) \\ Dark, & if\ mean(I) \le mean(\mathbf{p}) \end{cases}$$

Region-Aware Enhancement: $c_{\text{tone}} = \beta \cdot c + \gamma, \mid \{\beta, \gamma\} = f_{region}(c, e)$

Spatial-Aware Adjustment: $\tilde{C}_{\text{tone}} = C_{\text{tone}} + \delta \cdot C_{\text{tone}}(1 - C_{\text{tone}}) \mid \delta = f_{spatial}(e)$



Experiment Results

Method	FPS↑	GPU↓	Pulling PSNR↑	Pulling SSIM↑	Pulling LPIPS↓	Cutting PSNR↑	Cutting SSIM↑	Cutting LPIPS↓
EndoUIC [1]+Deform3DGS [25]	*2.02*	8 GB	27.15	0.892	0.180	22.74	0.842	0.231
EndoUIC [1]+Endo-4DGS [11]	*2.0*	12 GB	28.79	0.929	0.097	23.30	0.890	0.116
EndoUIC [1]+EndoGaussian [15]	*2.03*	12 GB	27.49	0.904	0.244	23.05	0.867	0.257
CSEC [14]+Deform3DGS [25]	*1.29*	3.8 GB	20.03	0.855	0.194	20.18	0.809	0.251
CSEC [14]+Endo-4DGS [11]	*1.27*	7.8 GB	19.89	0.876	0.140	20.14	0.838	0.186
CSEC [14]+EndoGaussian [11]	*1.29*	7.8 GB	18.63	0.838	0.283	19.41	0.800	0.339
DarkGS* [30]	524	2 GB	6.04	0.001	0.655	6.66	0.002	0.635
Gaussian-DK* [27]	*41.0*	2 GB	13.13	0.705	0.528	10.26	0.543	0.579
WildGaussians [13]	108	2 GB	15.28	0.724	0.431	17.71	0.752	0.376
Ours	61	6.5 GB	34.94	0.946	0.048	34.06	0.950	0.043

Quantitative results on EndoNeRF-EC Dataset for illumination correction.

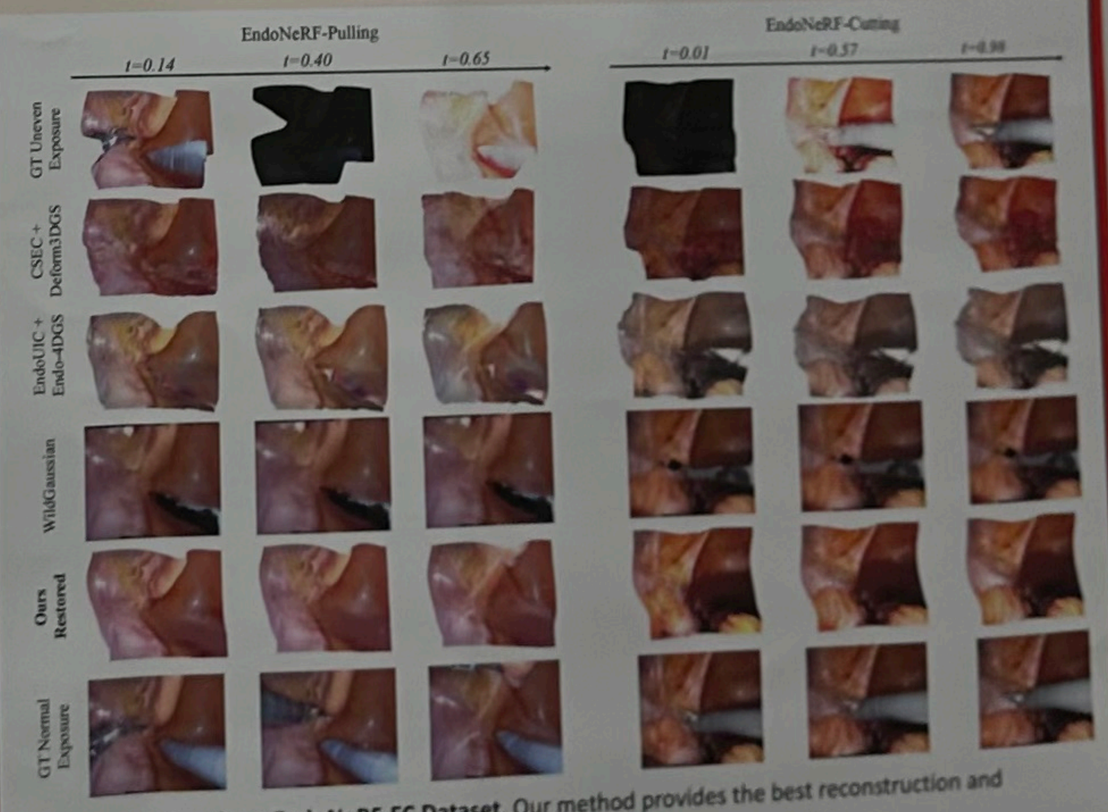
Method	EndoNeRF-EC Pullling PSNR↑	EndoNeRF-EC Pullling SSIM↑	EndoNeRF-EC Cutting PSNR↑	EndoNeRF-EC Cutting SSIM↑	StereoMIS P1_1 PSNR↑	StereoMIS P1_1 SSIM↑	StereoMIS P1_2 PSNR↑	StereoMIS P1_2 SSIM↑	C3VD Cecum_t2_b PSNR↑	C3VD Cecum_t2_b SSIM↑	C3VD Sigmoid_t2_a PSNR↑	C3VD Sigmoid_t2_a SSIM↑
Deform3DGS [25]	30.63	0.922	26.86	0.831	28.55	0.846	32.28	0.887	33.07	0.898	27.92	0.749
Endo-4DGS [11]	28.51	0.909	26.88	0.850	26.98	0.817	32.48	0.890	30.55	0.878	32.03	0.830
EndoGaussian [15]	12.93	0.327	12.49	0.289	27.61	0.841	32.20	0.896	5.10	0.001	5.99	0.001
Ours	39.95	0.966	39.64	0.968	28.73	0.853	32.70	0.899	33.55	0.904	33.13	0.838

Quantitative results on StereoMIS and C3VD datasets for uneven illumination scene reconstruction. Our method surpasses all state-of-the-art methods.

Illumination Embedding	Region-Aware Enhancement	Spatial-Aware Adjustment	Pulling PSNR ↑	Pulling SSIM ↑	Cutting PSNR ↑	Cutting SSIM ↑	Pulling-Correction PSNR ↑	Pulling-Correction SSIM ↑	Cutting-Correction PSNR ↑	Cutting-Correction SSIM ↑
✗	✗	✗	26.95	0.892	27.59	0.856	22.88	0.770	20.53	0.734
✗	✓	✗	10.40	0.535	14.64	0.624	12.66	0.579	13.96	0.712
✗	✗	✓	24.56	0.840	30.53	0.895	23.46	0.815	19.93	0.692
✓	✓	✗	39.64	0.965	37.33	0.957	34.79	0.945	32.66	0.933
✓	✗	✓	34.87	0.952	34.52	0.939	28.44	0.910	25.09	0.865
✗	✓	✓	14.36	0.627	31.06	0.925	21.94	0.804	24.26	0.740
✓	✓	✓	39.95	0.966	39.64	0.968	34.94	0.946	34.06	0.950

Ablation experiments on EndoNeRF-EC dataset

Reconstruction Results



Qualitative Result on EndoNeRF-EC Dataset. Our method provides the best reconstruction and illumination correction results for challenging illumination.

Conclusions

- We propose **Endo-4DGX**,an illumination-aware Gaussian Splatting framework for endoscopic 3D **reconstruction** and **real-time rendering** under **challenging lighting conditions**.
- The framework include illumination correction of dynamic lighting scenarios by unifying **region-aware** illumination enhancement and **spatial-aware** illumination adjustment, promoting the **precision** and **safety** of surgical procedures.

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