NUS National University of Singapore

Robust e-NeRF: NeRF from Sparse & Noisy Events under Non-Uniform Motion

Weng Fei Low   Gim Hee Lee

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Motivation

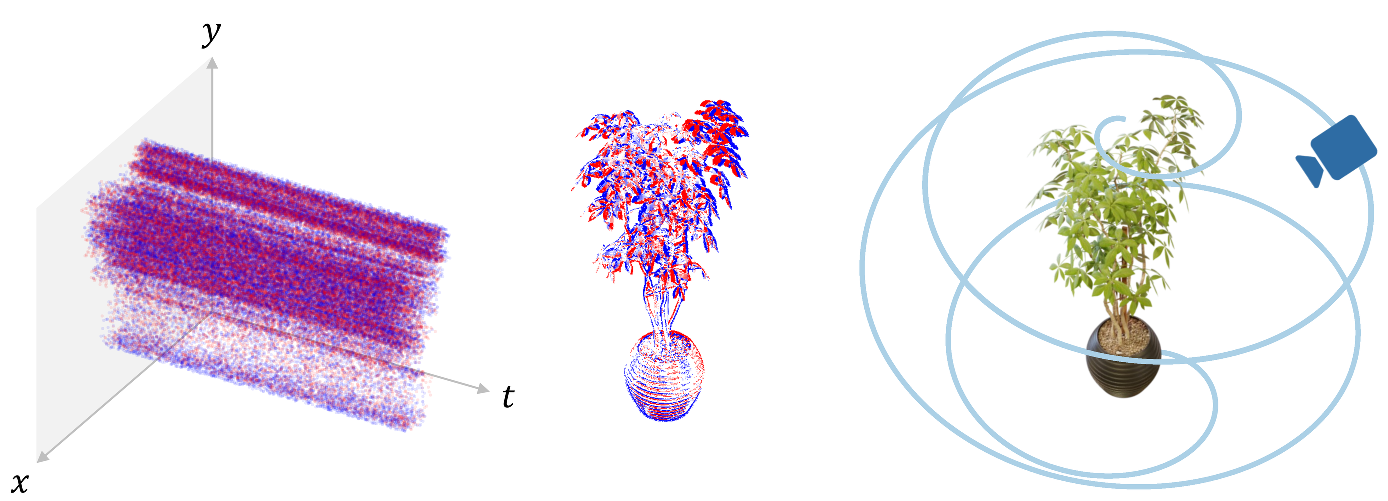
1. Event cameras offer many advantages over standard cameras due to their distinctive principle of operation:
   - ❖ Low power
   - ❖ High temporal resolution
   - ❖ Low latency
   - ❖ High dynamic range
2. Many downstream visual applications hinges on an efficient & effective scene representation, where Neural Radiance Field (NeRF) is seen as the leading candidate

Research Question

How to robustly reconstruct a NeRF from a moving event camera under general real-world conditions?

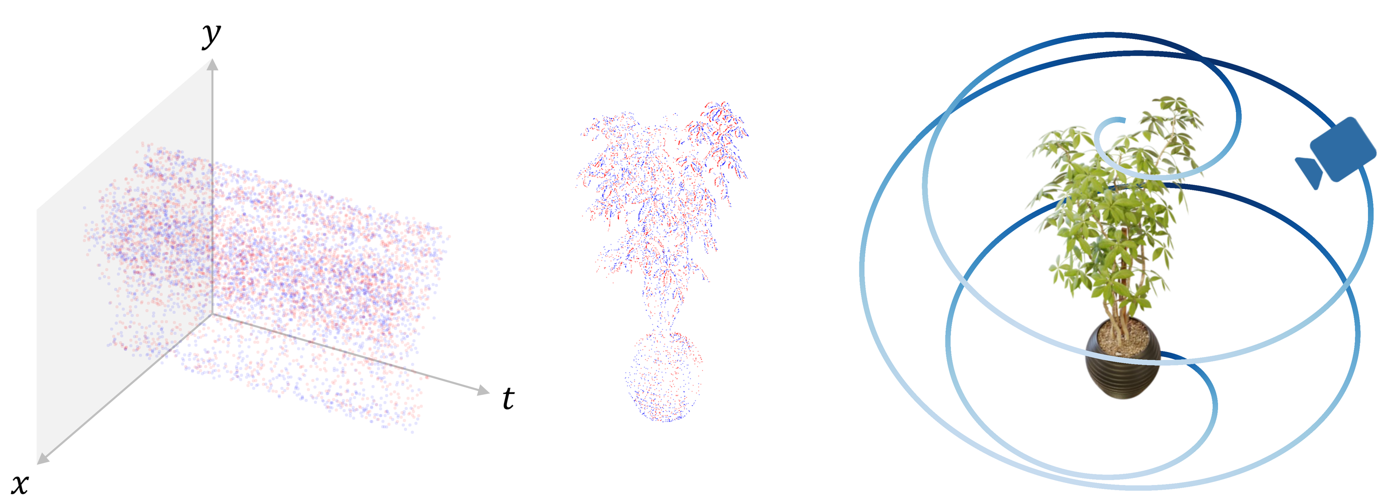
Limitations of Prior Work

1. Depends on a temporally dense & low-noise event stream
2. Does not directly & effectively generalize to arbitrary contrast threshold values & camera speed profiles



(a) Dense and low-noise events (left), and their projection onto the xy-image plane (right).

(b) Uniform-speed camera motion.

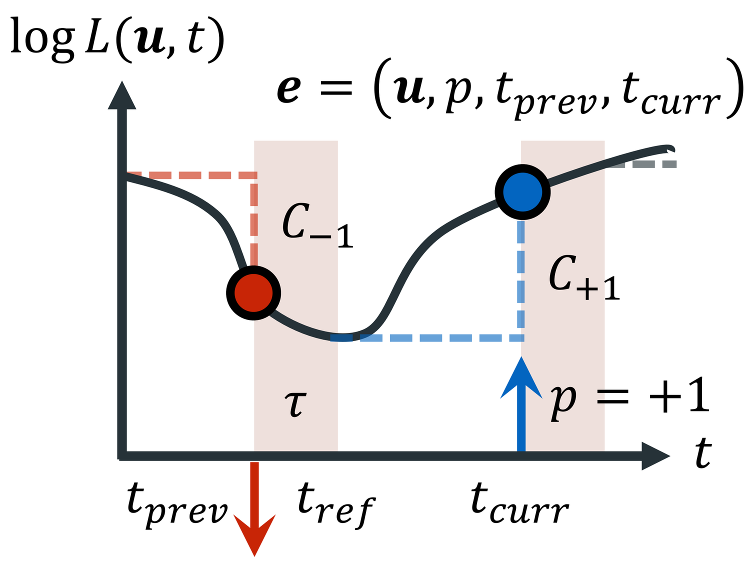


(c) Sparse and noisy events (left), and their projection onto the xy-image plane (right).

(d) Non-uniform-speed camera motion.

Proposed Method: Robust e-NeRF

Event Generation Model

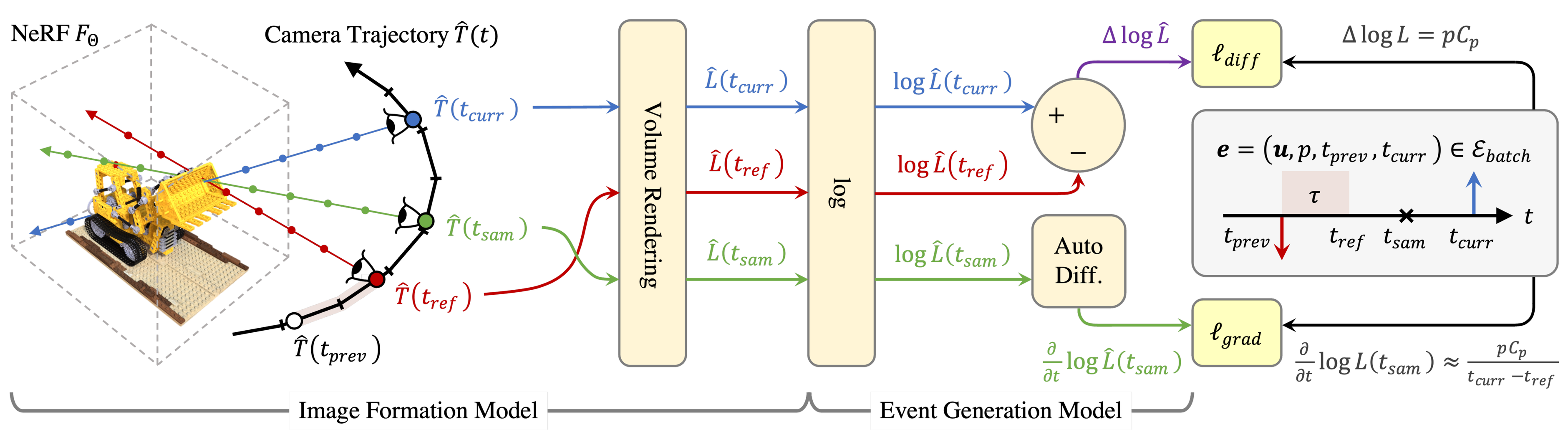


- ❖ $\boldsymbol{e}$ is an Event generated by pixel $\boldsymbol{u}$, with polarity $p \in \{-1, +1\}$, at timestamp t_{curr}
- ❖ Measured log-radiance difference:
  $$\Delta \log L := \log L(\boldsymbol{u}, t_{curr}) - \log L(\boldsymbol{u}, t_{ref}) = pC_p$$
- ❖ Reference log-radiance timestamp:
  $$t_{ref} = t_{prev} + \tau$$
  t_{prev} is the previous event timestamp at $\boldsymbol{u}$

✓ Accounts for:

1. **Intrinsic parameters:** Time-independent, asymmetric Contrast Threshold C_p
   Refractory Period τ (*i.e.* pixel dead-time → sparsity)
2. **Non-idealities:** Pixel-to-pixel contrast threshold variation σ_{C_p} (*i.e.* noise)

Training Pipeline



Threshold-Normalized Difference Loss:
$$\ell_{diff}(\boldsymbol{e}) = \left(\frac{\Delta \log \hat{L} - pC_p}{\bar{C}}\right)^2, \quad \bar{C} = \tfrac{1}{2}(C_{-1} + C_{+1})$$

Target-Normalized Gradient Loss:
$$\ell_{grad}(\boldsymbol{e}) = \mathrm{APE}\left(\frac{\partial}{\partial t} \log \hat{L}(\boldsymbol{u}, t_{sam}), \frac{pC_p}{t_{curr} - t_{ref}}\right)$$
where $\mathrm{APE}(\hat{y}, y) = \left|\frac{\hat{y} - y}{y}\right|$

✓ Effectively generalizes to arbitrary speed profiles & intrinsic parameter values, without such prior knowledge

✓ Does not involve accumulation of successive events, thereby reconstructions are detailed and robust to event sparsity & noise

Gamma Correction of Synthesized Views

***Affine*-corrected *log*-radiance prediction:** $\log \hat{\boldsymbol{L}}_{corr} = \boldsymbol{a} \odot \log \hat{\boldsymbol{L}} + \boldsymbol{b}$

***Gamma*-corrected *linear*-radiance prediction:** $\hat{\boldsymbol{L}}_{corr} = (\exp \boldsymbol{b})\, \hat{\boldsymbol{L}}^{\circ \boldsymbol{a}}$

Novel View Synthesis Results

Method	$v = 1\times$			$v_b = 8\times$			$v = \frac{1}{8}\times$			$v = 8\times$		
	PSNR ↑	SSIM ↑	LPIPS ↓	PSNR ↑	SSIM ↑	LPIPS ↓	PSNR ↑	SSIM ↑	LPIPS ↓	PSNR ↑	SSIM ↑	LPIPS ↓
E2VID + NeRF	18.92	0.832	0.316	18.92	0.832	0.316	18.92	0.832	0.316	18.92	0.832	0.316
Ev-NeRF	27.72	0.935	0.087	26.25	0.926	0.102	19.79	0.792	0.326	20.83	0.862	0.198
Robust *e*-NeRF	**28.19**	**0.945**	**0.057**	**28.19**	**0.945**	**0.057**	**28.19**	**0.945**	**0.057**	**28.19**	**0.945**	**0.057**

Method	Opt. C_p	$\sigma_{C_p} = 0.00$			$\sigma_{C_p} = 0.03$			$\sigma_{C_p} = 0.06$		
		PSNR ↑	SSIM ↑	LPIPS ↓	PSNR ↑	SSIM ↑	LPIPS ↓	PSNR ↑	SSIM ↑	LPIPS ↓
E2VID + NeRF	–	18.92	0.832	0.316	18.68	0.827	0.330	18.03	0.808	0.363
Ev-NeRF	×	27.72	0.935	0.087	24.42	0.895	0.155	8.07	0.841	0.260
	✓	27.43	0.911	0.123	23.66	0.826	0.261	15.43	0.708	0.441
Robust *e*-NeRF	×	**28.19**	**0.945**	**0.057**	**28.14**	**0.946**	**0.058**	**28.23**	**0.947**	**0.057**
	✓	**28.17**	**0.946**	**0.051**	**27.91**	**0.946**	**0.054**	**28.19**	**0.948**	**0.049**

Method	Opt. C_p	Opt. τ	$\tau = 0ms$			$\tau = 8ms$			$\tau = 25ms$		
			PSNR ↑	SSIM ↑	LPIPS ↓	PSNR ↑	SSIM ↑	LPIPS ↓	PSNR ↑	SSIM ↑	LPIPS ↓
E2VID + NeRF	–	–	18.92	0.832	0.316	14.87	0.797	0.427	14.15	0.791	0.467
Ev-NeRF	×	–	27.72	0.935	0.087	13.17	0.707	0.559	12.75	0.759	0.528
	✓	–	27.43	0.911	0.123	13.56	0.716	0.528	13.75	0.717	0.569
Robust *e*-NeRF	×	×	**28.19**	**0.945**	**0.057**	**26.30**	**0.934**	**0.066**	**25.51**	**0.929**	**0.072**
	×	✓	**28.18**	**0.945**	**0.052**	**23.43**	**0.910**	**0.090**	**22.48**	**0.895**	**0.105**

Method	Opt. C_p	Opt. τ	$v_b = 1\times, \sigma_{C_p} = 0.00, \tau = 0ms$			$v_b = 4\times, \sigma_{C_p} = 0.03, \tau = 8ms$			$v_b = 8\times, \sigma_{C_p} = 0.06, \tau = 25ms$		
			PSNR ↑	SSIM ↑	LPIPS ↓	PSNR ↑	SSIM ↑	LPIPS ↓	PSNR ↑	SSIM ↑	LPIPS ↓
E2VID + NeRF	–	–	18.92	0.832	0.316	14.98	0.796	0.433	14.07	0.801	0.448
Ev-NeRF	×	–	27.72	0.935	0.087	12.33	0.742	0.521	12.05	0.807	0.425
	✓	–	27.43	0.911	0.123	13.06	0.732	0.539	12.27	0.772	0.539
Robust *e*-NeRF	×	×	**28.19**	**0.945**	**0.057**	**24.10**	**0.913**	**0.086**	**23.51**	**0.900**	**0.110**
	✓	✓	**28.19**	**0.946**	**0.051**	**20.42**	**0.875**	**0.126**	**18.83**	**0.836**	**0.197**