Differentiable Surrogate Model for Photon Propagation in Liquid Argon Time Projection Chamber

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Conventional Photon Library

- Many accelerator neutrino experiments use liquid argon time projection chamber (LArTPC) for the high light yield from the LAr scintillation.
- Photon propagation in LArTPCs is commonly simulated using Geant4.
- Not realistic to run for each event in the light simulation and reconstruction.
- Build a photon library: the percentage of photons (visibility) can be read out at each light channel given locations of origin in the LArTPC.
- Conventional photon library: a sampled, discrete look-up table (LUT).
- Difficult to be scalable for large LArTPCs.

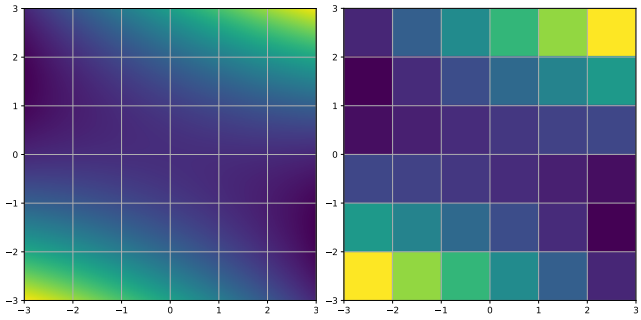
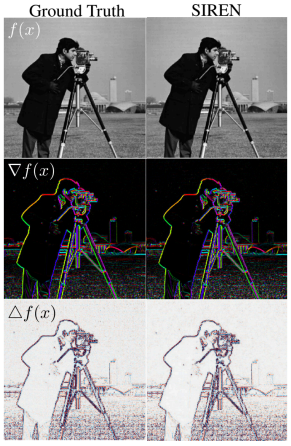


Figure 1: A toy example of a true distribution (left) and a sampled distribution with Poisson fluctuation

SIREN



- SIREN: Sinusoidal Representation Network.
- A multilayer perceptron network architecture with periodic activations of sine functions.
- A continuous, differentiable representation.
- Able to be adopted for making alternative photon libraries, first demonstrated in Ref [2].

Figure 2: Reproducibility and differentiability of SIREN [1]

Application of SIREN

- Small footprint, in-situ modeling and differentiable nature of SIREN will benefit the light simulation, reconstruction and detector systematic evaluation in neutrino experiments using LArTPCs.

Reference

1. *Implicit Neural Representations with Periodic Activation Functions* arXiv:2006.09661
2. *Implicit Neural Representation as a Differentiable Surrogate for Photon Propagation in a Monolithic Neutrino Detector* arXiv: 2211.01505

SIREN trained with LUT

- Train SIREN with the photon library LUT and compare the voxel visibility with weighted L2 loss
- For a 470 t LArTPC, a well performed SIREN model contains ~1.4 million parameters, while the LUT with 5 x 5 x 5 cm^3 voxel size has ~404 million parameters per light channel (~300 times in size). The example LArTPC has 360 light readout channels.
- LUT is sensitive to the sampling size (Poisson fluctuations).
- SIREN can represent the underlying distribution better than LUT.

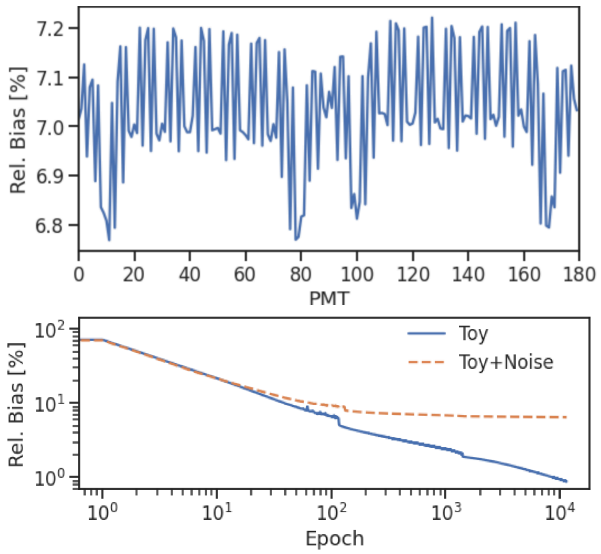


Figure 3: Relative bias to LUT of a SIREN trained with the same LUT (top). The bias is mainly due to the limited sampling size (10^6 photons per voxel). The bias labeled "Toy" is SIREN against an analytical distribution, and "Toy + Noise" is SIREN against the analytical model with Poisson flections for 10^6. [2]

SIREN trained with tracks

- Train SIREN with tracks and compare the predicted and measured number of photons in the light readout channels with negative log likelihood loss with Poisson distribution of target.
- No need of Geant4 simulation to produce the photon library.
- An in-situ photon library, not susceptible to potential mis-modeling in the light simulation (Rayleigh scattering, efficiency of the wavelength shifter etc.).
- Inclusive improvement of the modeling.
- No binning in the SIREN photon library.
- Can be trained with a small track sample (for a 150 kg LArTPC, the trained SIREN performance saturated with 50 k tracks).

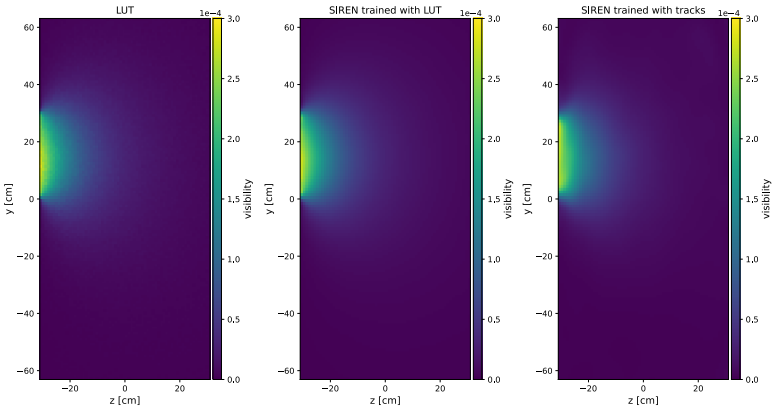


Figure 4: A slice along the drift axis in an example LArTPC showing the LUT (left), SIREN trained with LUT (middle) and SIREN trained with tracks (right).

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