Improving SPAD Imaging through Optical Filtering Techniques

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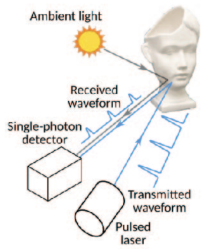
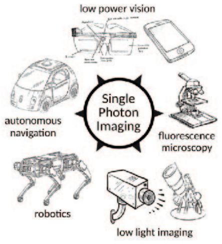
Background

SPAD Capturing Process and Applications

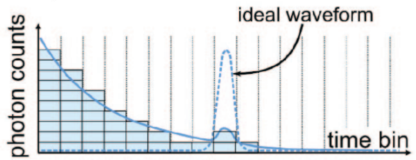


[Gupta et al. 2019]



[Gupta et al. 2019]

Pile-up Problem

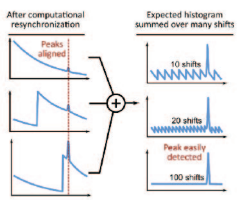


[Gupta et al. 2019]

- Single photon capture capabilties allow for high temporal resolution, but causes 'pile-up' effect
- Generalized Coates' Estimate (MLE) can be used to compensate for pile-up
- Ambient lighting causes loss in information for later time bins

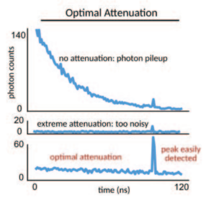
Existing Work

Asynchronous Capture



[Gupta et al. 2019]

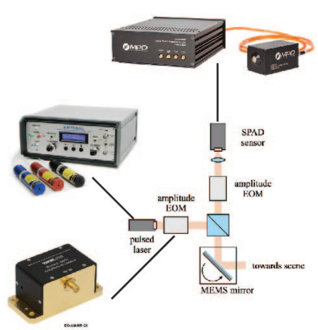
Optimal Attenuation



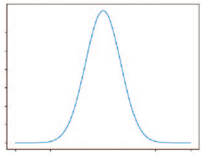
[Gupta et al. 2019]

Coded SPAD Exposure

Hardware & Setup

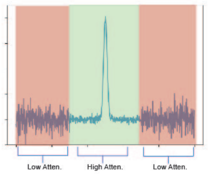


Gaussian Filter



Performance

With the appropriate priors on depth, coded exposure can achieve better results than conventional techniques such as optimal scalar attenuation. Coded SPAD exposures allow for reduction of pile-up (low attenuation value towards the beginning of the transient) while maintaining a high SBR (high attenuation value near the signal)



Effect on Variance

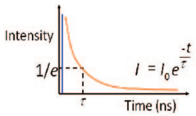
Scaling down the transient has the effect of increasing the variance of the estimator at those bins. Variable attenuation as opposed to constant scalar attenuation allows us to increase accuracy of estimate at certain bins at the expense of the rest of the time bins. This effect is illustrated above in the context of depth-sensing with SPADS

Similarity to Asynchronous Capture

While coded exposure can achieve better results compared to scalar attenuation, this requires an appropriate prior on depth. Improvements also pale in comparison to performance obtained through asynchronous capture. In a sense, asynchronous capture itself is a form of coded exposure through the use of box filters by controlling SPAD active time and gate position. While the above filters can be applied in the context of box filters, the difference in performance is minimal as the box filter serves as a close estimate of filters such as the gaussian

Pre-filtering for Time Domain - Fluorescence Lifetime Imaging

Time Domain FLIM

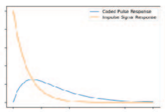


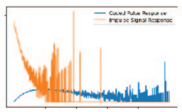
TD-FLIM, leverages transient imaging to recover flourescence lifetime of samples. Different to depth-sensing applications for SPADs, the ideal transient in FLIM imaging takes on the shape of exponential decay. Conventional techniques involve firing an impulse signal and recovering the transient image, while the lifetime is recovered by fitting an exponential ontop of the recovered tran-

Conventional FLIM with CWToF | RGB | FLIM

[Lee et al. 2019]

Ideal Transients | Recovered Transients

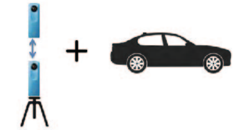




Coded Signal (Pre-filtering)

Ideal transient response from an impulse signal takes the form of an exponential distribution, but due to the nature of SPADs, the high signal value at start of the transient causes severe pile-up, preventing the use of high power sources. A coded signal, instead of an impulse signal of the same power could yield transients that suffer less from the effects of pile-up. Through a coded pulse, we obtain a convolved response curve which lessens the effect of pile-up.

Adaptive SPAD Gating



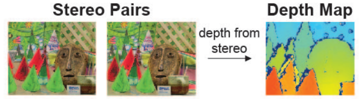
[Appiah et al. 2015]

[Bauer et al. 2019]

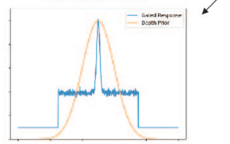
Motivation

Most modern depth sensing pipelines have multiple sensors that can recover depth. One example would be on autonomous vehicles, where depth from stereo and SPAD-based LiDAR systems are both present. We propose an adaptive gating technique that leverages depth priors provided by other sensors to improve SPAD depth-sensing performance

Stereo Pairs | Depth Map



Shifted Gate

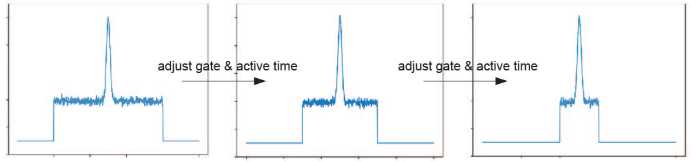


Gating with Depth Prior

Given a prior on depth, obtained from other depth sensors (i.e. stereo), we can leverage this approximation of depth to adjust the gate position and active time of the SPAD, lessening the effects of pile-up, increasing the number of effective laser cycles and increasing light efficiency. Leveraging this depth prior can provide up to 7x better performance.

Batch-Based Adaptive Gating

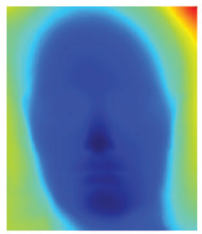
While using a suitable depth prior can give better results, a good depth prior is not always available. Instead, we can simply use previous laser pulses to establish a depth prior, allowing us to adjust the gate position and active time every fixed amount of laser pulses, or even in the extreme case, achieving per-pulse adaptation.



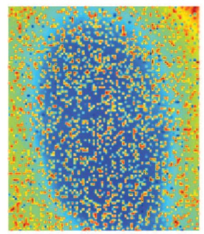
- Gate position and active time is adjusted per fixed number of pulses. New values are based on estimate from previous pulses

Simulated Renders:

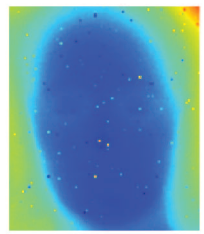
Ground Truth



Conventional



Depth-Prior (Proposed)



References

Appiah et al., "Obstacle detection using stereo vision for self-driving cars" 2015
Bauer et al., "UASOL: A Large-scale High-resolution Outdoor Stereo Dataset" Sci Data 6, 162 (2019)
Gupta et al., "Asynchronous Single-Photon 3D Imaging" ICCV 2019.
Gupta et al., "Photon-Flooded Single-Photon 3D Cameras" CVPR 2019.
Lee et al., "Coding Scheme Optimization for Fast Fluorescence Lifetime Imaging" ACM TOG 2019