Imaging Through Volumetric Scattering with a Single Photon Sensitive Camera

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Abstract: Imaging through highly scattering media holds many opportunities in underwater and biomedical imaging. Here we leverage a single photon avalanche diode (SPAD) camera, and experimentally demonstrate an imaging pipeline to see through turbid water in optical reflection mode.

OCIS codes: (110.1758) Computational imaging, (110.0113) Imaging through turbid media, (110.3200) Inverse scattering.

1. Introduction

Imaging through highly scattering materials has many applications in biomedical imaging, underwater exploration, and improved transportation systems in challenging weather. The challenge is even bigger in the case of imaging in optical reflection mode due to the significant backscattering and low signal-to-noise ratio (SNR). Previous works that leverage time-resolved sensing for wide-field imaging through volumetric scattering are usually limited to transmission mode [1–3]. Here we demonstrate an optimization framework for the recovery of occluded objects in turbid water with $\times 160$ mean free path compared to clear water. The method leverages a time-resolved single photon avalanche diode (SPAD) camera that provides superior imaging capabilities due to its performance in low light conditions.

2. Experimental Setup

The imaging system is presented in Fig. 1a. A pulsed source (NKT photonics SuperK with a repetition rate of 80 MHz, pulse duration of 5 ps, spectrally filtered to 580 ± 10 nm) is illuminating a water tank (13 cm deep). The detector is a SPAD camera (Photon Force P32) with 32×32 pixels and a nominal time resolution of 56 ps. The water tank is filled with water and Maalox with varying concentrations. The targets are placed at the far end of the tank (inside the turbid water). The opposite side of the tank includes an optical power meter to measure the water turbidity, measured by units of mean free path: 1μ for the case of clear water (no Maalox), and larger values for higher turbidity. We consider 7 different Maalox concentrations.

The SPAD camera measures single photon events. Each pulse sent to the scene results in a 32×32 frame, in which the value of each pixel is the time of arrival of the first detected photon associated with this pulse. Such measurement procedure is shot-noise limited and as a result provides better SNR at low light conditions. Each frame is gathered, and multiple photon counts per pixel can be processed to produce a time-of-arrival histogram. The reconstruction procedure is based on background subtraction followed by a total-variation minimization algorithm.

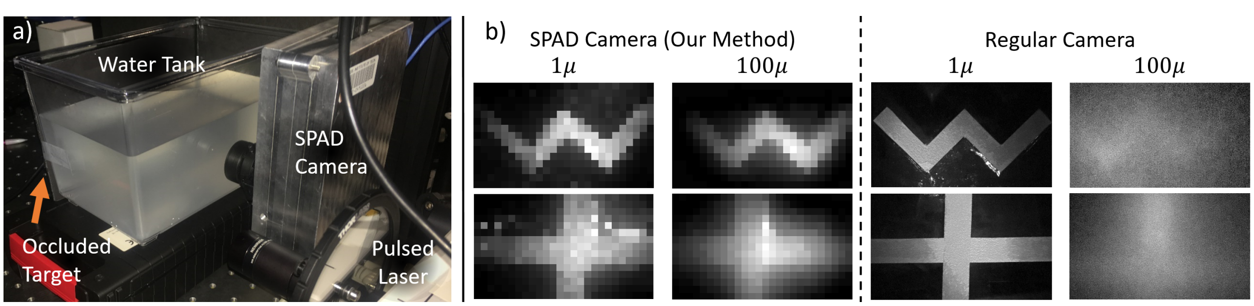

Fig. 1. a) Experimental setup. The target is occluded by the turbid water. b) Comparison between the suggested method and a regular camera. Our method produces similar reconstruction quality even when the mean free path is $\times 100$ shorter. The two rows show a 'W' shape and cross targets.

3. Results

Figure 1b demonstrates the advantages of single photon measurements compared to a regular camera. The obvious disadvantage of the SPAD camera is the low resolution. That is apparent when comparing the reconstruction in clear water (1μ). However, after adding Maalox such that the mean free path is $100\times$ shorter (100μ), our reconstruction is very similar to the reconstruction from clear water, while the recovery from the regular camera suffers from a blur and very poor SNR.

Figure 2 shows the recovery of three different targets at seven different Maalox concentrations. For each case we compare the recovery using raw photon counts to our optimization procedure and plot cross sections along the reconstructions. All cases show that our optimization enhances the reconstructed contrast and overall quality. For example, the recovery of the point target at 100μ demonstrates $2\times$ better contrast, 12.3 dB better PSNR, and $2.9\times$ better SSIM.

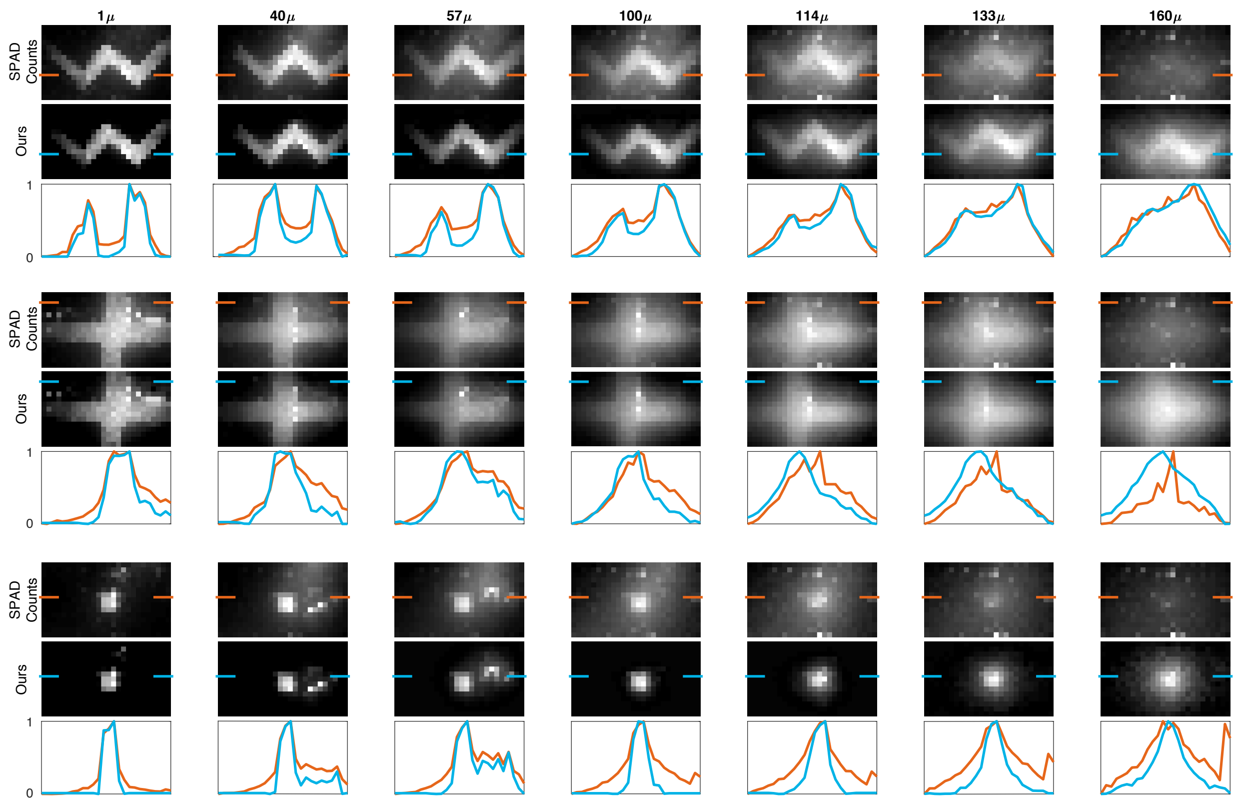

Fig. 2. Recovery using the suggested technique of three different targets ('W' shape, a cross, and a point). Each target is evaluated under seven different concentrations (increasing from left to right, leftmost is clear water). For each case we plot the raw SPAD counts (top), our reconstruction (middle), and horizontal cross sections demonstrating the improved contrast of the suggest approach.

In conclusion, we showed a technique for imaging through highly scattering media with a SPAD camera in optical reflection mode. We demonstrated the advantages of this method in recovery of multiple targets at different scattering levels. Furthermore, we demonstrated that SPAD measurements are a good source for imaging through volumetric scattering due to their noise performance at low light.

References

1. G Satat, B Heshmat, D Raviv, and R Raskar. All photons imaging through volumetric scattering. *Scientific reports*, 6, 2016.
2. A Boccolini, F Tonolini, J Leach, R Henderson, and D Faccio. Imaging inside highly diffusive media with a space and time-resolving single-photon sensor. In *OSA Imaging Systems and Applications*, ITu3E–2, 2017.
3. L Wang, PP Ho, C Liu, G Zhang, and RR Alfano. Ballistic 2-d imaging through scattering walls using an ultrafast optical kerr gate. *Science*, 253, 1991.