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# Rapid single-photon 3D imaging in highly scattering underwater environments

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## ABSTRACT

We demonstrated a transceiver system for underwater three-dimensional imaging, based on a 64 × 32 macro-pixel direct time-of-flight (dToF) SPAD detector array fabricated using complementary metal-oxide-semiconductor (CMOS) technology. The sensor featured integrated multi-event time-to-digital converters (METDC) per macro-pixel, and operated in a time-gated mode which allowed the improved rejection of the backscattering from the signal return. The performance of the system was assessed in a controlled underwater environment, utilizing a moving target placed in a water tank at a stand-off distance of 1.45 m in water. The system demonstrated rapid 3D imaging by using short acquisition times of 1 ms, which corresponds to a frame rate of 1000 fps. Depth and intensity profiles were obtained at attenuation levels equivalent up to 5.5 attenuation lengths between the transceiver and the target, and using average optical power of up to 32 mW.

**Keywords:** Underwater imaging, scattering, single-photon, CMOS SPAD, rapid imaging

## 1. INTRODUCTION

Underwater environments pose significant challenges for sensing and imaging technologies due to light absorption and high levels of optical scattering in turbid water. In recent years, single-photon techniques have emerged as a powerful tool for underwater imaging in highly scattering environments [1-4], providing high sensitivity and high temporal resolution in the picosecond regime. Single-photon detector arrays of both linear and rectangular geometries [5, 6] have been investigated with the aim of obtaining useful depth information using the time-correlated single-photon counting (TCSPC) technique. The use of detector arrays can significantly reduce the data acquisition time when imaging in highly attenuating media. When imaging moving targets, a SPAD detector array in the rectangular geometry is the preferred choice, as it provides the timing information for each pixel without the need for optical scanning. SPAD detector arrays fabricated in complementary metal-oxide semiconductor (CMOS) technology give the advantage of a high degree of parallelism [7] and per-pixel integration of the timing electronics [8].

Several SPAD architectures were developed over the years [9-11], however timing electronics typically included a first-photon time-to-digital converter (TDC), which timestamps only the first detected event per exposure time [12]. This can limit the frame rate of the sensors, as typically greater than several milliseconds (often in the range of 50 ms [6, 13]) are needed to build the histogram for theToF analysis.

In this work, we present a single-photon 3D imaging system based on a 64 × 32 macro-pixel dToF CMOS SPAD array [14]. Each macro-pixel of the array has 4 × 4 SPADs and was embedded with multi-event time-to-digital converters (METDC). This allowed the sensor to detect multiple photon events per laser pulse and to integrate several detection events within a single exposure time, significantly increasing the photon detection rate for a given illumination level. Moreover, the sensor operated in a time-gated mode enabling the detection of the events within a short temporal window (3.6 ns) centered on the expected return from the target and rejecting most the backscattering events which typically reduce the achievable maximum count rate from the target. We investigated the potential of the system for rapid 3D imaging in underwater environments. We demonstrated depth and intensity profiles by using short acquisition times of 1 ms per frame,

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corresponding to a frame rate of 1000 fps, in several scattering underwater environments with attenuation of light in water equivalent to up to 5.5 attenuation lengths. The experiments were performed in laboratory conditions, using a target placed at a stand-off distance of 1.45 m in water. The picosecond laser source had a central wavelength of 532 nm and operated at a repetition rate of 1.9 MHz, with average optical power of up to 32 mW, which was varied depending on the level of attenuation of light in water.

In this paper, Section 2 will introduce the characteristics of the sensor and the overall system setup. Section 3 will present the experiments and results. Section 4 will give discussion and conclusions.

## 2. SENSOR AND OPTICAL SYSTEM

The sensor utilized in the underwater 3D imaging system was a 64 × 32 macro-pixel CMOS SPAD array, which was fabricated using a standard 40 nm process [14]. Each macro-pixel in the array included a 4 × 4 SPAD configuration, resulting in an overall 256 × 128 SPAD detector array with physical dimensions 7.8 mm × 2.3 mm [14]. Each macro-pixel was integrated with METDC, which enabled the recording and timestamping of multiple photon detection events per laser pulse, unlike conventional TDC that typically captures only the first or a limited number of events as in [12]. This capability is critical for effective photon capturing, especially in highly scattering environments where the probability of detecting a scattering event is significantly higher than the probability of detecting the photon return from the target. If a first-photon TDC configuration is used, it will be considerably more difficult to detect the signal peak within the very high scattering background levels.

The sensor was operated in a time-gated mode, where the single frame output of the sensor was one time gate containing eight bins with a user-defined width. The time-gate could be sequentially shifted over 128 fixed positions, resulting in a combined histogram of 1024 timing bins. Furthermore, the bin-width of the sensor in each time gate was controlled by a bin-width control voltage. Figure 1 shows how the bin-width varies for different values of the bin-width control voltage; the bin-width gradually decreases as the bin-width control voltage increases up to the maximum value of 1000 mV. The adjustable bin-width range is from approximately 0.26 ns to 1.16 ns. In summary, the sensor included a total of 128 time gates, resulting in 1024 time bins and providing a maximum detection range of 510 to 518 nanoseconds. However, in this work only a maximum of 6 time-gates were recorded due to the short stand-off distance of the target.

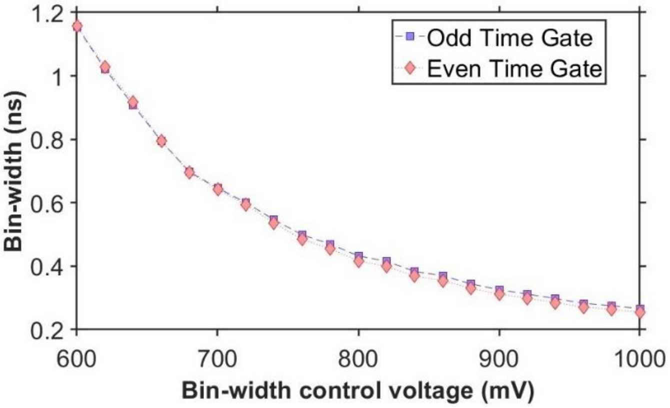

Figure 1. Values of bin-width (ns) versus bin-width control voltage (mV) in odd and even time gates.

The schematic of the experimental setup is shown in Figure 2. The laser source was a master oscillator fiber amplifier pulsed laser (VisUV, PicoQuant, Germany) with a central wavelength of 532 nm. The repetition rate of the laser was 1.9MHz, which was triggered by an FPGA (XEM7310, Opal Kelly, USA). The FPGA also controlled the CMOS SPAD sensor and synchronized the laser and return pulses in the TCSPC configuration. The laser output was connected to a fiber collimation package, directed through a diffuser and a 50 mm focal length zoom lens. The target was placed at a distance of approximately 1.45 m in water, inside a water tank measuring 1.75m × 0.25m × 0.25m. The received light was captured by an objective lens (Canon EF 50mm) with a 50 mm focal length. The transmittance of light in water was measured at the operational wavelength with the same method as indicated in [6, 13]. By measuring the optical power atpositions A and B indicated in Figure 2, the number of attenuation lengths between the system and the target (one way only) was estimated by:

$$\mathrm{AL} = -\frac{1}{d}\ln\left(\frac{P_B}{P_A}\right) * x \tag{1}$$

Where $d$ is the distance between A and B, and $x$ is the distance of the target in water.

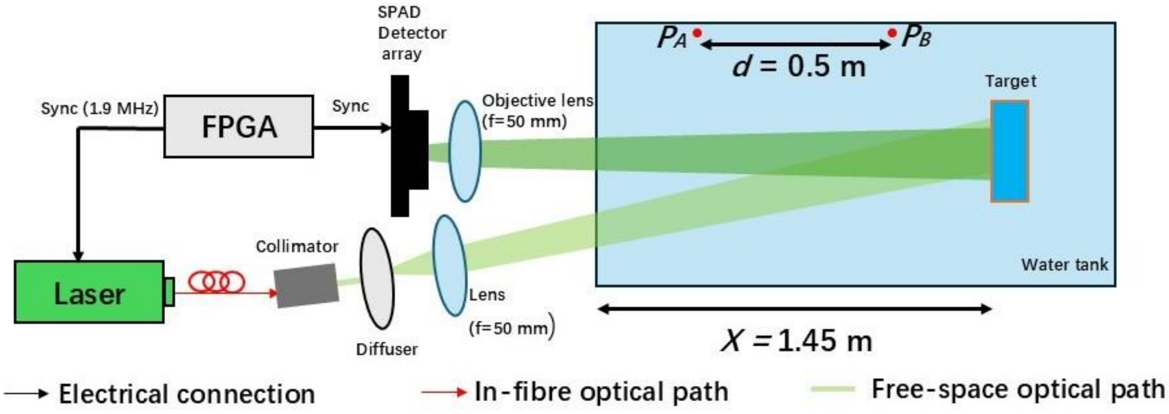

Figure 2. Schematic of the experimental setup based on the 64 × 32 macro-pixel CMOS SPAD detector array.

## 3. EXPERIMENT AND RESULTS

The target used in the experiment was a submarine model which was spray-painted with a white primer, and it is shown in Figure 3. The target was placed at a distance of 1.45 m in water and moved manually at a non-uniform speed within the field-of-view.

Figure 3. Photograph of the submarine model target used in the underwater 3D imaging experiments.

Figure 4 displays the combined histograms of an individual target pixel (pixel 32-16) obtained by shifting the time-gate by 6 consecutive positions in (a) clear water and (b) AL = 5.5. The exposure time was 1 ms per time gate, and the average optical power was 1.7 mW and 32 mW, respectively. The bin-width control voltage of the sensor was set to 790 mV, equivalent to a bin-width of 0.45 ns.

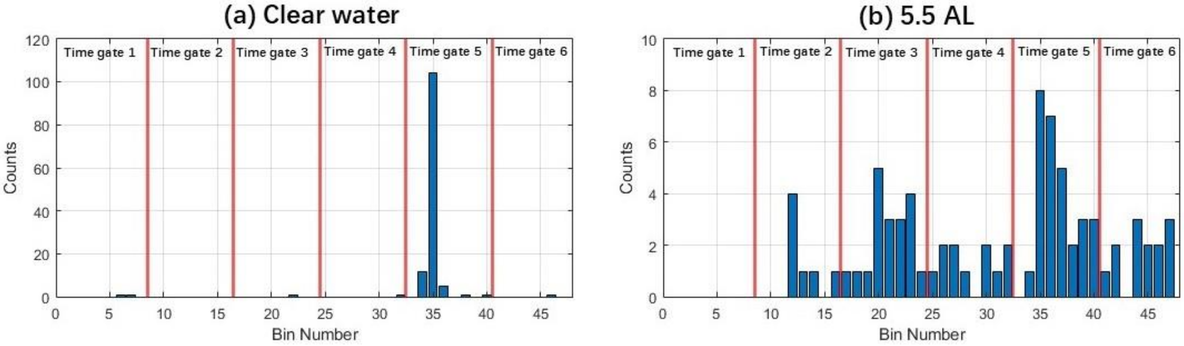

Figure 4. Histograms with 48 bins measured from an individual pixel corresponding to the center of the submarine model, with an exposure time of 1 ms per time gate in (a) clear water and (b) attenuation length of 5.5 AL. The average optical power was adjusted based on the attenuation of light in water and it was (a) 1.7 mW and (b) 32 mW.

A sharply defined single return peak was typically expected from histogram in clear water as shown in Figure 4(a). In terms of the histogram obtained in highly scattering water conditions, the return signal decreased dramatically as shown in Figure 4(b). Besides, increased counts in earlier time gates and a more spread-out distribution of counts across multiple bins of target return indicate the backward and forward scattering effects in the turbid water condition, respectively. By capturing only the output from a single time gate, time gate 5 in this case, we maximized the data acquisition efficiency of the system while effectively eliminating the accumulation of redundant photon data caused by backscattering in the previous time gates. During the experiments, we moved the submarine model constantly and captured the output data from time gate 5 with a 1 ms exposure time per frame. The 8-bit output data is then subjected to standard Gaussian fitting to estimate the ToF information. This temporal data was subsequently used to determine the distance information.

The depth map results are shown in Figure 5, presenting three individual frames (frame number 1, 1000, and 3000) across four different attenuation lengths up to 5.5 AL. In low scattering conditions (AL = 1.8), the resolved depth maps captured the submarine model with sufficient detail to resolve the outline of the target. As the turbidity of the water gradually increased to AL = 3.9, the target area was less defined but the shape and structure of the submarine remain distinguishable. When AL ≥ 5.5, the depth maps of the target was hardly distinguished due to scattering noise.

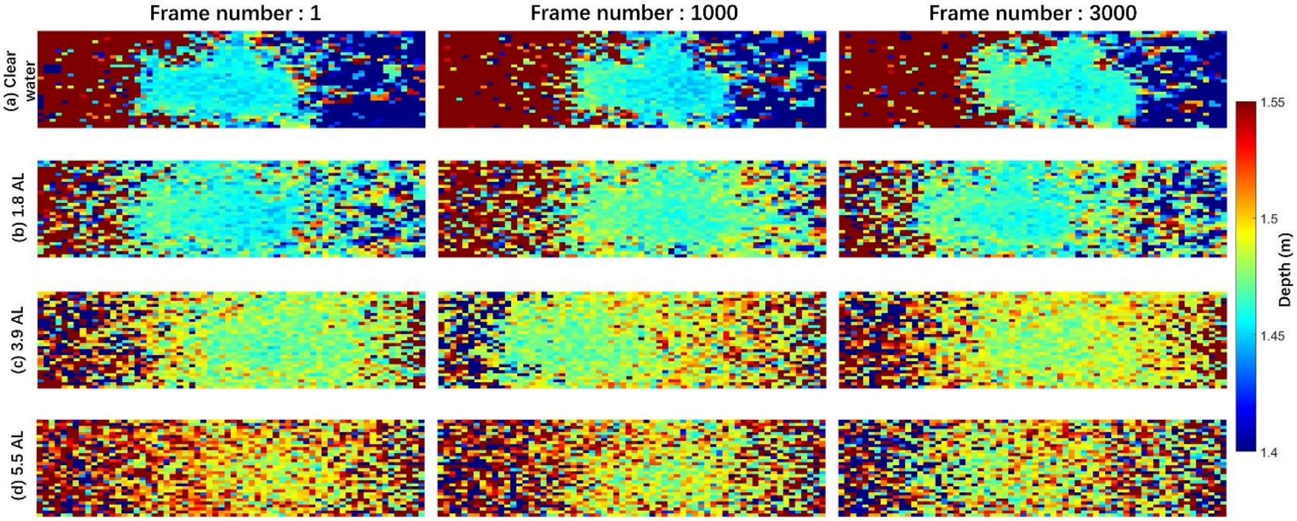

Figure 5. Depth maps from three individual frames (add frame numbers) in a range of underwater environments: (a) in clear water, (b) AL = 1.8, (c) AL = 3.9, and (d) AL = 5.5.

## 4. CONCLUSIONS AND FUTURE WORK

In this paper, we demonstrated an underwater 3D imaging system using a 64 × 32 macro-pixel CMOS SPAD detector array. The detector array was embedded with the METDC, allowing to capture multiple photon events during per laser cycle. This resulted in an improvement in the photon detection rate, enabling significantly more rapid single-photon 3D imaging in challenging underwater environments. We used short exposure time of 1 ms per frame, successfully achieving an imaging rate at 1000 fps with a maximum average laser power of 32 mW in highly scattering environments up to 5.5 AL. The results show the system has the potential to retrieve the depth information and clearly distinguish the contour of the targets up to 4 AL, while target detection was maintained up to 5.5 AL. Notably, the system has marked a significant advancement in imaging speed with respect to previous work, reaching 1000 fps up to an attenuation length of 5.5 AL. The resolvable attenuation length limit may further improve with increasing in exposure time or enhancements in the processing algorithms. Future research will investigate the relationship between exposure time and the attenuation length limit at which this system can effectively resolve 3D target imaging. Additionally, we will further explore the post-processing models to analyze the histogram data in highly scattering environments.

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