Pseudo-random single photon counting: a high-speed implementation

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Abstract: Pseudo-random single photon counting (PRSPC) is a new time-resolved optical measurement method which combines the spread spectrum time-resolved method with single photon counting. A pseudo-random bit sequence is used to modulate a continuous wave laser diode, while single photon counting is used to build up the optical signal in response to the modulated excitation. Periodic cross-correlation is performed to obtain the temporal profile of the subject of interest. Compared with conventional time-correlated single photon counting (TCSPC), PRSPC enjoys many advantages such as low cost and high count rate without compromising the sensitivity and time-resolution. In this paper, we report a PRSPC system that can be used for high-speed acquisition of the temporal point spread function of diffuse photons. It can reach a photon count rate as high as 3 Mcps (counts per second). Phantom experiments have been conducted to demonstrate the system performance.

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1. Introduction

The past decades have witnessed a growing interest in applications of diffuse optical tomography (DOT) in medical diagnoses and biomedical research, such as breast cancer detection [1–3], functional brain imaging [4–6] and small animal imaging [7]. DOT is noninvasive and nonionizing, has a large penetration depth and functional imaging capability. The three fundamental measurement schemes in DOT can be categorized as continuous wave, frequency-domain, and time-domain [8–12]. Compared to the frequency-domain and continuous wave DOT, it has been proved that the time-domain DOT may generate reconstructed images of higher spatial resolution due to the more information obtainable by investigating the full time spectra [8,9].

In most of the reported time-domain DOT systems, an ultra-short pulse laser was utilized as the light source for illumination of the turbid media while the diffuse photons were detected using the time-correlated single photon counting (TCSPC) method [10–13]. In such a system, the use of an ultra-short pulse (picosecond or femtosecond) laser and ultra-fast detection channels renders the system expensive and bulky. On the other hand, despite the large dynamic range, high linearity, and high temporal resolution, TCSPC has a problem with its data acquisition speed. The photon count rate is limited by the pile-up error, which occurs when the photon count rate is high enough so that the detection of more than one photon in each cycle becomes likely [14]. A typical photon count rate is below 1 Mcps (counts per second), though the state-of-the-art TCSPC modules can achieve a count rate as high as 10 Mcps by correcting the pile-up error. The limited photon count rate can result in low imaging speed, especially for multi-channel time-resolved instruments. For example, one complete scan usually takes 10–20 minutes for a 32-channel time-domain DOT system [11].

As a novel time-resolved optical measurement method, pseudo-random single photon counting (PRSPC) has the potential to achieve faster data acquisition through higher photon count rate. In our previous publication [15], we reported a prototype PRSPC system and conducted experiments to validate the method. The system calibration result showed a time resolution of 150 ps. Nevertheless, the PRSPC prototype is not the ultimate solution for real time data acquisition due to the long overhead time spent on reading data from the oscilloscope memory. In our current PRSPC system, this limitation is overcome by using a high resolution timing module which can continuously time-tag the photon pulses output from a single photon counting (SPC) detector. In this paper, we will present the architecture of this system and show the calibration result. We will also show the phantom based experiment result to demonstrate its potential in high-speed acquisition of the temporal point spread function (TPSF) of diffuse photons.

2. Method

2.1. System schematic

Our previous study has proved the feasibility of PRSPC. In the prototype system we built, a high-speed oscilloscope was used to record the pulse sequence output by the SPC. Due to its limited memory, the oscilloscope can only record a sequence over a 26.2 μ s time span at once while reading data from the oscilloscope memory resulted in a dead time around 0.5 second for each sequence. The total time for obtaining a TPSF could be greater than tens of minutes. To achieve real time data acquisition, we have developed a new implementation utilizing a

high resolution timing module (HRMTime, SensL) to record the pulse sequence representing detected photons. The time-tagging function of HRMTime allows continuous recording of the photon pulses in a time bin size down to 27 ps and fast communication of recorded time-tags to a PC.

Fig. 1. Schematic of the PRSPC system. The dash lines represent the optical signal path and the solid lines represent the electrical signal.

The schematic of our PRSPC system is presented in Fig. 1. A broadband PRBS source (TG2P1A, Centellax) is used to generate a 10 Gb/s PRBS with a pattern length of 2^{10} -1 bits. A 850 nm VCSEL transmitter (V-226, California Scientific), which has a maximal 2.2 mW output power and maximal modulation bit rate of 12.5 Gb/s, is modulated by the 10Gb/s PRBS, and its output is coupled to a multimode optical fiber. This multimode fiber directs the laser beam to the sample under investigation and the diffuse photons are collected by another multimode optical fiber (core diameter~62.5 μm). To ensure optimal photon detection efficiency, this fiber is coupled to a collimator and the collimated light beam is focused by a lens (focal length~2 cm) to the active area (diameter~20 μm) of a SPC module (id100-20, id Quantique). The collimator, lens and the SPC module are placed in a lightproof box to minimize room light influence. To control the actual photon count rate of the detector, neutral density filters are placed between the collimator and the lens when needed. The electrical pulses output by the detector representing the photon events are collected by the HRMTime timing module which continuously time-tags the rising edge of each single pulse. The time bin size is set to its minimum value of 27 ps. A pattern trigger signal, with a period of 32 times of the PRBS repetition time, is available from the PRBS generator and is taken by the timing module as a reference signal for synchronization. The time tags for both the photon pulses and the reference signal are continuously transferred to the PC, controlled by a Labview program. The Labview program accumulates the recorded photons to build up the signal arriving at the SPC detector, and then cross-correlates it with the original PRBS to retrieve the time spectrum of the detected photons. In contrast to TCSPC whose photon count rate is limited by the pile up error, the count rate of the PRSPC system is ultimately limited by the HRMTime timing module and the data processing time taken by the Labview program. A count rate of 3 Mcps has been achieved with the PRSPC system.

2.2. Calibration result

In order to characterize the system's impulse response, we removed the lipofundin phantom from the optical path shown in Fig. 1. The light beam was attenuated by appropriate neutral density filters before being collected by the SPC detector. In Fig. 2, the rise time (20%-80%) of the impulse response was measured to be around 130 ps. A few factors have contributed to

the timing performance of the PRSPC system. The timing jitter of the id100-20 SPC detector resulted from the transit time spread (TTS) is 40 ps. The maximal bit rate reachable by the VCSEL transmitter is 12.5 Gb/s and we used 10 Gb/s. Besides, the system response can also be spread due to the use of other components such as multi-mode fibers.

Fig. 2. Calibration result of the PRSPC system

3. Experiments and results

To evaluate our system in terms of its potential performance in time-domain diffuse optical imaging, we designed a lipofundin phantom based experiment. As a polydisperse, lipofundin at different concentrations can be used to mimic the optical properties of biological tissues in bioimaging research [16]. In our experiment, 1.32 mL Lipofundin MCT/LCT 20% was mixed with 86.64 mL distilled water so that the lipofundin concentration was 0.3%. The 0.3% lipofundin suspension was contained in a transparent beaker and placed onto the rotation stage shown in Fig. 1. The configuration of the laser probes and lipofundin sample is illustrated in Fig. 3. The target position shown corresponds to the initial state during experiment.

Fig. 3. Configuration of laser probes and lipofundin sample. Left, lateral view; right, vertical view. The dash square in the vertical view corresponds to the image reconstruction area.

The 0.3% lipofundin suspension has an absorption coefficient (μ_a) around 0.02 cm^{-1} , and a reduced scattering coefficient (μ'_s) about 3.0 cm^{-1} . The μ_a and μ'_s for the target are 0.1 cm^{-1} and 8 cm^{-1} respectively. During the experiment, each time the rotation stage carrying the lipofundin suspension and target was manually rotated by 3° and the corresponding TPSF was measured. The rotation over 180° allowed us to take 61 TPSF measurements in total. The photon count rate detectable at the SPC detector was around 10^4 cps. To acquire around 1 million photons for each TPSF, we set the data acquisition time to 100 seconds. It is worthwhile to mention that the low count rate was specific to the experimental setup we used. The acquisition time can be much reduced if a large active area SPC detector is available. For example, a $200 \text{ }\mu\text{m}$ SPC can help cut the TPSF acquisition time down to one second.

The image reconstruction was conducted in COMSOL/MATLAB environment. A 3D FEM forward model was built up in COMSOL Multiphysics 3.4 according to the geometry in Fig. 3. Laplace domain diffusion equation and Laplace transformed TPSF measurements were used. For demonstration purpose, we only considered the 2D image for the slice at $Z = 29 \text{ mm}$, which is at the same height with the laser probes. Rytov approximation and Levenberg-Marquardt algorithm with positivity constraint were used to solve the inverse problem and to simultaneously reconstruct the absorption coefficients and the diffusion coefficients [17]. The inverse method was conducted in MATLAB. The optical properties of the model were updated for each iteration, and so were the forward model and forward solution in COMSOL. The images in Fig. 4 are the reconstructed results after 5 times iteration. The images cover a transverse sectional area in which both x and y range from -1.4 cm to 1.4 cm . From Fig. 4, we can see the reconstructed target position is not much different from its true position. The error could stem from modeling errors and/or measurement errors, e.g. the X-Y plane centre for the beaker and the rotation stage were not precisely overlapping. Within the reconstructed target area (represented by solid circle), the μ_a has a mean value of 0.0975 cm^{-1} and standard deviation of 0.0128 cm^{-1} whilst the μ'_s has a mean value of 5.4117 cm^{-1} and standard deviation of 1.7488 cm^{-1} , which are close to the true values ($\mu_a \sim 0.1 \text{ cm}^{-1}$, $\mu'_s \sim 8 \text{ cm}^{-1}$).

Fig. 4. Reconstructed optical properties of the X-Y plane at $Z = 29 \text{ mm}$. The unit for the color bar is cm^{-1} . The dash circle represents the actual target position while the solid circle represents the reconstructed target position. (a) for absorption coefficients and (b) for reduced scattering coefficients.

4. Conclusion

We have developed a high speed implementation of the pseudo-random single photon counting method which was proposed in our previous work. Compared with the prototype PRSPC system, the current system can reach a photon count rate of 3Mcps which is limited by the HRMTime timing module and the data processing time taken by the Labview program. A 4 Mcps count rate is possible if we can further reduce the data processing time taken by the Labview program. The calibration result shows a rise time (20%-80%) of 130 ps. The

lipofundin phantom based experiments demonstrate that the system is capable of fast acquisition of temporal profile of diffuse photons and has high potential in time-domain DOT systems. In addition, our system also offers portability and low system cost mainly because it uses a continuous wave laser instead of a pulsed laser. The system can be easily integrated into a portable device.

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