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Adaptive coherent photoacoustic sensing

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Abstract

Sensitive detection is always crucial to photoacoustic sensing and imaging applications owing to the extremely low conversion efficiency from light to sound. Conventional approach to enhance the signal-to-noise ratio (SNR) of the photoacoustic signal is data averaging, which is quite time-consuming due to multiple data acquisitions for each photoacoustic measurement. Especially for high power pulsed laser source with only 10-20 pulse repetition rate, multiple data averaging will severely degrade the frame rate. In this paper, we present a simple but efficient way, called adaptive coherent photoacoustic (aCPA) sensing to obviously enhance the detected signal SNR with only single laser pulse. More specifically, The proposed aCPA employs an adaptive matched filter to cross-correlate with the raw time-domain PA signal iteratively. The optimum matched filter could be found after several iterations, leading to improved signal SNR. *In vivo* experimental results show that the proposed aCPA method improved the signal SNR by about 60 dB with single PA measurement. In conventional data averaging, 10^6 times PA measurements is required to achieve same SNR improvement. In other words, sensing and imaging speed is improved by 10^6 times in theory. It demonstrates the potential of aCPA to perform highly sensitive photoacoustic sensing and imaging with significantly accelerated speed.

Introduction

Photoacoustic sensing and imaging techniques have experienced a tremendous growth as one of the emerging imaging modalities in recent years [1-13]. Despite the remarkable achievements in PA imaging research community, one of the major challenges is the extremely low energy conversion efficiency from light to sound [14, 15], which inherently causes the much lower signal-to-noise ratio (SNR) of PA signal compared with conventional ultrasound imaging.

Fig. 1. (a) The matched filtering process between the raw measured PA signal and uncertain replica signal. (b) The close-loop system structure of the aCPA method to maximize the correlation peak and detection SNR accordingly.

Under constraint laser fluence, the conventional way to further improve PA signal SNR is averaging multiple PA signals during multiple PA measurements, which however will definitely slow down the sensing and imaging speed, given that the laser repetition rate is usually only 10~20. Except data averaging, another commonly used way is low-pass or band-pass filtering the raw PA signal. However, without knowing the waveform and frequency spectrum of the measured PA signal in advance, the selection of the cut-off frequency is uncertain. Furthermore, matched filter is recognized as the ideal filter that could maximize the SNR of the received PA signal, which requires an exact replica of the original PA signal without noise. Again, this exact replica of the original PA signal is not readily available for time-domain pulsed

laser induced PA sensing. Unlike frequency-domain PA with chirping laser source that can easily apply matched filtering using well-defined chirp modulation waveform [16, 17], the waveform and frequency spectrum of pulsed PA signal can hardly be predicted as shown in Fig. 1(a).

In this paper, we report a sensitive PA detection method, called adaptive coherent PA (aCPA) sensing by applying an adaptive matched filter to coherent detection of PA signal.

Methods

As shown in Fig. 1(a), to find out the replica $s_r(r)$ of the original PA signal $p_r(r)$ and maximize coherent PA (CPA) signal adaptively, we propose the aCPA method as shown in Fig. 1(b). This close-loop system enables the automatic maximization of the correlation peak and signal SNR. The working principle is as follows:

Step 1: Predefine some parameters for the replica signal, including the pulse cycle number (e.g. 1 cycle), initial pulse width (e.g. 0.1 μ s), tuning step (e.g. 0.1 μ s) and converge threshold (e.g. 5%).

Step 2: Iteratively calculate the cross-correlation between the raw measured PA signal and updated replica signal, then get the correlation peak and peak difference compared with the previous one. Extract tuning parameters from the peak difference and adjust the pulse width of replica signal in each iteration step.

Step 3: When the peak difference is smaller than the threshold (e.g. <5%), then the iteration stops and ideal matched filter is found. During the iteration process, it is expected that the correlation peak will be increasing gradually and converging. Meanwhile the peak difference is decreasing until the threshold is satisfied.

The experimental setup is shown in Fig. 2, which includes a pulse laser source (Opolett 355, OPOTEK) to fire 650 nm light, a mirror to guide the light, and a condenser lens to focus the light. A custom-made ultrasound transducer (Doppler Inc.) with an open hole inside was used to receive the PA signal without blocking the light. A layer of polydimethylsiloxane (PDMS) was placed between the transducer and human arm to couple both light and sound. The received PA signal was amplified by a low-noise amplifier (5662, Olympus) and recorded by an oscilloscope (WaveRunner 640Zi, LeCroy). A human arm was attached to the PDMS layer working as the sample for *in vivo* sensing.

Fig. 2. The setup for *in vivo* experiment. ConL: condenser lens; LNA: low-noise amplifier; PDMS: polydimethylsiloxane; UT: ultrasound transducer.

Results

Preliminary experimental results are shown in Fig. 3 and Fig. 4. In Fig. 3(a), one of the measured time-domain raw PA signal was plotted with a poor signal SNR of 5.6 dB. The ideal matched filter with tunable pulse width was shown in Fig. 3(b), which was swept from 0.1 μs to 50 μs . The SNR of CPA signal over the pulse width sweeping in Fig. 3(c) shows that there is an ideal matched filter existed for maximized SNR of around 60 dB when pulse width $\sim 100 \mu\text{s}$. By sweeping the laser fluence, the improvement was constantly significant for different SNR levels as shown in Fig. 3(d).

Fig. 3. (a) The raw PA signal. (b) The replica signal with tunable pulse width. (c) The signal SNR versus pulse width of the replica signal. (d) The SNR of raw PA signal and aCPA signal versus laser fluence.

To efficiently find the optimum pulse width of the replica signal, we applied the proposed aCPA method introduced above. Within only 7 steps of iteration shown in

Fig. 4(a), the signal SNR has been nearly maximized to ~ 60 dB, and the tuning parameter was reduced to ~ 0 as expected, which are shown in Fig. 4(b)-(c). Compared with commonly used data averaging way to increase PA signal SNR by 30 dB, the proposed aCPA (from step 1 to step 7 in Fig. 4(b)) achieved much less time consumption (1-time data sampling in aCPA v.s. 1000-times data sampling in data averaging), which is quite useful for high-speed real-time PA sensing and imaging applications.

Fig. 4. (a) The CPA signal waveform of seven iteration steps (b) The SNR of the aCPA signal, and (c) tuning parameter versus pulse width of replica signal during seven iteration steps.

Conclusion

In this paper, we proposed a sensitive PA sensing method named aCPA to maximize the signal SNR and system sensitivity. The proposed aCPA enables fast and automatic detection of weak PA signal in strong noise background with ~ 60 dB SNR improvement. This method may find interesting applications in PA sensing and imaging with constraint laser power, which usually only induce very weak PA signals.

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