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Ghost reduction in CP-SSOCT having multiple references using Fourier-domain Shift and Sum

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Abstract

We propose, test and validate a novel Fourier-domain based method for ghost image artifacts reduction in a common-path SSOCT system having multiple adjacent reference planes. Common-path probes with imaging systems containing high-index sapphire ball or other lenses produce multiple fixed references due to Fresnel reflections from the lens surfaces. The multiple reference planes produce multiple and overlapping OCT images. Since such ghost artifacts are the result of the superposition of multiple identical images having different amplitudes and spatial shifts, one can correctly shift and sum the images in the Fourier-domain once the relative amplitude and lateral position between the reference planes are known. This theory and numerical testing are presented to elucidate our method. We then validate the potential effectiveness using OCT imaging experiments.

Index Terms

Optical fiber sensors; Optical signal processing; Optical signal detection; Biomedical optical imaging

I. Introduction

Advanced optical coherence tomography (OCT) allows 3D imaging and instrument motion tracking which could enable intraoperative image guided surgery [1–3]. Functional OCTs can also provide various physical properties such as flow information and polarization sensitivity [4, 5].

To achieve axial surgical tool guidance, we have strategically chosen to incorporate common-path OCT (CP-OCT) into handheld microsurgical tools since CP-OCT allows a

simple design, dispersion free properties, relatively low cost and the potential for disposability [6]. In spite of these advantages, there are limitations when the system uses a bare fiber as the sensor probe. One of the main drawbacks is that the laser output from the single mode fiber probe divergence rapidly and the output power decreases exponentially with the depth. To prevent this rapid power fall-off, lensed fiber probes have been applied [7–9]. A CP-OCT probe based on a built-in conical micro-lens showed significant improvement in signal-to-noise ratio (SNR) [8]. However, such lensed fiber probe is still limited in the aqueous environment due to the fact that it uses the reflected beam at the fiber-tip as a reference beam. Thus, the intensity of the reference beam decreases when the fiber ($n=1.5$) is moved from the air ($n=1.0$) into an aqueous environment such as saline ($n=1.33$) or vitreous. To overcome this limitation, a sapphire ball lens having a high reflective index ($n=1.77$) was used at the tip of the glass fiber to attain SNR improvement. There are a number of advantages to this approach which includes a high focusing power, protecting the fragile fiber-tip, and a creation of a stable reference [10]. However, the introduction of a high index sapphire ball lens causes severe noises that result from the two highly reflective sapphire ball lens surfaces which in turn produce two additional references. One of the noises comes from autocorrelation noise. This type of noise has been extensively studied in prior works [11–13]. Among the methods, minimum variance mean line subtraction can effectively reduce this fixed-pattern noise [12]. However, the other mixed noise induced by the correlation between sample-reflected light and multiple reference-reflected lights create multiple ghost images and cannot be easily eliminated due to its variability in shape and position. There were some studies to actively utilize multiple references in order to expand imaging domain size and remove dc term as well as mirror noise using electrooptic phase modulator or piezoelectric fiber stretcher [14, 15]. These methods use electro or mechanical actuators to achieve multiple references but they still incorporate one reference at a time. In the present work, we utilize a Fourier domain image processing approach where known images from the multiple fixed references are shifted and summed appropriately to diminish distortion in the OCT images.

II. Methods and Materials

A. CP-OCT probe setup

For the fiber probe shown in Fig. 1, we attached 500um sapphire ball lens to the end of the standard 25-gauge hypodermic needle with UV epoxy adhesive. Then, an optical fiber was inserted into the needle and positioned with specific space to achieve designed focal length.

B. OCT signal with multiple references

The output current I_D of the detector in interferometer with multiple references can be described by the following equation:

$$I_D(k, w) = \rho \left\langle \left| E_{R_1} + E_{R_2} + \cdots + E_{R_m} + E_{S_1} + E_{S_2} + \cdots + E_{S_n} \right|^2 \right\rangle \quad (1)$$

where k , ω , and ρ are wave number and angular frequency, and responsivity of the detector, respectively. Additionally, E_{Rm} and E_{Sn} are the reflected signals from multiple layers of reference and sample. The angular brackets denote integration over the response time of the detector and this time averaging eliminates the terms related to temporal frequency. We can rewrite the Eq. (1) as shown in Eq. (2),

$$I_D(k) = \rho \left| s(k) \sum_m^M t_{Rm-1} r_{Rm} e^{i2kz_{Rm}} + s(k) \prod_m^M t_{Rm} \sum_n^N r_{Sn} e^{i2kz_{Sn}} \right|^2 \quad (2)$$

where $t(t_0 = 1)$ and r are transitive and reflective coefficients of the reference and sample; $s(K)$ is source spectrum. Then, we can get Eq. (3) after expanding Eq. (2) and then applying inverse Fourier transform,

$$\begin{aligned} i_D(z) = & \alpha_1 \left[\gamma(z) (R_{R_1} + \cdots + R_{R_m} + R_{S_1} + \cdots + R_{S_n}) \right] \\ & + \alpha_2 \sum_m^M \sum_n^N \sqrt{R_{Rm} R_{Sn}} \left[\gamma[2(z_{Rm} - z_{Sn})] \right. \\ & \quad \left. + \gamma[-2(z_{Rm} - z_{Sn})] \right] \\ & + \alpha_3 \sum_{n \neq m=1}^M \sqrt{R_{Rn} R_{Rm}} \left[\gamma[2(z_{Rm} - z_{Rn})] \right. \\ & \quad \left. + \gamma[-2(z_{Rm} - z_{Rn})] \right] \\ & + \alpha_4 \sum_{n \neq m=1}^N \sqrt{R_{Sn} R_{Sm}} \left[\gamma[2(z_{Sm} - z_{Sn})] \right. \\ & \quad \left. + \gamma[-2(z_{Sm} - z_{Sn})] \right] \end{aligned} \quad (3)$$

where γ is coherence function and α_n is the coefficient of each term including DC, cross-correlation, auto-correlation in reference, and auto-correlation in a sample in turn. Based on Eq. (3), we can deduce the shape of an A-scan having multiple references. First, we have a huge DC value at the zero position. Then, we have multiple sample signals having the same shape and the duplicate number is the same as the number of references. The A-scan also has large signals due to auto-correlation between references at fixed positions and we can typically ignore the auto-correlation within a sample.

C. Signal restore algorithm

The A-scan with a sapphire ball lens has several additional peaks in contrast to the typical A-scan data which only has a single zero-delay peak. Among the additional peaks, the three fixed peaks are caused by auto-correlation between the references including fiber surface and highly reflective inner and outer surfaces of the ball lens. The distance between the two main peaks caused by the inner and outer surface has a larger value than the diameter of the ball lens (500 μ m) because the refractive index of the sapphire ball lens is 1.77; thus, the distance looks like 885 μ m. Although these auto-correlated peaks have an undesirably high

intensity, they can be removed by background subtraction. This is in part because their position and intensity are nearly constant. A greater issue is there are multiple sample signals in the A-scan due to the multiple references. Further complicating this is that multiple signals can overlap due to the close proximity of the two reference lines used to create the sample image. The distance between these two reference lines including fiber-tip and inner surface of the ball lens is determined by the lens equation to attain focusing and this was around 150 μm . Thus, any sample which is thicker than this distance can induce an overlapping sample signal in the A-scan data. This problem can be critically problematic in a distal sensing application and it can also degrade the image quality of manually scanned OCT images.

According to Eq. (3), the multiple and overlapped A-scans share common features. The signal can reasonably be decomposed into one basic signal with differing amplitudes and delays. We can then write the measured discrete signal by the sum of three template signals with different amplitudes, delays, and noise. We can then describe this assumption as the following discrete equation:

$$y[n] = x[n] + a_1 x[n - n_1] + a_2 x[n - n_2] + s[n] \quad (4)$$

where $x[n]$, $y[n]$, and $s[n]$ are the desired original data, the measured A-scan data, and the noise data respectively. Additionally, n_1 and n_2 are the delay terms. Based on the above equation (4), we can correct the distorted signal by converting it into a frequency domain [16].

$$Y[k] = X[k] + a_1 X[k] e^{-\frac{j2\pi n_1 k}{N}} + a_2 X[k] e^{-\frac{j2\pi n_2 k}{N}} + S[k] \quad (5)$$

$$x[n] = IFFT \left(\frac{Y[k] - S[k]}{(1 + a_1 e^{-\frac{j2\pi n_1 k}{N}} + a_2 e^{-\frac{j2\pi n_2 k}{N}})} \right) \quad (6)$$

where $X[k]$, $Y[k]$, $S[k]$ are the results of discrete Fourier transform of $x[n]$, $y[n]$ and $s[n]$. The delay term in a time domain is extracted into the exponential term in a frequency domain. Then, we can get $x[n]$ by applying inverse Fourier transform. This Fourier-domain shift and sum (FSS) is easy to implement and only requires an initial reference measurement without a sample to deduce the amplitude and delay of the multiple reference planes. Note that, if the noise term, $S[k]$ is large, it has to be known to properly solve the equation. However, the noise terms can be also made small enough through A-scan averaging and background subtraction before applying the proposed methods which were demonstrated in this work. Also, note that the coefficients a_1 and a_2 are normalized to the maximum A-scan peak and range between 0 and 1. To test this method, we simulate the setup shown in Fig. 1(a) based on Eq. (3). We used Gaussian function for coherence function, γ and assume that there are three reflectors in reference and ten reflectors in a sample. The reflectance values

for reference were determined based on the preliminary experiment result and the reflectance values for sample were chosen arbitrarily. The ground truth sample signal is shown in Fig. 2(a) and random noise is added to the simulated signal as shown Fig. 2(b). The dc component and auto-correlated signal between references can be removed by background subtraction as shown in Fig. 2(c). Fig. 2(d) shows the corrected signal after applying FSS method.

III. Results and Discussion

Based on the above simulation, two types of experiments were conducted in order to evaluate the effectiveness of the proposed method we collected actual OCT data under two conditions, one as reflected from a mirror and the other as reflected from 7-stacked layers of adhesive cellophane tape. The mirror is a good sample that has one reflector. Then, we substituted the multiple layers of cellophane tape as the target to assess our method on samples with more complex reflectors. In particular, we conducted manual scans to acquire B-scan images of the inner structure of the sample.

A. Single-reflector sample experiment

The raw A-scan shown in Fig. 3(a) is contaminated by multiple peaks coming from the highly reflective sapphire ball lens surfaces and their auto-correlation. This fixed noise can be removed by background subtraction method as mentioned earlier and the result is shown in the blue graph, Fig. 3(b). The noise inside of the sapphire ball lens is not completely removed due to the variability in local intensity caused by fiber polarization changes which are dependent on the motion of the optical fiber. However, this is not a critical problem as we know the position of the outer surface of ball lens in the A-scan and the noise within the outer surface can be removed. The three mirror signals are created by interfering with the reference beams coming from (1) outer ball lens surface, (2) inner ball lens surface and (3) fiber tip in order of position. After applying the proposed method, we can drive the corrected signal (red graph) shown in Fig. 3(b). It has the same shape as the first mirror signal, the blue graph. Signal correction works well here because the signal coming from the mirror is easily identified against the background noise.

B. Complex-reflector sample experiment

As expected, in contrast to the mirror experiment, the cellophane tape experiment had more obstacles to overcome in that the signal was weaker and its shape was more complex. A particular difficulty was that the sample signal created by the reference beam, coming from the outer surface of the ball lens, was not strong enough to image the deeper structure in the sample. This was not the case with the other two signals; as a direct result, the first sample signal has a different shape from the other sample signals. This is a critical violation of our assumption and it can induce substantial side effect when we deal with the signal in the frequency domain. Therefore, we need an alternative way to solve this issue.

As we know the relative distances between each sample in the A-scan data set, we can separate the A-scan into two regions once we locate the starting point of the first sample signal as shown in Fig. 3(b). We used the same method to detect the sample surface that is

described in our previous work [17]. Then, we added the modified sapphire ball lens diameter (885 μm) to the starting point of the sample signal in order to determine the first region. The second region is therefore in the remaining area. This process requires more processing time and computing power compared to the simple mirror case. In mirror case, we do not need to find the sample position. Then, we deal with these two regions separately. For example, when dealing with the first region, we set zero on the points in the second region and vice versa. This alternative method improved the SNR in the corrected data while decreasing the undesirable side effect due to the lossy signal in the first area. In the second region, our method decomposed the overlapped signal. Finally, we can get the corrected signal shown in the red graph in Fig. 4(b).

A one-dimensional A-scan graph is not enough to verify whether the proposed method restores the features of the sample because it is hard to deduce the sample shape only observing the 1D signal. As shown in Fig. 5, we conducted manual scanning to get B-mode images of the cellophane tapes using the same method as reported in our prior work [18]. The raw B-mode image shown in Fig. 5(a) has several bright horizontal lines induced by the sapphire ball lens. After background subtraction, the image quality is improved by removing the fixed structural noise and lowering the DC-base line. The final restored image shows each individual layer of the cellophane tape that is similar to prior work.

IV. Conclusion

The use of the ball lens provides an unequivocally better SNR. The optics of the sapphire ball lens provides an excellent option for our OCT fiber probe due to its high focusing power and small size. In common-path setup, however, the use of ball lens induces a large amount of background noise as well as multiple ghost signals because of its highly reflective lens surface. This severe distortion of the A-scan signal was a significant barrier to overcome for our common-path based OCT distal sensing and manual scan imaging. To solve this problem, we proposed a novel FSS method to reduce ghost artifacts. Through simulation testing, we demonstrated how the proposed method can be used to successfully decompose the spatially mixed signals even in high noise setting. We further validated the method by a mirror experiment that confirmed that our method worked effectively to generate common-path OCT A-scan data. Finally, the cellophane tape experiment demonstrated that our method is applicable to multilayered samples with complex internal structure.

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Fig. 1. Schematic of the system; (a) fiber probe with sapphire ball lens having $500\mu\text{m}$ diameter, (b) system overview, and (c) photo image of the probe.

Fig. 2.

Simulation result; (a) ground truth signal synthesized with the combination of 10 reflectors, (b) simulated raw A-scan with random noise, (c) background (fixed) noise subtracted A-scan signal, and (d) the reconstructed signal graph.

Fig. 3.

Mirror experiment result; (a) raw A-scan graph and (b) background subtracted A-scan graph (blue) and distortion corrected A-scan graph (red).

Fig. 4. Cellophane tape experiment result; (a) raw A-scan graph and (b) background subtracted A-scan graph (blue) and ghost corrected A-scan graph (red).

Fig. 5. Cellophane tape B-scan images; (a) raw, (b) background subtracted, and (c) ghost corrected B-scan images.