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Active feedback wide-field optical low-coherence interferometry for ultrahigh-speed three-dimensional morphometry

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Abstract
A novel optical interferometric scheme for ultrahigh-speed three-dimensional morphometry is proposed. The system is based on wide-field optical coherence tomography (WF-OCT) but with optically chopped illumination. The chopping frequency is feedback-controlled to be always matched with the Doppler frequency of the OCT interferometer, which provides an efficient page-wide demodulation suitable for ultrahigh-speed volumetric imaging. To compensate the unwanted variation in the OCT Doppler frequency of the system, the illumination frequency is phase-locked with an auxiliary laser interferometer which shares the reference arm with the OCT interferometer. The two-dimensional (2D) interference signals projected on the 2D array pixels of a 200 Hz CCD are accumulated during one imaging frame of the CCD. Then, each pixel of the CCD demodulates the OCT signal automatically. Owing to the proposed active frequency-locked illumination scheme, the demodulation does not depend on the variation in the axial scanning speed. Volumetric topograms or/and tomograms of several samples were achieved and rendered with a sensitivity of 58 dB at an axial scan speed of 0.805 mm s⁻¹.

Keywords: optical imaging, optical coherence tomography, wide-field optical coherence tomography, Doppler frequency, frequency-locked illumination

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

Recently, high-speed three-dimensional (3D) measurements have been increasingly required in many fields such as quality inspection in micro-processing industry or structure analysis of multi-layered materials including scattering media like bio-specimens. It is of importance that the rapidity of 3D visualization enables immunity to environmental fluctuation such as vibration, temperature drift and even heart beating of a living sample. Optical approaches for high-speed 3D imaging have gained much attention owing to the advantages of non-contact, non-invasive, non-destructive, robustness...
and real-time imaging features [1]. Digital holographic microscopy (DHM) is one of the most representative 3D optical imaging techniques [2–6]. Even with a single CCD (charge coupled device) image acquisition, the DHM can give a nanometer scale topology of the sample. The approach of tomographic imaging based on the DHM was reported [6]. A set of holograms recorded by manually swept wavelengths were numerically superposed, which made short coherence gating necessary for the depth-resolved tomographic imaging. However, the DHM needs a heavy data processing time, and thus, it is not suitable for real-time 3D imaging.

Lately, the possibility of getting high-speed 3D retrieval with a large volume specimen has been studied using the optical low-coherence interferometry named as optical coherence tomography (OCT) [7–11]. OCT is a well-established coherence-gated imaging technique that is generally used to get the internal structures of scattering materials including biomedical specimens. In general, the high-speed imaging performance of the OCT has been mainly demonstrated with XY raster scanners [7–11]. But as mentioned in many documents, the time-elapsed scanning scheme eventually restricts the 3D OCT imaging rate. To overcome this drawback, many researchers have proposed wide-field OCT (WF-OCT) [12–15]. WF-OCT based on a bulk Michelson interferometer provides en face oriented images without any lateral scanning. Depth-resolved en face tomographic images are obtained with a 2D sensor array, and only one axial scan is necessary for 3D image reconstruction.

Several schemes for WF-OCT have been devised and developed. Akiba et al have demonstrated the heterodyne parallel detection technique using a pair of identical CCDs operated in the frequency-synchronous mode [12]. With a single axial scan, a 3D data set of 0.8 mm × 0.8 mm × 0.36 mm was acquired at a rate of 100 frames s⁻¹ [12]. Laubscher et al have demonstrated the fast 3D OCT imaging scheme with the parallel detection technique based on a silicon pixel array incorporated with a series of dedicated signal processing unit [13]. A 3D volume image of 0.21 mm × 0.21 mm × 0.8 mm was achieved at 25 Hz. In the conventional ones, however, there are several issues in the precise alignment of dual CCDs for pixel matching [12] and complexity in the chipset fabrication [13, 14]. Recently, Watanabe et al developed the WF-OCT system using an ultrahigh-speed CMOS (complementary metal oxide semiconductor) camera operating at a rate of 1500 frames s⁻¹ [15]. This method utilized the lock-in detection technique, modulating the OCT beam with the Doppler frequency of the system, which allowed the rapid acquisition rate of 4 volume s⁻¹ of a 2.6 mm × 2.6 mm × 1.2 mm sample.

In this paper, we report a novel technique, which is simple but efficient for ultrahigh-speed 3D WF-OCT imaging. It employs the frequency-synchronous lock-in detection scheme, somewhat similar to that of the Watanabe group [15] but able to overcome the problems of the conventional scheme. The motion of an axial scanner is not linear in general but easily affected by acceleration, friction, backlash and unstable driving force [16–18], which alters the Doppler, or beat frequency of the OCT signal. The time varying Doppler frequency tends to smear out the OCT signal in the conventional scheme due to the mismatch with the modulation frequency of the OCT illumination beam [15]. In our proposed system, by utilizing an auxiliary laser interferometer, which shares the reference arm with the OCT interferometer, the modulation frequency mismatch problem could be completely overcome. The feasible ultrahigh-speed 3D imaging nature of the proposed scheme is presented by realizing en face OCT images (8 mm × 6 mm) at a 0.805 mm s⁻¹ axial scan speed and displaying their volume rendering.

2. Experimental set-up

As shown in figure 1, the main key of the proposed scheme is introducing the frequency lock-in module (indicated with the dotted red box) to a WF-OCT system. For the low-coherence OCT interferometer, a 5 mW super-luminescent emitting diode (SLED, EXS8005-B001, center wavelength λ₀ = 805 nm, FWHM 33.6 nm, Exalos) was used. The SLED was switched on and off according to the feedback signal from the auxiliary laser interferometer (indicated with the blue beam in the figure). An objective lens, MO1 (10×, Mitutoyo), in front of the SLED, collected the beam and yielded wide illumination of an 8 mm diameter to the sample. A part of the beam was guided to the reference arm through a beam splitter (BS1) and reflected by the reference mirror (M1). The beams from both the sample and the reference arms were projected onto a 2D CCD camera (TM6740CL, 640 × 480 pixels, 8 bits, 200 fps, Pulnix), which gave an OCT interference fringe pattern, referred to as interferogram. A slightly tilted neutral density filter (NDF) was inserted at the reference arm to enhance the interference fringe visibility.

An auxiliary laser interferometer was designed to share its reference arm with the OCT interferometer (sharing the

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**Figure 1.** Schematic of experimental setup. SLED: super-luminescent emitting diode; BS1–2: beam splitters; MO1–2: micro-objective lenses; L1–2: lenses; S: sample; NDF: neutral density filter; M1–3: mirrors; PD: photo-detector; LD: laser diode; AS: aperture stop; BPF: bandpass filter; Amp: amplifier.
frequency was fixed; thus, it could not ensure the OCT signal system [15]. However, in their scheme, the demodulation by modulating the SLED with the Doppler frequency of a high frequency, the Doppler frequency, with a slow CCD introduction, an effort of getting the OCT signal modulated in the OCT is defined as

\[ \lambda = \text{center wavelength of the light source}. \]

Figure 2. Spectra of SLED (black line) and LD (red line). Center wavelength of SLED was 805.10 nm and its Gaussian FWHM was 33.6 nm. For LD, these were 805.57 nm and 0.02 nm, respectively.

delay line in figure 1). A 10 mW LD (laser diode, L808P010, lasing wavelength 805 nm, Thorlabs) and a silicon-based PIN photo-detector (PD, 818-BB-22, Newport) were used for the auxiliary interferometer. By sharing the reference delay line and using the light sources of similar center wavelengths (see figure 2), both interferometers were made to have the same Doppler frequency, which was given by the axial scanning speed and the center wavelength of the light source. The signal from the PD was band pass filtered, converted into a dc-free pulse train, and finally fed to the current driver of the SLED. With these, the SLED was automatically fired only when the OCT interferogram signal was in a constructive phase state regardless of the Doppler frequency variation. Subsequently, the OCT signal on the CCD was accumulated during a time period that was long compared to the inverse of the Doppler frequency.

3. Image acquisition

In the proposed system, 3D image acquisition is simply achieved with just one-way continuous scan of the reference mirror. Generally, the Doppler frequency of a time-domain OCT is defined as \[ f_D = \frac{2V}{\lambda_0} [19], \] where \( V \) is the scan speed and \( \lambda_0 \) is the center wavelength of the light source. The OCT signal for a single point is given as the slowly varying curve enveloping a rapidly varying carrier signal of the Doppler frequency. Unfortunately, the Doppler frequency in most OCT systems is much higher (~kHz) than the CCD frame rate (~Hz). Therefore, the CCD captures only the average of the high frequency carrier signal, which loses most of the slowly varying OCT signals. As was stated in the introduction, an effort of getting the OCT signal modulated in a high frequency, the Doppler frequency, with a slow CCD was reported, in which the OCT signal was demodulated by modulating the SLED with the Doppler frequency of the system [15]. However, in their scheme, the demodulation frequency was fixed; thus, it could not ensure the OCT signal extraction when the Doppler frequency was not constant but varying for any reason. Therefore, the active feedback scheme assisted by the auxiliary laser interferometer is proposed to match or lock-in the demodulating frequency with any Doppler frequency under variation.

3.1. Image acquisition process

Figure 3 shows the timing charts of the proposed active lock-in detection scheme. It is assumed that an OCT interferogram signal (figure 3(a)) exposed on a pixel of a CCD is modulated by the Doppler frequency \( f_D(t) \) but under drift. The interferogram signal detected with the laser interferometer is shown in figure 3(b); we know that it has the same Doppler frequency as the OCT interferogram, \( f_R(t) = f_D(t) \), since they share the same reference arm. The laser interferometer signal is used to modulate the SLED OCT light source to demodulate the OCT signal under drift Doppler frequency. First, using an electric comparator, a 50% duty cycle rectangular wave train is generated from the signal in figure 3(b) as shown with figure 3(c), and then fed to the SLED, the OCT light source. Therefore, the SLED is flashed only when the OCT interferogram is in the high state of interference. The CCD integrates the modulated OCT signals for many pulse periods as shown in figure 3(d). In experiment, the integration time of the CCD was about 5 ms and the readout time was 10 μs. The output signal per each frame of the CCD is schematically depicted in figure 3(e) with the asterisk symbol. We can see that the CCD output signal follows the shape of the envelope curve of figure 3(a). For comparison, the same scheme but with fixed demodulation frequency \( f_F \) is depicted in figures 3(a′)–(d′). We can see that due to the phase mismatch between the signals of figures 3(a′) and (b′), the output signal in figure 3(d′) becomes far from the envelope curve of figure 3(a′).

At the moment, with the spectral density \( S(\omega) \) of the OCT light source, the light intensity at the CCD pixel plane is given as

\[
I = \int_{-\infty}^{\infty} S(\omega) \left( A_r^2 + A_s^2 + 2A_rA_s\cos(2k\Delta z) \right) d\omega, \quad (1)
\]

where \( A_r \) and \( A_s \) are the reflectances of the reference mirror and the sample, respectively. \( \Delta z \) is the initial path difference between both arms of the OCT interferometer. Provided that the light source has a Gaussian power spectral density of

\[
S(\omega) = S_0 \left( \frac{2\pi}{\sigma^2} \right)^{1/2} e^{-\frac{\omega^2}{2\sigma^2}}, \quad (2)
\]

and considering the axial scan motion of the reference arm, the interferometric photocurrent is well known as [19]

\[
I(t) = (A_r^2 + A_s^2) S_0 + 2A_rA_s S_0 e^{-\frac{\omega^2}{2\sigma^2}} \cos(2\pi f_D(t)t), \quad (3)
\]

where \( f_D(t) \) is the Doppler frequency under drift as mentioned above. We note that the Doppler frequency is proportional to the scan speed \( V \), and the group delay mismatch \( \Delta \tau_2 \) is a function of time through the scanning.

The signal of equation (3) is composed of dc and ac components as

\[
I_{dc} \equiv (A_r^2 + A_s^2) S_0, \quad (4.1)
\]

\[
I_{ac}(t) \equiv 2A_rA_s S_0 e^{-\frac{\omega^2}{2\sigma^2}} \cos(2\pi f_D(t)t). \quad (4.2)
\]
Since the rectangular pulse train shown in figure 3(c) is designed to have a 50% duty cycle and the same frequency with the OCT signal, it is presented with a Fourier series and normalized sinc function

\[ m(t) = \frac{1}{2} + \sum_{n=1}^{\infty} \text{sinc} \left( \frac{n}{2} \right) \cos (2n \pi f_D(t) t + \theta_m), \]  

(5)

where \( \theta_m \) is the initial phase difference between two interferograms.

The CCD output signal is obtained by integrating the signal of equation (3), after multiplying it with the demodulation function of equation (5), during the CCD accumulation time period \( T \) as

\[ I_{\text{CCD}}(t) = \int_{t'}^{t+T} (I_{dc} + I_{ac}) m(t') \, dt' \]

\[ = \frac{T}{2} I_{dc} + I_{dc} \sum_{n=1}^{\infty} \text{sinc} \left( \frac{n}{2} \right) \times \int_{t'}^{t+T} \cos (2n \pi f_D(t) t + \theta_m) \, dt' \]

\[ + A_r A_s S_0 \int_{t'}^{t+T} e^{-\frac{\sigma^2}{2T}} \cos (2n \pi f_D(t) t) \, dt' \]

\[ + 2A_r A_s S_0 \sum_{n=1}^{\infty} \text{sinc} \left( \frac{n}{2} \right) \int_{t'}^{t+T} e^{-\frac{\sigma^2}{2T}} \times \cos (2\pi f_D(t) t) \cos (2n \pi f_D(t) t + \theta_m) \, dt'. \]

(6)

In equation (6), the second term vanishes when the accumulation period \( T \) is much longer than the oscillation period of the OCT interferogram, or \( T \gg 1/f_D(t) \). Moreover, the third term becomes negligible when the temporal width of the Gaussian envelope function of the OCT system is much wider than the interference period, or \( \sigma \gg 1/f_D(t) \). The same approximation can be made with the last term. The summation of the last term is expanded for the first few terms as

\[ \sum_{n=1}^{\infty} \text{sinc} \left( \frac{n}{2} \right) \int_{t'}^{t+T} e^{-\frac{\sigma^2}{2T}} \cos (2n \pi f_D(t) t + \theta_m) \, dt' \]

\[ \approx \frac{1}{\pi} \int_{t'}^{t+T} e^{-\frac{\sigma^2}{2T}} \left[ \cos (4n \pi f_D(t) t + \theta_m) + \cos (\theta_m) \right] \, dt' \]

\[ - \frac{1}{3\pi} \int_{t'}^{t+T} e^{-\frac{\sigma^2}{2T}} \left[ \cos (8n \pi f_D(t) t + \theta_m) + \cos (4\pi f_D(t) t + \theta_m) \right] \, dt' + \cdots. \]

(7)

The even terms regarding the summation index \( n \) vanished due to the normalized sinc function, and the odd terms were decomposed by the mathematical identity. With the condition of a wide envelope function of the OCT system, \( \sigma \gg 1/f_D(t) \), same as for the third term of equation (6), all terms of equation (7) become negligible except the term

\[ \frac{1}{\pi} \cos \theta_m \int_{t'}^{t+T} e^{-\frac{\sigma^2}{2T}} \, dt', \]

(8)

and the light intensity at the CCD plane is approximately given as

\[ I_{\text{CCD}}(t) \approx \frac{T}{2} I_{dc} + \frac{2A_r A_s S_0}{\pi} \cos \theta_m \int_{t'}^{t+T} e^{-\frac{\sigma^2}{2T}} \, dt'. \]

(9)

Interestingly, it does not depend on the Doppler frequency drift. However, the signal contrast is degraded by \( \theta_m \), the initial phase difference between the demodulation signal and the interferogram signal. Further, it says that when the CCD captures the image near the center of the OCT envelope function the image contrast becomes good. The absolute difference of the two adjacent CCD frames gives
Figure 4. Measured electric feedback signals: (a) SLED modulation signal, (b) band-pass filtered dc-free interferogram signal, (c) interferogram signal of the LD interferometer.

3.2. Synchronous frequency lock-in detection using active feedback

Figure 4 shows the electric signals, regarding the active feedback procedure, taken with a digital oscilloscope (DSO6054A, Agilent). From the LD interferogram (figure 4(c)) of the laser interferometer, the dc-free sinusoidal signal (figure 4(b)) was extracted with band pass filtering. Then, the rectangular wave train (figure 4(a)) was made, for the SLED modulation or the system demodulation, by using a comparator circuitry. The axial scan of 0.805 mm s$^{-1}$ gave about a 2 kHz Doppler frequency in the experiment.

In order to show the feasibility of the proposed scheme, the OCT interferogram signal of a flat mirror was taken with a photo receiver, instead of the CCD. Figure 5(a) shows the OCT interference signal taken when the axial scanning was in a deceleration state. We can see that the signal is highly down chirped. To get the down chirping intentionally, the interferogram was taken near the end of the motion span of the scanner which was in triangular motion, thus a little bit before when it turned the direction of motion. A part of the figure, in the white box, is enlarged and shown in figure 5(b). The demodulation signal automatically generated with the proposed feedback scheme is depicted with the red solid line and compared with the fixed one, the blue dotted line, from a function generator operating at 2.48 kHz. The fixed demodulation frequency was designed to match the Doppler frequency at the middle of the motion span, where the scanner was at a highly constant speed. In the experiment, the scanning was made by a voice coil-driven mechanical scanner (V-106.11S, PI). In figure 5, we can see that the proposed frequency-locked signal was well phase-matched with the OCT interferogram even with the severe chirping in the Doppler frequency.

The down chirping of the interferogram shown in figure 5 is mainly attributed to the non-uniform scan motion of the reference arm. In the experiment, the signal was intentionally taken when the scanning was in severe deceleration. However, even with non-intentional motion, we can suffer from Doppler frequency variation. An auxiliary experiment was made with an air-bearing linear stage (PM500-4L, travel range: 100 mm, Newport) and a He–Ne interferometer. The given resolution of the stage was 0.1 μm; however, as figure 6(a) shows, the interferogram had a non-uniform Doppler frequency. Figure 6(b) shows a detail of the interferogram (yellow dotted box of figure 6(a)).

Even with the proposed scheme, there are many factors that can affect the system accuracy or the stability in getting the same signal. The fraction of the Doppler cycle being integrated might be different when the Doppler frequency is chirped; therefore, the amplitude of the signal will be affected by the chirp. Unfortunately, the detailed analysis of the
Figure 6. (a) Interferogram taken from the He–Ne interferometer and the not well-tuned linear scanner, (b) enlarged view of the interferogram (indicated by the yellow dotted box in (a)).

Figure 7. (a) OCT image of the USAF 1951 test target (4.27 mm × 4.47 mm) and (b) the line profile of group 4 (along the white solid line in (a)).

Figure 8. Measured sensitivity of the system. An OCT signal at a pixel of the CCD was monitored. A weak reflective glass plate (~0.78%) was used as the sample, and no data averaging was done. System noise is not in the scope of this paper, which is under preparation.

To obtain figure 5(a), the sample position was finely adjusted to minimize the effect of the initial phase difference $\theta_m$ of equation (9). Even though both the OCT interferometer and the auxiliary one share the same reference arm, they have different sample arms; thus, the initial interference phases are different to each other in general. In measurement of real samples, however, this adjustment in the initial phase is not necessary. With a sample having continuous boundaries, not a discrete one like the mirror plane in figure 5, the initial phase distribution is also continuous in the CCD pixel coordinate. It means that most of the pixilated OCT signals, except for $\theta_m(x, y) = \pm 90^\circ$, are recovered to form the en face image of the sample. Of course, at the zero phase difference, the OCT signal is extracted most strongly. Detailed analysis of the effect of the initial phase is necessary for full understanding of the proposed scheme. We hope to present it in the near future.

4. Experimental results

4.1. Measurements of image resolution and detection sensitivity

The lateral resolution of the system was measured with the USAF 1951 test target. Figure 7(a) shows the OCT image of the test target (4.27 mm × 4.47 mm). The line profile of the group 4 is presented with figure 7(b), which resolves at least a
Figure 9. WF-OCT images (8 mm × 6 mm) of a spring watch: (a) at surface and (b) 1.054 mm below the surface. (c) Photograph of the spring watch. The 524 OCT topograms were taken and presented together with (d). (e) 3D reconstructed spring watch. Volume size is 8 mm × 6 mm × 2.19 mm (X × Y × Z) corresponding to 640 × 480 × 524 pixels. A movie of the 3D rendering can be found in the supporting information, available at stacks.iop.org/MST/21/045503/mmedia.

35 μm line pair. By the classical Abbe resolution criterion, a theoretical lateral resolution of 3.8 μm is evaluated with a NA 0.13 single achromatic lens. However, it is entirely limited by the pixel size of the CCD imager.

The detection sensitivity was obtained by measuring the minimum detectable reflectivity [20]. Considering the full-well capacity (FWC) of the CCD pixels being 40,000, the theoretical sensitivity of 60 dB was calculated without averaging. With a 0.78% reflector as a sample, the OCT measurement was made and the OCT signal intensity at a certain pixel of the CCD was monitored. As figure 8 shows, the OCT signal had a background noise level of ~ −58 dB. One easy way of enhancing the sensitivity is increasing the image accumulation time. But this would adversely affect the high-speed 3D OCT imaging. Pixel binning [15, 21] is also effective to provide the enlarged FWC of the CCD.

4.2. 3D imaging results

To show the ultrahigh-speed 3D imaging performance of the proposed WF-OCT system, first, the internal structure of a spring watch was imaged. A 256 gray-scaled 3D structure of the spring watch was real-time imaged at a scan speed of 0.805 mm s⁻¹ (Doppler frequency of 2 kHz). The imaging volume was 8 mm × 6 mm × 2.19 mm (X, Y, Z), and the 3D data acquisition time was 2.7 s. Figures 9(a) and (b) show the OCT images of the spring watch taken at the top surface and at 1.054 mm below where a gear wheel was located, respectively. In figure 9(d), both tomograms were collocated to compare with the photograph of figure 9(c). By stacking a total of 524 OCT images taken with a depth step of 4.02 μm along the sample, a 3D image reconstruction was achieved, and the pseudo-rendered image, using the Amira software, is presented in figure 9(e).

As the second sample, a printed circuit assembly (PCA) of an electronic display was selected to show the feasibility of 3D micro-scaled structural imaging. A total of 24 tomograms (8 mm × 6 mm × 0.1 mm) were taken with a depth step of 4.02 μm; it took only 124 ms. Figure 10(a) shows a photograph of the PCA sample. The 3D reconstruction of the PCA is rendered in figure 10(b). To show the tomographic feature more clearly, the stacking of tomograms is separated into two parts. The stack of tomograms taken at the first half (from surface to ~56 μm) of the sample is shown in figure 10(c), and the other one taken at the second half (from ~60 μm to ~100 μm) is presented in figure 10(d). As the photograph shows, figure 10(a), the sample had a thin polymer coating on a printed circuit pattern and a resin drop was placed on the polymer film. In the first tomogram stack, figure 10(c), we can see the resin drop clearly (indicated with a white arrow). However, in the second stack, figure 10(d), we can see only the printed circuit pattern without being appreciably affected by the polymer film and the resin drop on it.

5. Conclusions

We developed the active lock-in wide-field OCT system that has the merit of ultra-high speed 3D image acquisition. A page wide interferogram of a time-domain bulk OCT interferometer was demodulated simultaneously with a 2D CCD array and by flashing the OCT light source according to the Doppler frequency of the OCT system. To come up with OCT Doppler frequency variation, an auxiliary laser interferometer sharing the reference arm with the OCT interferometer was utilized. With the auxiliary interferometer, the OCT light flashing could be actively synchronized with any variation in the OCT Doppler frequency. With a single one-way continuous axial scan, a 3D depth-resolved wide-field XY OCT image at a large area (8 mm × 6 mm) could be obtained. OCT imaging with several objects has been successfully performed at the ultrahigh rate limited by the scanning speed of the mechanical scanner not by the image capture speed of the CCD (200 Hz). Since only the synchronous triggering of the OCT light allows
the OCT signal demodulation in parallel, the proposed system does not need delicate manual manipulation or complicated signal processing but is robust to the scan speed irregularity. It is expected that the proposed technique would find applications in a variety of morphological and tomographical measuring fields that require fast and stable 3D measurements.

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