Voice coil based robust and miniature optical delay for multiple reference optical coherence tomography

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ABSTRACT

Multiple reference optical coherence tomography (MR-OCT) is a recently developed time-domain interferometric imaging platform, which promises to fit into robust, cost-effective designs that are virtually solid state. An optical delay is created by the reference mirror which is mounted on a piezo-electric transducer (PZT) and the key element of MR-OCT technology is the presence of a partial mirror in front of the reference mirror. However, the limited axial displacement range at higher scanning-frequencies are a limitation of a PZT-based optical delay. Moreover, PZT-based actuators require a relatively high operational voltage and are expensive. In this paper we present a voice coil actuator as an alternative to a PZT-based optical delay. Voice coil actuators are light in weight, inexpensive and offer other advantages such as zero hysteresis, low operational voltage and a long life. We demonstrate a voice coil actuator as a feasible alternative to PZT-based actuators for the purpose of creating an optical delay, which can provide fast and precise axial displacements at high scanning rates.

Keywords: *Optical coherence tomography, multiple reference optical coherence tomography, image processing, time-domain interferometry, biomedical optical imaging, optical interferometry, voice coil actuator, optical delay*

1. INTRODUCTION

Optical coherence tomography (OCT) is an emerging optical imaging technique for biomedical research and clinical medicine [1]. OCT has the potential to perform high-resolution, cross-sectional (2-D & 3-D) tomographic imaging in materials and biological tissues by measuring the echo-time delay and magnitude of backscattered light with the help of low coherence interferometry.

In conventional time domain (TD) OCT systems, depth scanning is achieved by modifying the relative optical path length of the reference path and the probe path. There are various techniques for varying the reference path length through the use of galvanometers [2, 3], moving-coil actuators, rapid scanning optical delay lines [4,5,6] and rotating polygons [7]. All of these techniques involve moving parts that which have to move a substantial distance and can have limited scan-speeds. There are solutions with no moving parts (for example acousto-optic scanning [8]), however these are costly, bulky and have significant problems relating to thermal control and associated thermal signal-to-noise ratios. Fiber-based OCT systems use fiber stretchers; however these can limit speed and introduce issues of polarization. Similarly, rotational diffraction gratings can run at high speed, however they are bulky and require very accurate alignment. Piezo devices can achieve high accuracy, however they exhibit non-linear operation and have limited ranges of axial displacement at higher scanning frequencies. Moreover, they require a relatively high operational voltage. We demonstrate the use of a focusing/tracking voice coil motor (VCM) as an alternative scanning solution for MR-OCT. Voice coil-based actuators are commonly used in the pick-up heads of compact disk players and offer numerous advantages over PZT actuators due to their low cost, light weight, long life and low operational voltage.

1.1 Multiple reference optical coherence tomography system (MR-OCT):

Multiple reference optical coherence tomography (MR-OCT) [9-10] is a recently developed miniature time-domain low coherence interferometric imaging platform, which promises to fit into robust, cost-effective designs which are virtually solid state (see Fig 1). The key element of MR-OCT is a multiple reference optical delay introduced by the reference mirror which is mounted on a VCM actuator and a partial mirror (PM), which causes light to be reflected multiple times between the partial mirror and the reference mirror. The resulting multiple reflection orders provide a systematic increase in the magnitude of each successive scan region and a corresponding increase in the beat frequency of the interference signals associated with the multiple orders.

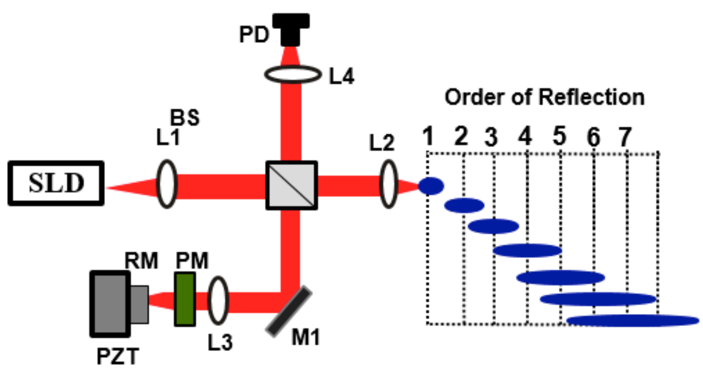

Fig. 1 Schematic of the MR-OCT system; scan segments (blue color) are displaced vertically in this illustration simply for clarity.

The detected MR-OCT signal (I_d) at the output of an interferometer can be expressed as:

$$I_d = I_{R\times n} + I_s + I_{PM} + 2\sqrt{I_{R\times n} \times I_s}\, e^{-4\ln(2)\left(\frac{\Delta l - nd}{L_c}\right)^2} \times \cos\left(\frac{4\pi}{\lambda_0}\Delta l - nd\right) \quad (1)$$

where Is is the sample arm intensity, I_{PM} is the reflected intensity from the partial mirror and represents the background signal, λ_0 is the central wavelength of the light source, L_c is the coherence length of the light source, n is the order-number, d is the separation between the reference mirror and the partial mirror and Δl is the optical path difference between the sample and the reference arms. The term $I_{R\times n}$ can be written as $(T^2\ (1-T)^{n-1}) \times I_R$ where I_R represents the input intensity to the reference arm and T represents the transmission ratio of the partial mirror and represents the reference arm intensity for each order n .

2. EXPERIMENTAL SETUP & METHODS

2.1 Voice coil based MR-OCT system:

A schematic of MR-OCT system used in this study is shown in Fig. 2. The light source is a broadband super luminescent diode (SLD, DenseLight, Singapore) with a central wavelength of 1300 nm and a spectral bandwidth of 56 nm which provides an axial resolution of ~13 µm. The light from SLD is coupled into a fiber-based Michelson interferometer via an optical isolator.

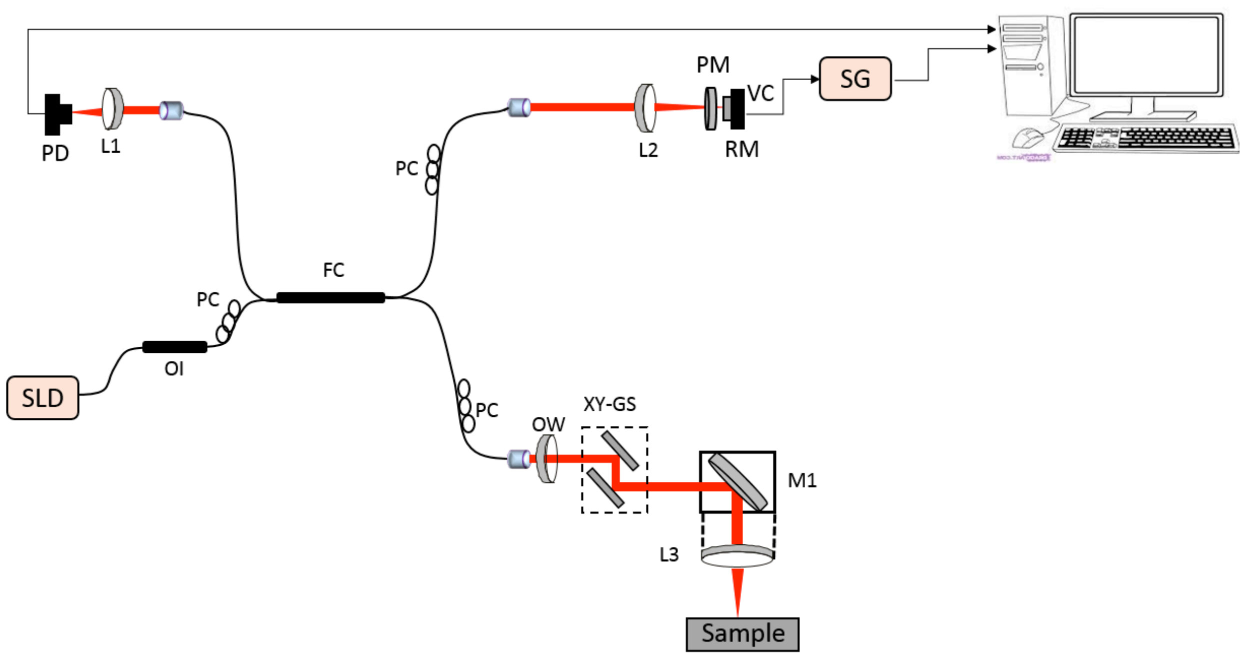

Fig. 2 Experimental setup of the MR-OCT system. SLD, superluminescent diode; OI-optical isolator; PC, polarization controller; L1-L3, Lenses; FC, fiber coupler; PM, partial mirror; RM, reference mirror; VC, voice coil; SG, signal generator; PD, photodetector; XY-GS, galvo scanner; M1;mirror.

In the reference arm, the light is delivered onto a scanning mirror. The depth scanning is achieved by VCM actuator (retrieved from SONY, CD-R/RW/DVD-ROM DRIVE UNIT, MODEL NO: CRX330E-DR) driven at a frequency of 400 Hz with a scan range of ~57 µm. A partial mirror (PM) is placed in front of the reference mirror with a separation distance of

~90 µm. This causes the light to be reflected back and forth multiple times between the partial mirror and the reference mirror. The sample beam is focused with an objective lens of focal length 50 mm which provides a lateral resolution of ~27 µm. The sample is scanned in the *x*-direction by a galvo mirror with a scan range of 3 mm.

A 2 × 2 optical fiber coupler recombines the light which is backscattered from the sample with that which is reflected from the reference mirror. This combined beam is routed to a photo detector (InGaAs) via an optical circulator. Furthermore the output of the photodetector is low-pass filtered in order to remove large (80%) reflection from the partial mirror. The analogue MR-OCT signal is digitized using a 12-bit A/D card (AlazarTech, ATS9440) and is recorded on a workstation.

2.2 MR-OCT processing:

Figure 3 depicts the flowchart for MR-OCT processing. As a first step of processing, the nonlinearity of the raw interferogram caused by the non-linear axial scanning of the VCM is corrected with an algorithm implemented using a pre-calculated look-up table by measuring the speed of the reference mirror. The scan time was mapped to the exact scan time for one A-scan. The raw interferogram is filtered using a polyphase filter bank which separates the fringes according to their fundamental frequencies. After the separation of the fringes according to their frequency, a Hilbert-transform is applied to the respective orders in order to obtain the envelope of the fringe signal.

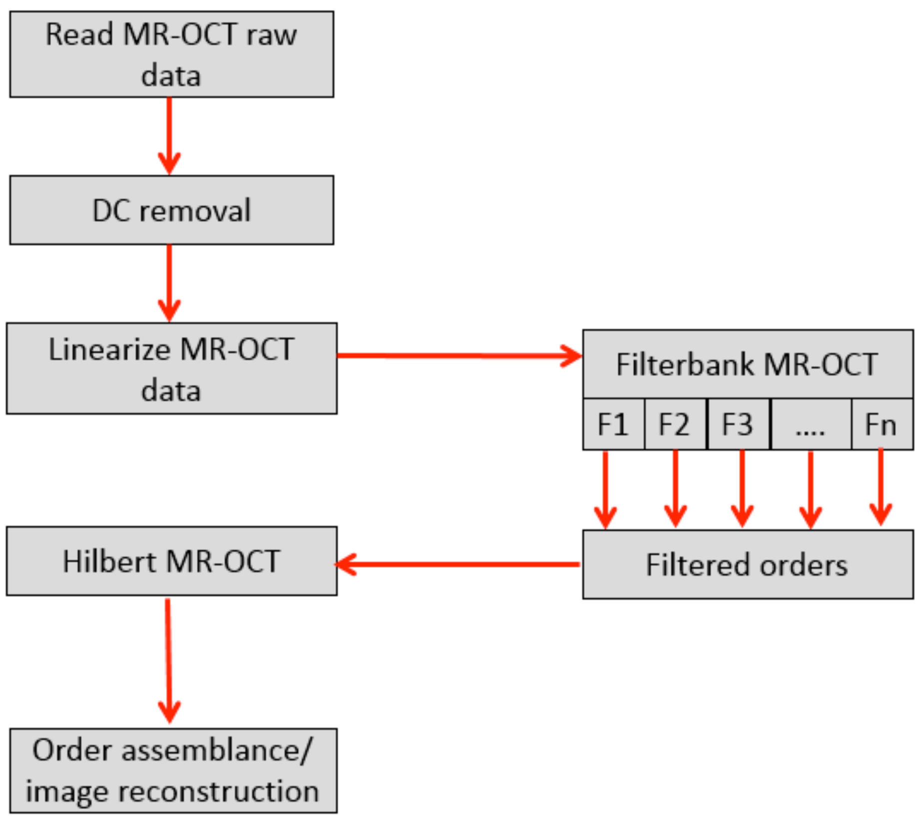

Fig. 3 Flowchart for MR-OCT processing.

Finally, scan segments corresponding to each of the MR-OCT orders are positioned according to the equation (2) at the actual depth position and stitched together by averaging the overlapping region.

$$dx = \left(\frac{S * sep}{R} + \frac{S}{2} \right) * n \tag{2}$$

where *S* denotes the number of samples, *sep* is the distance of the moving reference mirror to the partial mirror, *R* is the scan range and *n* corresponds to the orders (for e.g. *n*=1:10). In our experiments, the first 10 orders were used to reconstruct the MR-OCT signal with a total scan range of 1mm.

3. RESULTS & DISCUSSION

3.1 Mirror test for MR-OCT system:

A routine test of the MR-OCT system was performed by obtaining a data-set by scanning a sample mirror which is translated axially through the sample beam in 5 micron steps over a 1.2 mm range.

Fig. 4 Depth scans acquired as a sample mirror.

Firstly, the sample mirror is aligned with the output coupler surface (where a low frequency signal is observed). Next the sample mirror is moved 1.2 mm away from the system and hence the sample mirror is stepped away from the system in 5 micron steps. A single A-scan is captured at each step. A typical distance for the coupler-to-mirror spacing is 90 microns and the resulting set of data includes the interference signals from the first ten reflections. The recorded scans are linearized and the scan segments associated with each of the 10 frequencies corresponding to the 10 orders are separated by filtering. The scan segments are then aligned with respect to each other based on the distance between the coupler and VCM. Finally the aligned scan segments are normalized in amplitude and combined to give a single depth scan which is shown in Fig 4.

3.2 Phantom imaging with MR-OCT:

Figure 5(a) shows an MR-OCT image of a cover slide. The thickness of the slide is measured to be ~1 mm with a lateral span of 2 mm. Figure 5(b) shows an MR-OCT scan of a section of transparent tape on top of white paper. The layers of tape can be easily differentiated in the image.

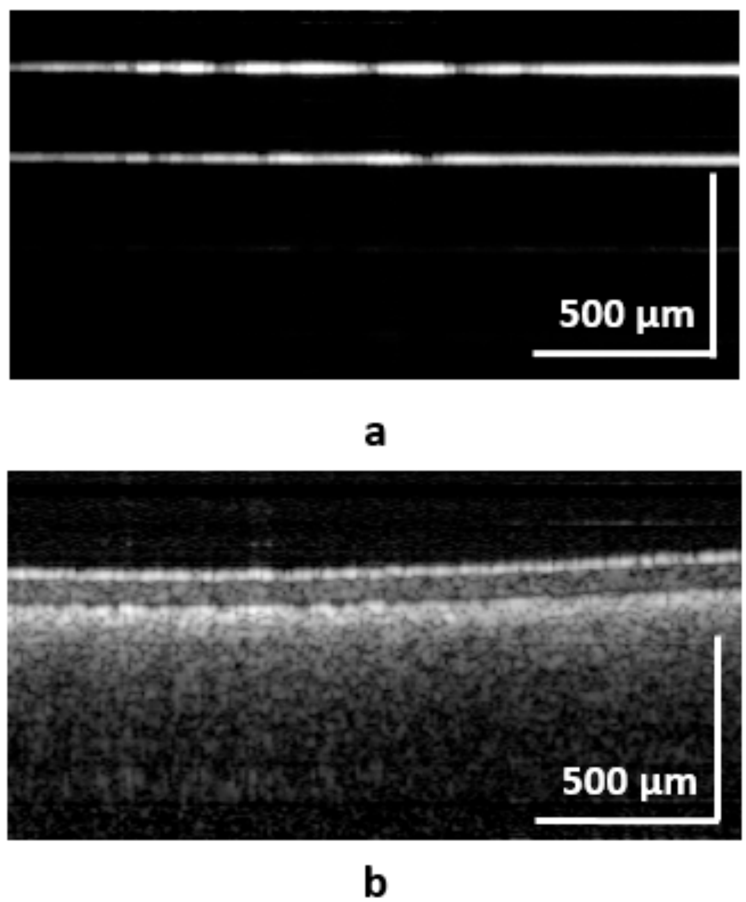

Figure 5: (a) MR-OCT image of a cover slide. (b) MR-OCT image of a layer of transparent tape on paper.

4. CONCLUSION

In this article, the feasibility of a voice coil-based optical delay for MR-OCT technology was presented. MR-OCT technology allows depth scans at multiple depths to be performed in parallel by simultaneously acquiring the scan in multiple segments using a design that is inherently miniature, robust, low cost and virtually solid-state. The operation of the system was demonstrated using two example targets, clearly showing the ability to distinguish the cross-sectional structure. These promising results demonstrate a voice coil as an alternative to PZT-based optical delay.

5. REFERENCES

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