A High Speed OCT System Developed at the CSIR National Laser Centre

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Abstract. Light-based techniques continue to gain momentum in different spheres of diagnostic and therapeutic applications due to their non-invasive, non-contact properties. One such technique is Optical Coherence tomography (OCT). Since first being reported by Huang in 1991, OCT has made significant strides in different fields such as dermatology, ophthalmology, polymer characterisation and biometrics. The type of OCT system employed can be a simple, cost effective solution or a complex, highly specific and fast system depending on the application. As part of a larger project, we have designed and built a high speed OCT system that can image a large surface area (25 by 25 mm) to a depth of 11 mm (sample dependant). Resultant 3-D images (512 x 512 x 2048 pixels) are acquired in less than 3 seconds. The heart of the system is a 200 kHz swept laser source and two-axis galvanometer based scanner. Signal acquisition is made possible through a high-speed analogue-to-digital converter capable of speeds greater than 1GS/s. This paper will give an overview of the system design and the specifications that have been obtained.

1. Introduction

OCT is a non-invasive, non-contact, optical imaging technique that is able to yield sub-surface morphology (2D or 3D) of scattering samples in situ and in real time. OCT is often described as the optical analogue to ultrasound and uses the technique of low coherence interferometry to compensate for the high speed of the backscattered light. The technique was was first demonstrated by Huang in 1991 [1] and later for a different configuration by Fercher [2]. Since then, it has been applied extensively to biomedical applications, especially ophthalmology, dermatology and cardiology [3-6]. Many other applications also exist in material science, artwork, biometrics etc. [7-10].

2. Basic theory

The OCT technique involves a broadband (low coherence length) light source, which is split between a sample and a reference mirror (reference path). When the difference between the distance travelled by the light for the sample and the reference paths is within the coherence length of the light source, then interference will occur at the detector. OCT measures the echo time delay and intensity of backscattered light.

The process starts by acquiring an A-scan as shown in figure 1, below. The A-scan provides information about the reflective or scattering properties of the sample as a function of depth at a fixed position (point) of the sample. The light source can be linearly scanned across a sample to obtain a cross-sectional image (B-scan), which is collection of successive A-scans. The collection of successive B-scans results in a volumetric image.

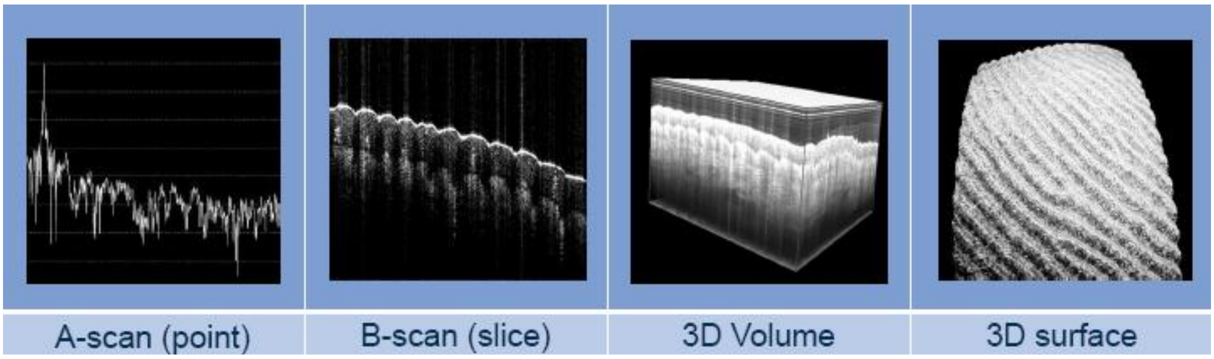

Figure 1. Imaging progression from an A-scan to a 3D surface image.

There are different configurations of OCT but all are based on the same principle. These configurations are Time Domain (TD) OCT and Fourier Domain (FD) OCT. TD OCT involves scanning the reference mirror back and forth to match different depths in the sample to within the coherence length of the light source. Fourier Domain (FD) uses a fixed reference mirror and measures the spectral response of the resultant interferogram. The interferogram is encoded in optical frequency space and undergoes a Fourier transform to yield the reflectivity profile of the sample. FD OCT can be further divided into Spectral Domain (SD) OCT and Swept Source (SS) OCT. Spectral Domain (SD) requires a broadband light source for illumination and separates the spectral components with a spectrometer. Swept Source (SS) OCT uses a light source which probes the sample with different optical frequencies sequentially (swept source). The power is then measured with a single photo detector.

OCT systems operate at different wavelengths (depending on the application) either in the infrared (800-900 nm) or in the near infrared (NIR) band (1250–1350 nm). The NIR wavelengths are preferable when imaging non-transparent tissue due to the better penetration depth. Ophthalmology is performed at 800-850 nm due to the transparent nature of the eye in this band. High-resolution applications require shorter wavelengths. Longer wavelengths are considered for samples with higher scattering properties.

3. System design

The design of an OCT system involves the design of the optical system (light source to detector) and the data acquisition system (detector to digital data/image). A few factors need to be considered when building an OCT system. These are briefly described below:

a. The type of OCT system is the first design choice. TD OCT is the simplest and easiest to implement but the moving reference mirror mechanism makes it slow. FD OCT systems are faster but implementation is more complicated with more computation required to obtain an OCT image. The SD OCT system is also known to suffer some signal to noise ratio (SNR) degradation that is not prominent in SS OCT systems. SD OCT systems are usually developed in the 800 nm band, due to the availability of high speed line scan cameras at these wavelengths but is unsuitable for skin tissue. SS OCT operates at 1.3 µm due to the available swept source light sources and uses a single photo detector. It has other advantages over the TD and SD configurations including lower noise and does not suffer from SNR drop-off, due to the narrow bandwidth of the light source.

b. The light source firstly depends on the choice of OCT system. The wavelength band of the chosen light source is an important specification and is determined by the application. The scan rate is also important when considering a SS OCT system.

c. The type of detector is dependent on the type of OCT system and application. The sensitivity, detection band and speed are important criteria. The resolution of the detector arrays in the SD OCT systems should also be considered. Low noise amplification usually accompanies the detector to improve the signal to noise ratio..

c. The Field of View (FOV) determines the area that is to be imaged. When building an OCT system, this is determined by the properties of the scan lens. The FOV also depends on the range of the scanning system (e.g. galvanometer).

d. Sensitivity is another parameter that has an effect on the contrast of the resultant images. The choice of photo-detector and digitisation electronics determines the sensitivity.

e. Resolution is dependent on the centre wavelength and other properties as described in the theory section.

f. Scan rate refers to the speed with which the 2D cross sections can be imaged. B-scan profiles of intensity versus depth are affected by the chosen configuration. For an SD OCT system, the scan rate is determined by the camera speed of the detection spectrometer whereas in SS OCT, it is determined by the sweep rate of the swept laser source and the speed of the scanning system. SS OCT systems are known to provide the highest scan rates. There is a tradeoff between the high scan rate and sensitivity. However fast scan rates are required for applications where motion artifacts affect the resultant images, such as in cardiovascular imaging and fingerprint acquisition etc.

g. The speed and resolution of the data acquisition system is important and is determined by the choice of electronic components (e.g. analogue to digital converter). The configuration of the data acquisition system may vary slightly depending on the type of OCT system and the target application.

4. Optical system design

The first design choice is the type of OCT system. Our requirement was to build a high speed OCT system to capture images of skin tissue within a few seconds. Based on the literature review, this could be achieved through a SS OCT system at 1.3 µm. A fiber-coupled, 200 kHz swept source laser (Thorlabs SL1310V1-20048) with a custom built Michelson interferometer with fibre coupled detector was used. The fiber coupled sample arm feeds into a large area scan lens, such that the light can be directed to the sample to be imaged. The reference arm is also fiber coupled and directed towards a mirror. This setup is shown in figure 2.

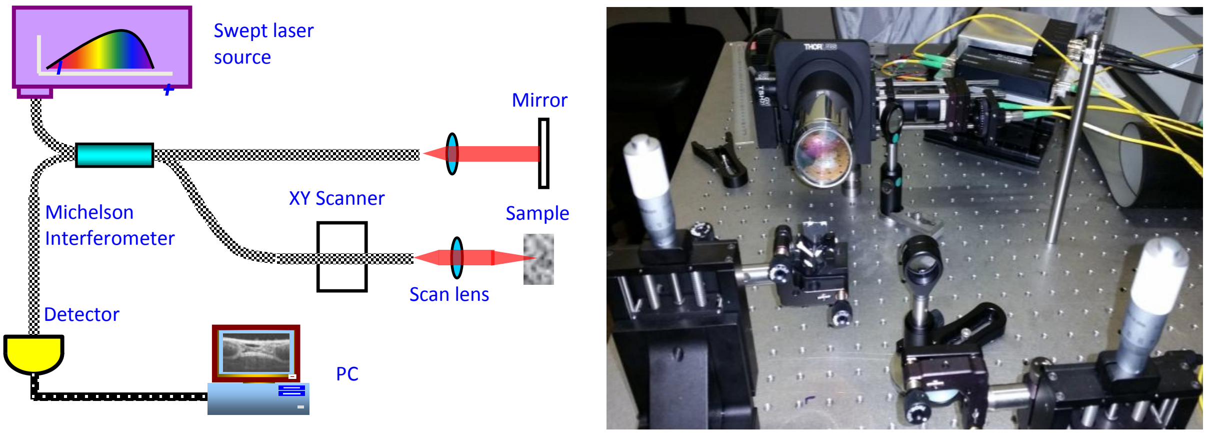

Figure 2. Optical layout of SS OCT system and a photograph of the initial test setup in the laboratory.

5. Data acquisition system design

Speed and resolution of the data acquisition are important when considering data capture in a SS OCT system. The main component is high-speed analogue to digital converter (ADC), which converts the detector signal to digital data for storage. A layout and interconnections between all the main components in the data acquisition system is given in figure 3. The system can be divided into three main sections: the PC, the Scanner and the Optical interface. The high speed PC houses the digital to analogue converter (DAC) card for the scanner control and synchronisation, the ADC card, which interfaces mainly with the laser and optical detector. The scanner includes the XY galvanometer and the power supplies and driver electronics. The optical interface includes the laser interface and the photodiode detector. The swept laser source provides two main signals i.e. the DAQ trigger and the DAQ k-clock. The rising edge of the digital DAQ trigger signal indicates the time for the next A-scan and the k-clock trigger, trigger the capture of samples within a single A-scan. As the laser sweeps in wavelength, the k-clock trigger rising edge indicates the time at which the laser has swept to the next wavelength increment. The bottom right plot in figure 3 shows the laser output signals involved. The A-scan trigger (DAQ trigger) occurs at 200 kHz and K-clock trigger occurs at ~1 GHz.

The framestart signal is generated by the DAC and triggers the capture of successive B-scans. The top right plot in figure 3 indicates how the fast (X) and slow (Y) axes are controlled to rasterise the sample surface. The signals are generated by the DAC and synchronised in software. The framestart signal is delayed to compensate for the change in direction of the fast axis and to allow for both axes to stabilize into a linear motion. The fast axis is scanned at 180 Hz.

The high bandwidth signal from the detector is captured by the analogue to digital card (ChA) which can sample at rates up to 1.8 GHz. The ADC is optimised for high-speed data capture and uses an Auto-DMA mode, which captures data continuously to onboard dual port memory and simultaneously streams the acquired data to the PC memory at a slower rate. Capturing data in a SS OCT system also involves some data processing, in particular, an inverse Fast Fourier Transform (FFT) is required. The ADC card used has a field programmable gate array (FPGA) which allows the reali time computation of the FFTs This is done via the software interface.

These two features along with the ability to be triggered externally for both A- and B-scans ensure that all large volumetric scans can be captured in under 3 seconds without any data loss. At 12-bit resolution, the resultant data file size is ~1 GB. The software interface, which generates the scanner control signals and synchronises them with the data capture, is coded in LabVIEW.

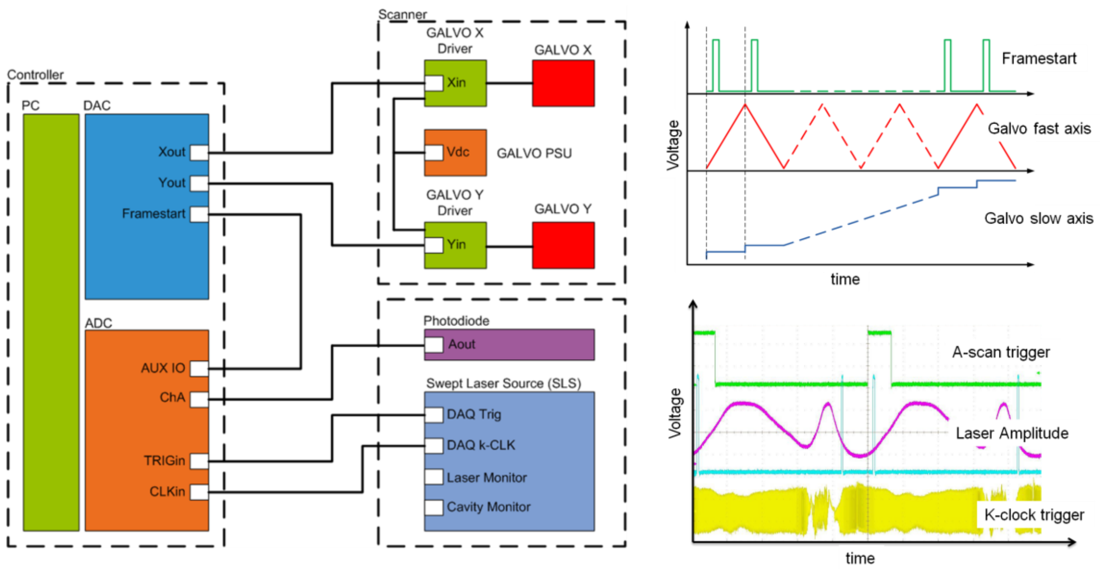

Figure 3. Schematic layout of the data acquisition system and the different timing and scanner control signals.

6. Mechanical system design

The prototype system was integrated into a custom-built enclosure after initial tests were performed in a lab setup. The enclosure was fitted with wheels for easy mobility. Figure 4 below, shows a schematic of the system layout.

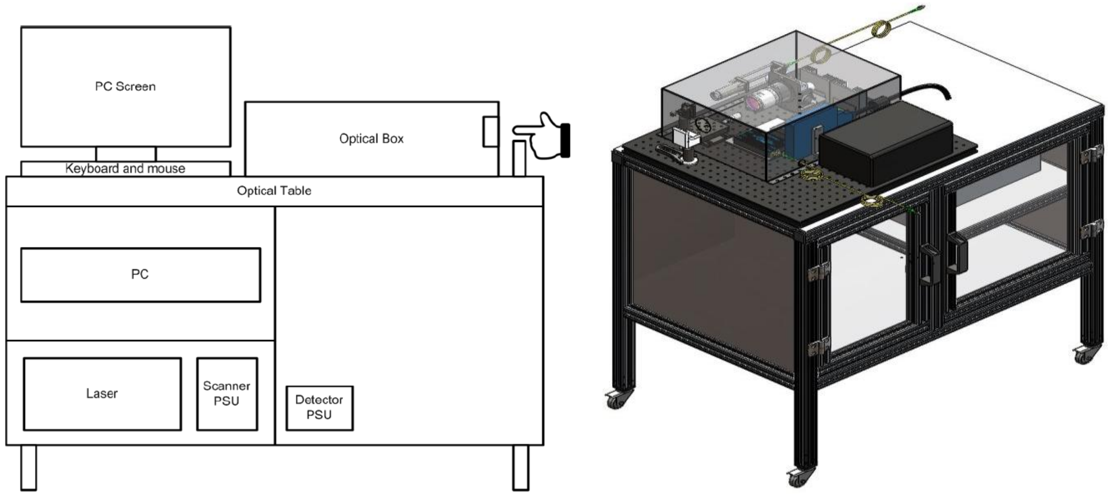

Figure 4. A schematic layout and 3D model of the integrated system in the trolley enclosure.

The top of the trolley has an optical breadboard on which the optical, opto-mechanical components, XY scanner and some electronics are fitted and housed in a shielded box. The 'optical box 'shields the components against dust and electromagnetic interference and has a port for the electrical and optical fiber connections and a port for the laser output beam. The swept source laser and power supplies for the scanner and detector are installed on the lower level. The PC, which is connected to the laser source and optical box, is installed on the second level with the mouse, PC screen and keyboard on top, next to the optical box.

7. System specifications

The system specifications are summarised in table 1 below and a photograph of the system built into the mechanical enclosure is shown in figure 5.

Figure 5. A photograph of the system.

Table 1. Summary of system specifications.

OCT system type	Swept source
Laser scan rate	200 kHz
Centre wavelength	1310 nm
Bandwidth	104 nm
Max. image area	25 mm x 25 mm
Max. image depth	11 mm
Area resolution	512 x 512 pixels
Depth resolution	2048 pixels
ADC Sampling rate	1 GHz
ADC voltage range	+/- 400 mV
B-scan rate	180 Hz
3D image capture time	2.8 s
File size (12 bit)	1 GB
Data transfer rate	2500 Mb/s

8. Conclusions

A swept laser source OCT system has been built and tested at the CSIR National Laser Centre (NLC), which involved the design and integration of an optical system as well as a high-speed data acquisition and control system. The prototype was constructed and installed into a mobile enclosure. Initial results have indicated that the system provides valid 3D image data, at adequate resolutions, for numerous applications. Our partners at CSIR Modelling and Digital Science (MDS), have confirmed that the speed of the data acquisition system is comparable with other systems available worldwide [11,12] for biometric applications (3D fingerprint acquisition) where larger areas and higher speeds are required. Research is ongoing in this application area and a future paper will provide a description of the system test results.

Acknowledgments

The authors would like to acknowledge the Department of Science and Technology (DST) for funding this joint project between the CSIR NLC and CSIR MDS. The authors would also like to acknowledge the technical assistance provided by Gary King, who assisted with the laboratory setup and Corrie van der Westhuizen, who designed and built the mechanical enclosure and trolley.

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