OPTICAL COHERENCE TOMOGRAPHY: SIGNAL PROCESSING AND ALGORITHM
What is OCT?

- Medical imaging modality with 1-10 μm resolutions and 1-2 mm penetration depths
- High-resolution, sub-surface non-invasive or minimally invasive internal body imaging technique for structural and quantitative imaging
- Signal processing intensive suited for embedded implementations using digital signal processors (DSP) and system-on-chip (SoC) application processors
- Performance given in cycles per scanline and total number of scanlines that can be processed per second
- Enables cross-sectional imaging of tissue microstructure in situ and in real time
Principle and Instrumentation:

- Based on the principle of low coherence interferometry
- By stacking the axial scans in X and/or Y directions, two or three dimensional imaging.
- Imaging is performed by measuring the echo time delay and intensity of back-reflected or backscattered light.
- Performed fiber-optically using delivery devices such as handheld probes, endoscopes, catheters, laparoscopes, and needles.
- Measurements are performed using a Michelson interferometer with a low coherence length light source.
A standard Michelson Interferometer with a low-coherence light source is used. Incoming broadband beam of light is split into the reference path and the sample path. After back-reflection from the reference mirror and the multiple layers of the sample, respectively, they are recombined.
Thus an interference signal is formed.

Due to broadband nature of light, interference of the optical fields occur only when the path lengths of the reference and the sample arm are matched to within the coherence length of the light.

This interference signal carries information about the sample at a depth determined by the reference path length.
Steps in OCT System processing

- Signal processing intensive
- Real-time data is to be acquired
- Acquired data is processed to extract meaningful information
- and then the information is displayed
Sample arm of the interferometer illuminates the light on the tissue and collects the backscattered light.
Time-domain OCT (TD-OCT)

- Reference arm of the interferometer has a reference path delay which is scanned as a function of time.
- Optical interference between the light from the sample and reference arms occurs only when the optical delays match to within the coherence length of the light source.
- Photo-detector detects the average intensity over the range of frequencies.
- The detected signal consists of a DC term and an interference term that contains the sample information.
- Dual balanced approach is used to subtract a portion of source signal through the use of a second photo-detector before digitizing the signal is used to remove the DC term partially.
Spectral-domain OCT (SD-OCT)

- A broadband-source of light with short temporal coherence length is used as an input to the interferometer.
- Reference mirror position is fixed.
Spectral-domain OCT (SD-OCT)

- Echoes of light are obtained by Fourier transforming the interference spectrum.
- Depth information is obtained by measuring the spectral density in the detection arm using a spectrometer, where the interference beam is dispersed by a diffraction grating and the individual wavelength components are detected by an array detector.
- The path difference remains fixed and is assumed to be zero without loss of generality.
Advantage of SD-OCT over TD-OCT

- Permits faster acquisition of the entire depth profile (A-scans)
- Video-rate imaging is possible
- High-speed acquisition without any moving parts minimizes any distortion in the OCT images due to motion in the sample
- Theoretical signal-to-noise (SNR) ratio is independent of the spectral bandwidth of the light source leading to increase in axial resolution
Swept Source Systems (SS-OCT)

- A frequency-swept laser or a tunable laser with just a single detector is used to obtain the spectrogram.
Swept Source Systems (SS-OCT)

- Require rapid tunable, narrow line-width lasers, which use high-speed analog-to-digital (A/D) converters and single-point detectors.
- The sample of received spectrum is probed with narrow band but frequency varying source.
- Also the sample is probed with chirp like signal source and the received signal is reflections from the reference and from the samples.
- After data capturing the operations are same as SD-OCT.
A dual-balanced detection is used to remove the DC before digitization.

Thus full dynamic range can be used to capture the interference signal.
Background Subtraction

- To eliminate the reference power term, the reference spectrum from only the reference arm is detected and subtracted from the interference spectrum.
- The reference spectrum is acquired at the beginning of every image acquisition to account for fluctuations in the source between measurements.
- From the acquired data derive the reference spectrum since the interference is usually high frequency fringes, whereas, the background term has low frequency components.
- In swept source systems, using dual-balanced photo-detectors allows this subtraction in analog domain.
In SD-OCT systems, spectrometers measure optical intensity as a function of wavelength.

In order to apply the fast Fourier transform (FFT) reconstructing the axial scan as a function of depth, the spectrum should be evenly sampled in k-space.

Therefore, the spectrometer output must be transformed from the wavelength to the frequency space.
Image Formation (FFT)

- The basic operation to get the depth resolved A-scan from the interference fringes.
- The structural image is obtained by taking the magnitude of the complex FFT output.
- Each FFT creates a particular A-scan.
- By moving the galvanometer in x direction, the successive A-scan line is created, which is stacked together to create a B mode image.
- By moving the galvanometer in both x-y direction, a full 3D volume can be generated.
Two dimensional OCT images are typically represented using a density plot.
The horizontal axis typically corresponds to the direction of transverse scanning and the vertical axis corresponds to the scanning depth.
A gray level is plotted at a particular pixel on an image corresponding to the magnitude of the depth profile at a particular depth and transverse scanning position.
Pixel intensity range is compressed using the logarithmic non-linearity before displaying it.
Image Enhancement

- Speckle noise that arises from the interference between coherent waves backscattered from nearby scatters in a sample is the dominating source of noise in OCT images.
- Non-linear direction preserving digital filters such as mean and median filters are used to improve the image quality.
- Simple signal averaging over the same line can also be used to improve the signal-to-noise ratio of the data collected at the cost of reduced frame rate.
- A secondary camera is sometimes used to track involuntary movements and control the data acquisition in a closed loop manner.
Dispersion Compensation

- The refractive index of the biological tissues is, in general, frequency dependent slowing down certain optical frequencies to a greater extent than others, therefore, dispersing the light.
- Dispersion correction can take place both in the hardware and the software.
- As the sample being imaged itself could also be dispersive, an automated numerical method of dispersion compensation is desirable.
Benchmarking of the key signal processing algorithms needed to produce a B-mode image was done on Texas Instruments’ C64x+ DSP architecture.

TI has several variations of processors based on C64x+ architecture.

These devices allow development of OCT systems at a fractional power compared to x86 or graphics processing unit (GPU) based units while maintaining the same programmability feature.
Within limits of processing capabilities, the same device can be used to perform various modes of operations like B-mode imaging, Doppler, polarization sensitive, etc.

Due to programmability, the same processing unit used for main signal chain can be utilized for calibration and different estimation algorithms needed to identify system parameters.

Due to smaller footprint, DSP-based systems allow the development of smaller, low power, low cost as well as battery-operated portable systems.
Basic Introduction on OCT Algorithms

- Using TI’s Embedded Processor Software Toolkit for Medical Imaging provides optimized functions to implement such a signal processing chain on DSPs based on the C64x+ architecture.
- TI has several variations of processors based on C64x+ architecture.
- Figure shows the basic signal processing chain needed to create a structural image from the recorded interference signal.
Background Subtraction

- A simple operation where the background is subtracted from the acquired data
- This subtraction takes care of the DC component in the signal that is due to the reflectance from the reference arm
- Additional variations due to fixed pattern noise in the line scan camera and variations in power spectral densities of the source can also be suppressed by this method
In SS-OCT, the frequency sweeping is usually non-linear in frequency (or k-space).

In SD-OCT, spectrometers are used that measure optical intensity as a function of wavelength. The signal obtained is non-equidistant in frequency (or k) space.
Resampling

- In either of the systems, the captured information is not linearly spaced in frequency.
- A re-sampling technique is usually employed to resample the recorded discrete intensities from the acquired domain to linear frequency domain.
- The cubic spline interpolation algorithm is used as defined in to perform the re-sampling function.
After resampling, the data is linear in the k-space and an FFT is performed to reconstruct the axial scan as a function of depth.

The MED-STK has several variations of the FFT available from the TI DSPLib.

The routines use 32 bit internal precision math operations with 16-bit twiddle factors and only allows power of 2 FFT sizes.

For the sizes of FFT used in OCT with 16-bit input, there is no possibility of internal saturation.
The 16-bit output is derived using your programmable right shift value

- Magnitude Computation
- Log Compression
A DSP-based software implementation of these OCT algorithms consists of well defined APIs.

For all the OCT algorithms through the API all the physical parameters related to the image of interest such as number of scanlines, number of samplers per scanline, number of frames, etc should be specified.

Specific algorithms that have additional parameters should also be specified.
Flexibility

- The DSP-based OCT algorithms should be flexible in terms of having the ability to operate in different modes.
- The same DSP used for the main signal chain can be utilized for calibration and different estimation algorithms needed to identify system parameters like background signal, the re-sampling points, the phase corrections for dispersion compensation, etc.
- These parameters are either pre-computed during calibration or computed automatically before the image acquisition process.
The implementation should be highly efficient so that minimum DSP CPU bandwidth is consumed for these algorithms, allowing more space for future OCT algorithms to be implemented.
The I/O bandwidth requirements for CPUs to access all the necessary data is algorithm dependent to a certain extent.

In the resampling algorithms, eight lines of data have to be accessed simultaneously for the efficient implementation of the algorithm.

The effect of cache on benchmarking depends on memory organization and system function partitioning.

All of the benchmarking provided here is done on a TMS320C6455 device.
Precesion Requirement

- The system will suffer from poor images if the precisions used throughout the system are not sufficient.
- If more than necessary precision is used, that will unnecessarily increase the cycle count and reduce the number of scanlines that can be processed through the system.
- The APIs for 16-bit input and output have been optimized except for the compression module, which outputs 8-bit data for visualization.
- Since the analog to digital converter samples the interference data with 10-14 bit precision, 16 bit is sufficient for high-quality image production for this application.
Clinical Applications

- As a noninvasive biomedical imaging modality that enables cross-sectional visualization of tissue microstructures in vivo.
- Architectural morphology to be visualized in situ and in real time.
- Enables imaging of structures in which biopsy would be hazardous or impossible, and promise to reduce the sampling errors associated with excisional biopsy.
Clinical Applications

- Translated from bench to various clinical applications including ophthalmology, cardiology, gastroenterology, dermatology, dentistry, urology, gynecology, among others.
- Due to programmability, the same processing unit used for main signal chain can be utilized for calibration and different estimation algorithms needed to identify system parameters.
- The most developed clinical OCT applications are those focusing on ophthalmic, cardiovascular, and oncologic imaging.
THANK YOU

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