**1. Optical coherence tomography (60%)**

a) Draw a diagram of a typical time-domain optical coherence tomography (OCT) system, label the major components, and briefly explain their functions.

b) OCT techniques were based on low time-coherence interferometry. Give one example of light sources used in OCT system. What is the center wavelength 0 and spectral bandwidth  of this light source? Explain how you will use 0 and  to calculate the axial resolution of the OCT system.

c) What are the major differences between Frequency-domain OCT (FD-OCT) and Time-domain OCT (TD-OCT)? What are the key advantages of FD-OCT over TD-OCT?

Ans:

Part (a)

Beam Splitter

Light Source

Mirror

Detector/Reconstruction

Depth Scan

Z Direction

Lateral Scan

X-Y axis

X-Y Direction

Z axis

Light Source:

Any low coherence light source and the selection depends on the application. For some endoscopic, this can be a fiber optic, and for others this can be a wideband LED or other low-coherent light source. This provides the light that is the source for our interferometric-like system. The light sources are selected for their wavelength, bandwidth, power, and stability. For example to satisfy the equation below:

Text

Description automatically generated with medium confidence

We need to solve for “dz” for the specific sample that we are measuring. Which means that we need to pick lambda, our wavelength, and design a delta lambda( the spectral width) to correspond correctly for our system. ( Some examples are SLD, LED or super fluorescence light sources with typically coherent power in the range of 40mW to 100mW)

Mirror

The Mirror provides the path for the reference beam so that the beam can be offset from the path of light that is used to stimulate our sample. In a time-domain system, the movement of the mirror acts as our depth displacement that will allow us the ability to sample data in the X-Y plane. Here again we need to make the range of motion of our system for “dz” that we selected our light source for.

Beam Splitter

The beam splitter must deliver some fraction of the energy to both our reference and our target and allow them to recombine as they head to the detector. It is easier to see this high-level function in the generic example of a fiber-optic OCT, where a fiber coupler( similar to an RF coupler) is used to supply a portion of light to the reference and a portion to the sample, but then on the return pass allows both to go thru with their full power.

Sample

At the sample we need to have a lateral beam scanning assembly to get our planar information. So, while the axial depth depends more on the light characteristics for resolution, the lateral resolution and definition relies more on the traditional optics criteria like Abbe’s equation which considers numerical aperture for resolving power.

Detector/Reconstruction

The detector can be of the variety of a single photon detector, like a PIN or a CCD. In either case we need to account for the photodiode or detectors responsivity across the wavelength that we designed our system. Below is an example of a spec from a OCT detector from Thor Labs.

Chart, line chart

Description automatically generated

Part (b)

One example of a light source in an OCT system is show below in the NIR range

Diagram

Description automatically generated

Here there are low absorption for water and Lipid. So , calculating gives us the best way of how we use the wavelength and spectral bandwidth to determine our resolution. In general, if we want higher resolution we need to use a smaller lambda and more bandwidth.

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% Descr:

% Calculate axial resolution of OCT system

%---------------------------------------------------------------------

lambda = 900e-9; % This is nm for NIR light source

spectral\_bw = 40e-9 % Full widht half maximum ( in nm)

dz = (2 \*log(2)\*(lambda)^2)/(pi\*spectral\_bw);

dz = 40 nm resolution

Part ( c)

The major differences of the time domain and the Fourier domain is that in the time domain our resolution is part of the envelope of our pulsed wave. Therefore we need a low coherence light source as the shape of our pulses light, our bandwidth provides us with our axial resolution information. Now in a Fourier based system, the bandwidth of our received interfered light has to be Fourier transformed to generate our “peaks of interest” , and here those peaks in the Fourier domain have a bin width that now corresponds to the axial resolution of what we can resolve.

A key advantage of a Fourier-domain OCT system over a time-domain is that for the axial resolution we do not need to sweep that direction with discrete motion of our mirror. We can replicate the equivalent time-domain axial resolution with Fourier domain techniques by either diffraction grating the combined interference of both the reference and sampled light source or by sweeping a narrow beam of light at the original low-coherent light source. As a result of this difference in how we resolve in the axial resolution, we can make the FD system have a smaller form factor for the scanning mirror reference, which can translate into a power, and parts savings in the construction of a real system. Also, if we opt for a FD system, it may be possible with the correct selection of bandwidth and operating frequency to get more range of our axial resolution that we could get with our reference mirror movement. This of course could make the FD system more practical and offer a wider range of products from one design.

**2. Photoacoustic tomography (20%)**

Describe the basic principle of the photoacoustic tomography.

Ans:

In a similar way to one-photon and two-photon microscopy where the radiative relaxation from a higher energy level to a lower energy level causes the system to have fluorescence , the photoacoustic effect causes a dissipation of heat from the system. Because photoacoustic takes into account the scattering of tissue, it can penetrate deeper than a confocal single or dual photon microscopy. The excitation of the tissue causes a volume expansion where the pressure of the wave propagation is mathematically proportional to an absorption coefficient and the local optical fluence.

Now, having briefly discussed the photoacoustic effect as a physical phenomenon the basic components of photoacoustic compute tomography(PAT) are a laser to illuminate, typically a short-pulse laser for a good wideband PA signal, a wideband ultrasonic transducer or transducer array for signal detection, and like many biomedical computational systems a DAC, and computer system for reconstruction. Of course for a PAT the transmitter and receiver should be tuned for the same ranges.

Finally, for PAT there are two strategies for computation, forward and reverse processing. In a forward system, one has a model of expected behavior and then takes measurements from the system. Here those measurements would consist of ultrasonic transducer measurements. The process is iterated until the difference from the forward is within some epsilon of the predicted. Now , for a reverse computational method, we do not have enough measurements to characterize all the hidden values, so typically we run some optimization techniques that involve trying to determine how to extrapolate and underdetermined system. There are many such techniques in literature with a gradient descent and some regularization terms to help constrain the system as examples.

**3. Diffuse optical tomography (20%)**

Describe a potential clinical application of diffuse optical tomography.

Ans:

One possible clinical application of diffuse optical tomography(DOT) is in functional brain imaging. When imaging the brain, the working assumption is that increases in Hb02 is proportional to brain activity. Owing to the greater temporal resolution of DOT as compared to functional MRI(fMRI), a clinical application could be for the subject to perform some tasks as then DOT would give a good resolution of where the activity in the brain is occurring with good temporal resolution, essentially giving you a one-to-one marker with the activity to the area of the brain that this is occurring. While fMRI can give more spatial resolution as to where exactly the activity is occurring, fMRI does not have the same temporal resolution as DOT.

So, a scenario then with DOT as applied to functional brain imaging, it could be used to monitor hemorrhaging or other time-dependent events with good resolution. So perhaps after a surgery DOT can be used as a post-surgical check , with an observation period to make sure that whatever procedure occurred has no anomalies.

Another closely related clinical application for DOT functional brain imaging could be to monitor epilepsy episodes and to help diagnose that ailment. In a similar way to looking at hemorrhaging , the assumption is that an increase in Hb02 pertains to an increase in activity or an event taking place.