Optical Coherence Tomography

For the Proseminar Informatik in der Medizin

Author: Lorenz Diener
Advisor: Yaokun Zhang

Medizingruppe
Fakultät für Informatik

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1 Introduction

In the following text, I will give a brief introduction to an imaging method known as Optical Coherence Tomography and the principle behind it, low coherence interferometry. I will offer a comparison to other imaging techniques and introduce different techniques of visualizing the acquired data as well as common applications, and finally present an outlook into OCT research.

1.1 What is OCT?

Optical Coherence Tomography (OCT) is an optical imaging method with medium penetration and high resolution primarily used in medicine. It has the potential to create live cross-sectional images even of non-transparent tissue at depths of up to 3 millimeters [FD08, p. 11] at a resolution of little more than a micrometer, with frame rates of several frames per second. This is achieved by using interferometry to measure optical echoes, a technique which will be explained in detail in chapter 2. [Bop03]

1.2 Comparison to other imaging techniques

Optical Coherence Tomography has much in common with two other imaging techniques, filling the space between them, in a way: Ultrasound and Confocal Microscopy. [FD08, p. 2]

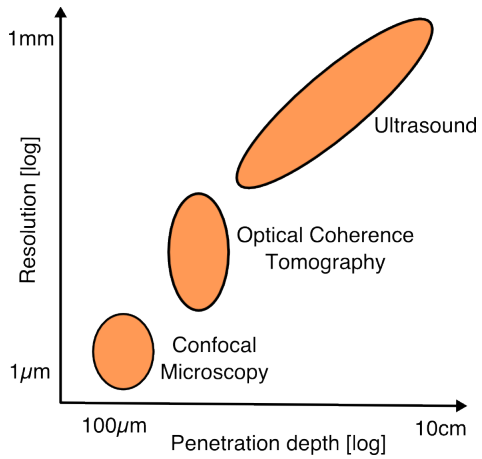

Figure 1: Resolution and penetration of imaging techniques. [FD08, p. 3]

Confocal microscopy is an optical imaging method with high resolution, approaching 1 micrometer, limited by the diffraction of light. The penetration, however, due to optical scattering, is very poor. In most biological samples, only a few hundred micrometers of depth are achievable, which makes confocal microscopy unsuitable for applications where significant imaging depth is required. [FD08, p. 3]

Ultrasound, on the other hand, can provide great imaging depths of up to around 10 centimeters, due to the low attenuation of sound waves at frequencies typically used in clinical applications. However, these frequencies (Between 3MHz and 40MHz) limit the resolution that can be achieved to around 0.1mm to 1mm. Higher frequencies of around 100MHz have been used to achieve resolutions of 15 to 20 micrometers, but the strong attenuation of sound waves at those frequencies in biological tissue limits the depth to about 15 millimeters in that case. [FD08, p. 3]

Optical coherence tomography fills the gap between these two imaging techniques. It is an optical imaging method, with resolutions limited by the bandwidth of the light source used - typically, around 1 micrometer to 15 micrometers - and a penetration depth of around 2-3mm, better in transparent tissue. Furthermore, as OCT is an optical method, it can easily be integrated with endoscopes, catheters or similar instruments, providing for simple in-body 3D tissue imaging. [FD08, p. 4]

2 Principle

Optical Coherence Tomography can essentially be thought of as a sort of "Ultrasound with light". In ultrasound imaging, sound echos are measured, while OCT measures the echoes of back-scattered light after passing through a sample. [FD08, p. 1]

In ultrasound, echoes are measured by measuring the time delay of a generated sound wave. In OCT, because of the high speed of light, this is impractical - direct electronic measurement of time differences of mere femtoseconds are too complex, so an alternative method of measuring the optical echoes is used. [FD08, p. 4]

2.1 Low-Coherence Interferometry

In low-coherence interferometry, an interferometer is used with a broadband (white) light source. The beam of light from the source is split into two at a half mirror, which creates a measurement and a reference path. The light is then reflected, by the mirror in the reference arm and the sample in the measurement arm, and recombined to create interference before it hits a detector, usually a photodiode, measuring the field strength of the interfering beams of light. Figure 2 below illustrates this setup. [FD08, p. 8]

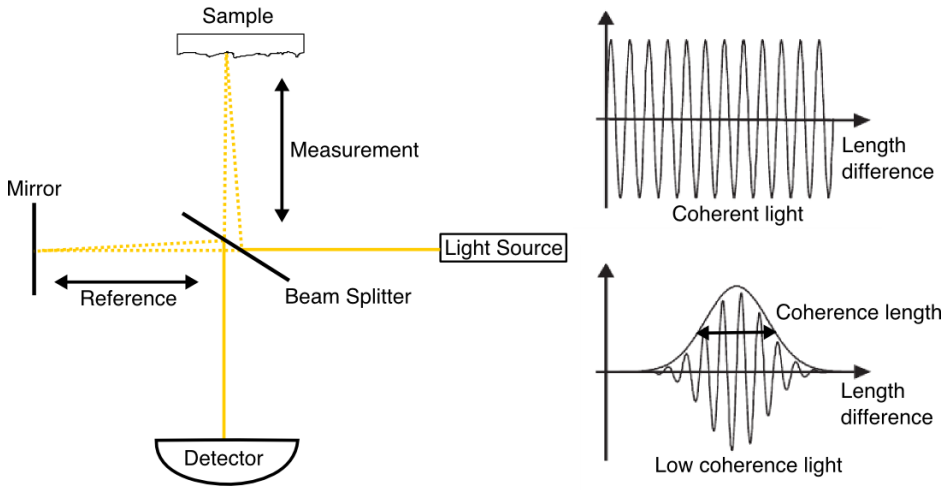

Figure 2: Principle of interferometry. [FD08, p. 8]

When used with a monochromatic light source, it would be hard to tell anything from the resulting signal. The light source used here, however, has a short coherence length. The coherence length is the maximum length after which the phase of light is still predictable, and thus, the maximum length after which interference can still be observed. It is inversely proportional to the width of the lights spectrum.

Since the spectrum of the light used in low coherence interferometry is broad, interference is only be observed when the lengths of the measurement and reference arm are matched to within the small coherence length of that light, allowing for very good axial resolution. [FD08, p. 7]

2.2 Time-Domain OCT

Based on low coherence interferometry, it is possible to measure the amount of light reflected by the sample in a specific depth by translating the reference arms mirror in the direction of the reference path while measuring, which is the principle used in *Time-Domain (TD) OCT*. The signal giving the reflectivity is, sampled over time, as only light traveling a specific distance creates interference in the detector due to the small coherence length. [FD08, p. 8]

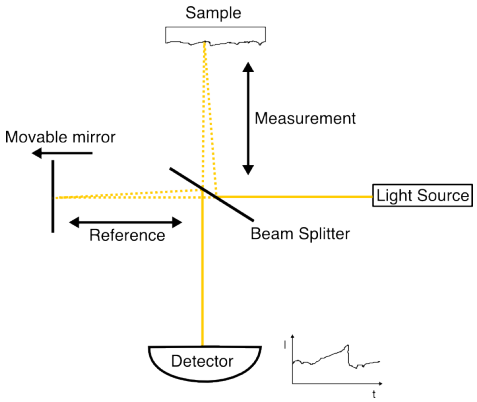

Figure 3: Principle of TD-OCT.

2.3 Frequency-Domain OCT

While the time-domain approach can be used to create 1D or even 2D cross-sections of samples, translating the mirror and then scanning takes too much time to image big areas of the sample in real time. *Frequency-Domain (FD) OCT* solves this problem. It makes use of the fact that a signal is fully defined not only by how its value changes over time, but also by its spectral information - the makeup of the signal separated by frequency.

Thus, the reflectivity of the sample can be measured for all depths at once by measuring the interference not, as before, in the time-, but in the frequency domain and then applying the so-called Fourier transform to get from the spectrum information back to the time domain, getting the same information about the echos magnitude and delay as with TD-OCT. [FD08, p.30-31]

Using these techniques, acquisition rates upwards of 20000 scans per second with good resolution (Compared to around 4000 scans per second in very fast TD-OCT systems, which sacrifice some resolution) become possible, enabling the scanning of big areas of tissue in real time. [WBG+04]

There are two different ways of acquiring this spectrum information: *Spectral/Fourier domain OCT* and *Swept-Source OCT*.

2.3.1 Spectral/Fourier domain OCT

In spectral/Fourier domain OCT, instead of using a single photodetector, the interfering light is separated into different beams according to wavelength by a dispersive element such as a prism, and then detected using a linear detector.

This method has an additional advantage over techniques using a single photodetector: Since less non-interfering light reaches each part of the detector array, the signal-to-noise ratio improves by several hundredfold. [dBCP+03]

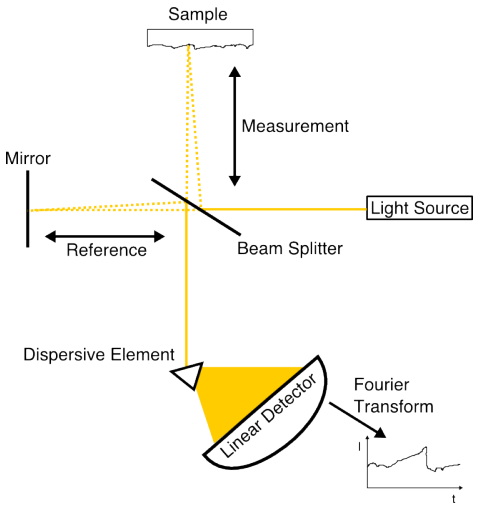

Figure 4: Principle of spectral FD-OCT.

2.3.2 Swept-source frequency domain OCT

In swept-source frequency domain OCT, the frequency information is not, as in spectral FD-OCT, extracted by using spectroscopy. Instead, it is encoded

in time by sweeping the frequency of a light source with narrow spectrum (e.g. a Laser) in time. The resulting interference is then detected with a single photodetector over the span of one sweep, corrected for sweep nonlinearities, and Fourier transformed to get the optical echo information. [FD08, p. 35]

The advantage of the swept-source method over using a linear detector array such as a typically silicon-based line-scan camera is that light in wavelength ranges of around 1000nm to 1300nm can be used, which are well-suited for imaging scattering tissues, since they are less attenuated than the shorter wave lengths used otherwise. Silicon based detectors lack sensitivity in higher wavelength ranges, so not having to use them is a clear advantage in this case. [FD08, p. 36]

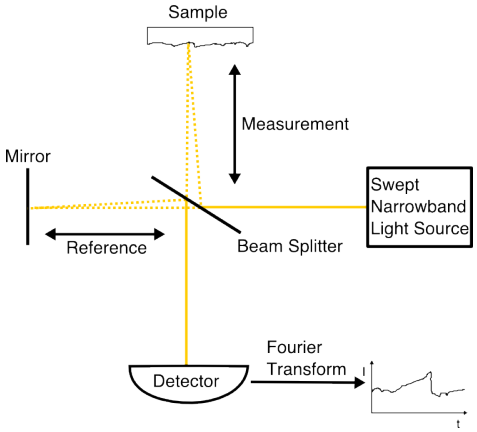

Figure 5: Principle of Swept Source FD-OCT.

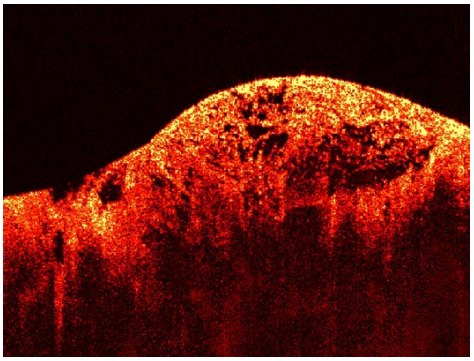

Figure 6: B-Scan of a sarcoma. [Bop07]

3 Processing and display

3.1 Scanning modes

The signal acquired by doing a single axial scan is called an *Amplitude (A) Scan*. By moving the beam over the sample in one direction, a cross-sectional image of part of the sample, called a *Brightness (B) Scan*, can be acquired. Many of these scans next to each other give a *3D-OCT* scan of a whole area of the sample. [FD08, p. 2]

With a slightly different setup full-field scans (Using a CCD-based detector) can be acquired in one go. [DVBB02]

No matter what method of sampling is used, the resulting data set is essentially an array or scalar field of reflectance values, which now needs to be visualized. For this, the OCT scanners output values are first digitized. They can then be digitally processed and displayed. The processing and display works analogous to other medical imaging methods such as MRI or CT imaging, which produce similar data sets.[FD08, p. 15]

3.2 Single A-Scan

In the case of a single A-Scan, the visualization is trivial: The data for each point can be plotted for depth / time as a bar graph. Since there is only one direction information, no information is lost or obscured this way, and patterns or significant changes can easily be spotted. [FD08, p. 2]

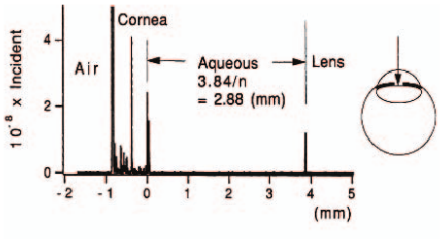

Figure 7: Example of an OCT A-Scan. [FD08, p. 8]

3.3 B-Scan

For multiple A-Scans in a row, it still isn't hard to visualize the data set. As the name already suggests, treating the depth on and position of the scanning axis as x- and y coordinates in an image and plotting the acquired reflectance as a gray-scale value already results in a very intuitive visualization in which each column of pixels represents a single A scan, as can be seen in figure 8.

To allow for better contrast between different values, so that big differences become more clearly visible, alternate mappings from the scan values to the pixel color can be used. [FD08, p. 2]

Further processing, to automate detection of certain structures or extraction of data (e.g. retinal thickness) is also possible. [FD08, p. 18]

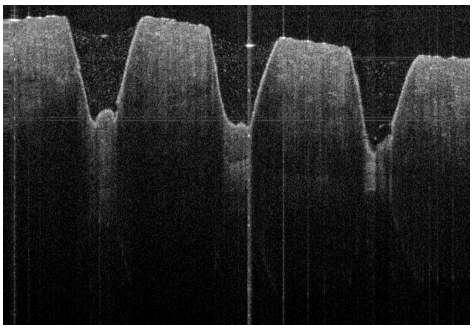

Figure 8: Example of an OCT B-Scan. Every column of pixels represents one A-Scan.

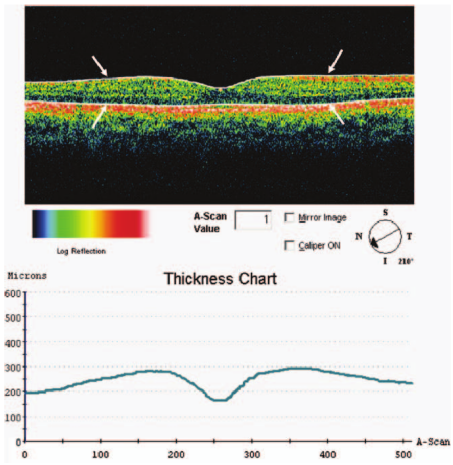

Figure 9: Automatically extracted retinal thickness. [FD08, p. 18]

3.4 3D-OCT

In 3D-OCT, the visualization process is somewhat more involved. While it is possible to draw the acquired data as a set of voxels colored according to the reflectance values acquired, putting many B-Scans next to each other in a 3D volume, this sometimes does not result in very clear images, so other techniques, like those used in MR imaging, are used as well. [FD08, p. 34]

One possible method is simply displaying cross-sections along one axis, and allowing the viewer to chose which depth should be displayed, or allowing the viewer to choose any cross-section plane. Another is showing a cross-sectional image for all three axial planes going through a certain point and displaying these to give a 3D cross-section of the sample, or using any of a number of techniques of rendering volumetric data, such as treating it as an isosurface of some adjustable level. [FD08, p. 34]

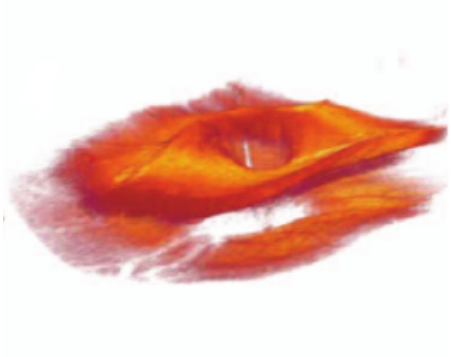

Figure 10: 3D Volume rendering of an OCT data set. [WSF+05]

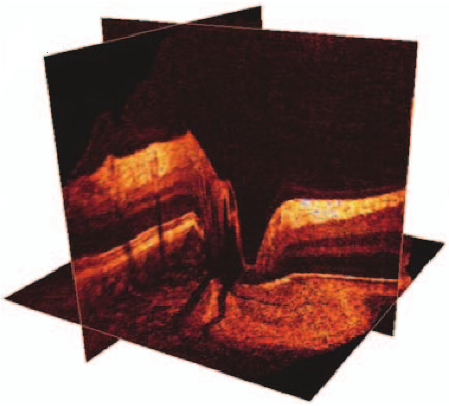

Figure 11: Three cross-sections of an 3D-OCT data set. [WSF+05]

4 Applications in medicine

OCT is already used as a medical imaging method today, and has great potential for future applications, as well. Since it works with light, it can non-invasively image tissue in-vivo without causing any long-term after effects.

4.1 Ophthalmic imaging

Due to being an optical imaging method, OCT is most well-suited for imaging transparent tissue. The most obvious transparent tissue on humans is the

eye, and this is indeed the area where OCT is currently most widely in use. [FD08, p.9-10]

The first in-vivo images of the human retina were created as early as 1993, and has progressed rapidly since then. Today, it is used to detect macular holes, edema and degeneration, thickness of the retinal nerve fiber layer and other symptoms of eye disease, before actual damage to vision occurs. [FD08, p. 10]

4.2 In-body imaging

Another common application, due to the possibility of using OCT via an optical catheter or endoscope, is using OCT to acquire images from inside the body. Imaging is performed via rotating, pushing/pulling the tube, or other optical or mechanical mechanisms, generating transverse scans from inside vessels or hollow organs. [FD08, p. 19]

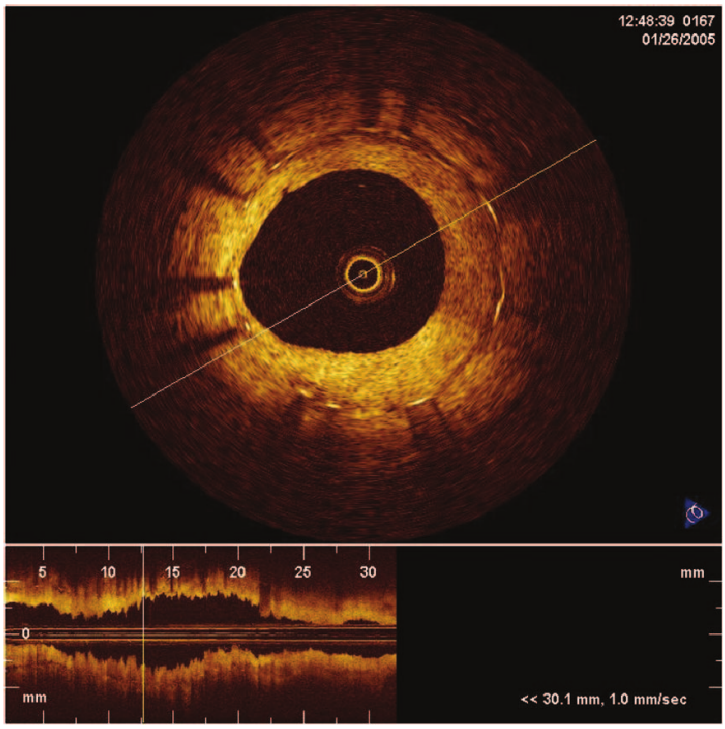

Figure 12: In-vivo image of a human artery. [FD08, p. 23]

There is considerable interest in using OCT for the detection of cancer symptoms in the esophagus, stomach and colon, as - unlike biopsy - it would enable cancer detection without requiring the excision of tissue. Since the performance of OCT is often not quite at the level required for a stand-alone diagnosis, there is also ongoing research into using OCT to assist biopsy, by picking a good location for excision. [FD08, p. 21]

Intra-vascular imaging using OCT would allow for a more detailed view as is currently possible using ultrasound, allowing for clear differentiation of blood vessel layers. Due to the highly scattering nature of blood, flushing with saline solution or obstructing blood flow with a balloon is necessary to acquire clear images from inside blood vessels. [FD08, p. 22]

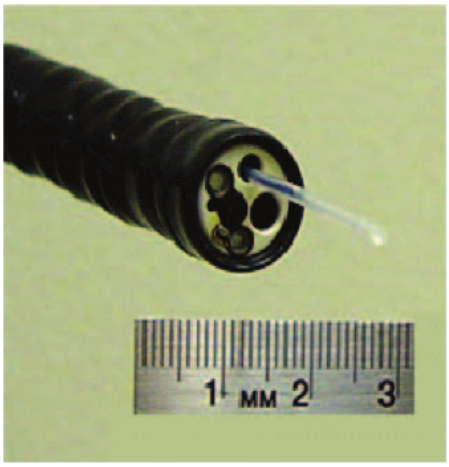

Figure 13: Endoscope with OCT probe. [CAH+07]

5 Summary and outlook

OCT is a versatile imaging method with the potential for live 3D sub-surface imaging, the potential applications are numerous.

There is research into developing mobile, hand-held OCT systems for in-the-field medical imaging, using light-pen-like devices which scan the beam piezoelectrically. [FD08, p. 22]

In general, applications range from imaging through non-transparent tissue such as skin to get cross-sectional images of bones to imaging small animals or to non-medical applications in material science. The potential for

OCT in diagnosing heart-related diseases as well as cancers, via intra-vascular imaging and "optical biopsy", respectively, is great, and there is much ongoing research into these areas, which might eventually lead to ultra-high-resolution live in-vivo 3D imaging of internal tissue, enabling earlier, simpler, less-invasive diagnosis than is currently possible. [FD08, p.38-39]

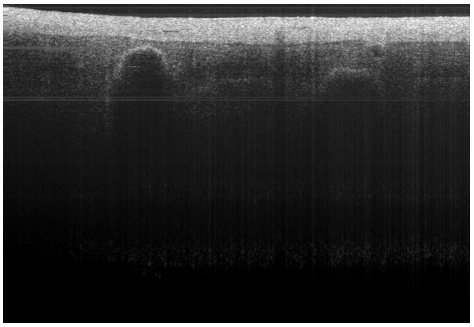

Figure 14: OCT scan of a bone with a hole.

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