Optical Coherence Tomography for medical imaging and non-destructive testing

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ABSTRACT

This paper presents a review of the activities on optical coherence tomography (OCT) in the Applied Optics Group (AOG), University of Kent, encompassing optical devices, sources for OCT as well as OCT applications. Out of the directions of applications approached, two fields are selected, applications in medical imaging with emphasis on ophthalmology and endoscopy and in non destructive testing. An important advantage of OCT is that high axial resolution is achievable at comfortable working distances, which is an important requirement for safe scanning of patients as well as of valuable materials or objects of art.

Keywords: optical coherence tomography, eye, non destructive testing

1. INTRODUCTION

OCT is a non-invasive high-resolution imaging modality, which employs non-ionizing optical radiation. OCT derives from low- coherence interferometry and heterodyne scanning microscopy[1]. This is an absolute measurement technique that was developed for high-resolution ranging and characterization of optoelectronic components[2,3]. The first application of the low- coherence interferometry in the biomedical optics field was for the measurement of the eye length[4]. Adding lateral scanning to a low-coherence interferometer, allows depth- resolved acquisition of 3D information from the volume of biologic material (as proven in 1991 at the MIT by a team that has also coined the OCT term[5]).

Developments in OCT have expanded its clinical applications for high-resolution imaging of the retina, as a standalone diagnostic and in combination with other optical imaging modalities. After an initial push for combining OCT with

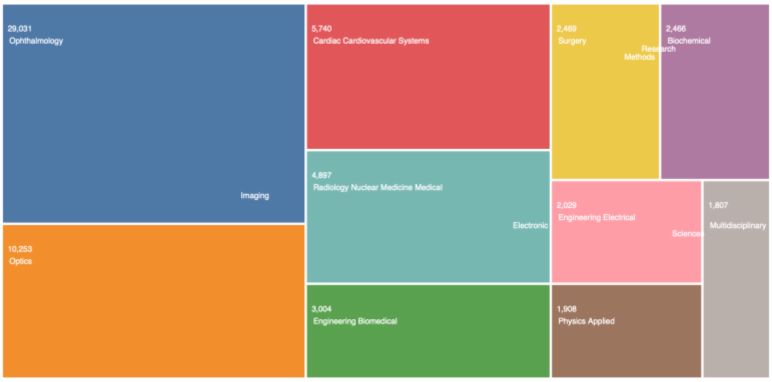

Fig. 1. Number of web of knowledge reports on OCT per most cited subjects

scanning laser ophthalmoscopy (SLO), the AOG has explored subsequent combinations including modalities such as adaptive optics (AO) and axial tracking.

A web of knowledge search in Nov 2021 has returned 59680 reports on OCT. As shown in Fig. 1, more than 50% of these are in ophthalmology followed by other medical imaging fields, however with other non medical subjects gaining interest.

Different OCT modalities[6] were developed, such as time domain and spectral domain[7,8], adapted to the needs of specific applications.

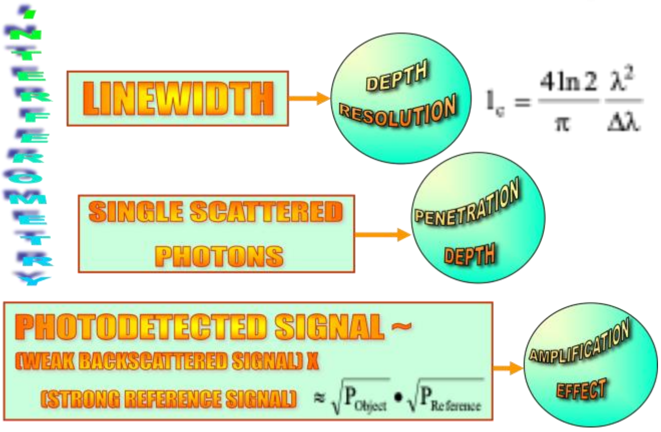

Fig. 2. The 3 key parameters of OCT

Suitability for imaging tissue or objects for non-destructive testing (NDT) dictated the type of OCT method, as well as scanning modality, either laterally scanning the beam of light over the target (flying spot) or illuminating all target pixels at once, ie using flood illumination and cameras to implement full field configurations (using an area or line illumination). In terms of priority scanning, two principle procedures were evaluated, *en-face* and longitudinal OCT. The first OCT image reported[5] was a cross section (B-scan) obtained by assembling depth reflectivity profiles (A-scans), ie the priority was along the depth axis.

A-scans were produced in time domain OCT by mechanically varying the length of one of the interferometer arms. *En-face* imaging employs lateral scanning priority. When using the flying spot method, the beam is scanned laterally over the target fast, while at a slower pace, the depth is advanced, again by varying the length of one of the interferometer arms. *En-face* imaging is used in conventional microscopy and SLOs are by excellence *en-face* instruments. In full field swept source (SS)-OCT, a camera replaces the mechanical lateral scanning of the optical beam and several *en-face* views, each for a different optical frequency are acquired and then by the end, for each pixel in a 1D or 2D camera, a spectral content composed signal versus tuning is assembled. A Fourier transform of such composed signal leads to an A-scan.

The main parameters of OCT[6] are illustrated in Fig. 2.

The most characteristic parameter is the axial resolution. OCT has the potential of achieving high depth resolution, determined by the coherence length of the source (inverse proportional to the optical spectrum width of the broadband source used in time domain OCT and spectrometer based OCT) and by the tuning bandwidth of the tunable laser used in swept source OCT (in which case, the instantaneous coherence length is much longer and determines the axial range). The axial resolution is decoupled from the confocal gating of the interface optics, allowing better axial sectioning, determined by the source.

The second parameter in Fig. 2. determines the penetration depth in the object investigated. Due to the fact that OCT is based on interference, this requires a strict phase relation between the wave returned by the object and that from the reference path of the interferometer. The larger the scattering, the higher the chance that the photons are scattered more than once that leads to loss of phase relation and hence of the strength in the interference signal.

The 3rd parameter is advantageous for OCT, due to interference we have an effect of beating of two signals, where the weak signal from the object is multiplied by the strong signal form the reference path, leading to an equivalent amplification of the weak signal. In skin for instance, when comparing penetration depth of a confocal microscope (Lucid) with an OCT system at a similar wavelength (800 nm), the penetration depth is improved from 0.35 mm to over 1 mm respectively.

1.1 Optical sources for OCT

Several OCT parameters depend critically on the properties of the optical source. A major impetus in the OCT progress in the last five years is due to development of novel large band tunable sources, with tuning rates exceeding 1 MHz.

Two Marie Curie Doctoral Schools in the University of Kent aimed at advancing the technology of optical sources for OCT.

A Marie Curie European Doctoral School (2014 – 2018) with beneficiaries University of Kent and NKT Denmark has advanced the spectrometer based OCT technology using supercontinuum NKT sources. Significant results were obtained, such as demonstration of tolerance to dispersion of Master Slave OCT[9], of the value brought by ultra high axial resolution in examining skin[10] and long wavelength OCT examination for non destructive testing of materials with low water content[11] as documented more below. Using sources with extremely short coherence length, submicron depth resolution is achievable even when the microscope objective is far away from the investigated target, feature not achievable with confocal microscopy. This is one of the most important advantage of OCT, which explains the high level of interest for OCT in ophthalmology and renewed interest in non destructive testing allowed by investigation for security documents using ultra broadband sources such as supercontinuum lasers.

A current Marie Curie Innovative Training Network (ITN) (2020- 2024) aims to develop novel tunable lasers for swept source OCT method. One of the methods researched in Kent is based on dispersive cavity mode-locked lasers. This presents the potential of achieving MHz tuning rates with no mechanical means (akinetic)[12]. This is one of the directions researched within this ITN. In this respect, better control of mode locking is planned, by modulating semiconductor optical amplifiers (SOA) in the laser cavity using Mach Zehnder electrooptic modulators, in order to improve previous reports based on modulating the current of SOAs.

1.2 Signal processing

We introduced Master Slave (MS) - OCT[13], that radically changed the main building blocks of the processing workflow of a spectral (Fourier)-domain OCT set-up. The signal conventionally provided by a Fourier Transform (FT) or equivalent

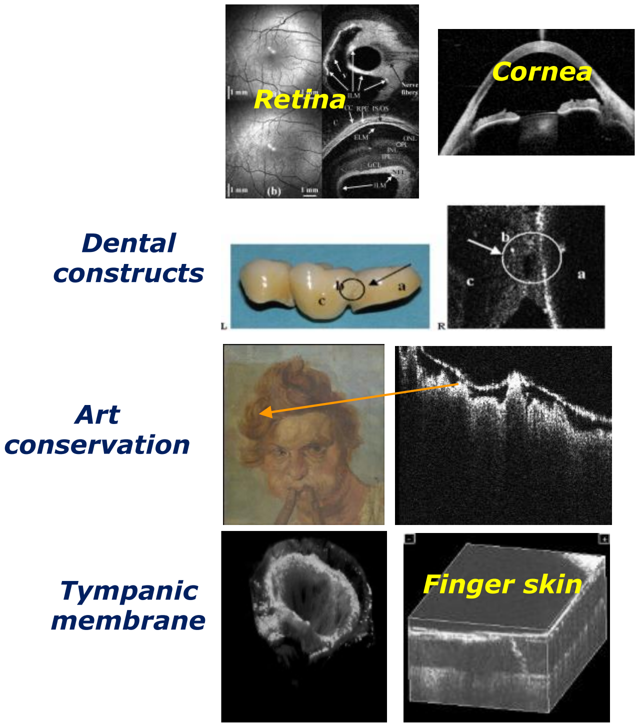

Fig. 3. Examples of OCT images
Top left: reprinted with permission of Optica from[20]; 2nd row reprinted with permission of SPIE from[30]; 3rd raw reprinted with permission of SPIE from[24]; bottom right: reprinted with permission of Optica from[22].

is replaced by delivery of multiple signals, a signal for each optical path difference in the sample investigated. In this way, it is possible to: (i) directly access the information from selected depths; (ii) eliminate the process of resampling, required by the FT based conventional technology, (iii) reduce the time to display an *enface* OCT image and (iv) lower cost OCT assembly by not requiring a clock in swept source OCT and (v) tolerate the dispersion left unbalanced in the OCT interferometer.

1.3 Applications enabled by the Master Slave OCT method

In addition to MS-OCT applied to medical imaging and NDT, 4 specific applications are presented: 1. Axial correction due to information provided by an axial tracker, where the correction is non mechanical, based on real time adjustment of the set of MS masks used to calculate each A-scans[14]; 2. SS-OCT without a clock, where the MS method can enable an axial range as wide as allowed by the instantaneous coherence length of the swept source, not limited by the clock frequency of the swept source[15]; 3. Taking advantage of the tolerance to dispersion in the interferometer of the MS method in a system operating in coherence revival[16] regime that doubles the axial range of the OCT investigation, property advantageously used in imaging the anterior chamber in the human eye that requires a log axial range. 4. Decoding the channeled spectrum at the interferometer output when using the Vernier principle of tunability in a swept source OCT[17]. Such sources present the advantage of akinetic tuning however due to the Vernier effect, some optical frequencies are emitted more than twice during a tuning interval. Before any use, a calibration procedure requires elimination of such frequencies. The MS protocol provides a simpler decoding procedure, that within some limits can tolerate the whole emitted spectrum, including the frequencies which would otherwise be eliminated by the calibration procedure.

1.4 Translation of OCT technology to clinics and industry

A major activity in Kent has been to assemble fully functional OCT systems, translated to collaborators for different applications. Fig. 3 illustrates some of the images acquired from a diversity of targets: human retina, human cornea, dental constructs, mock paintings, tympanic membrane and human skin.

A portable system installed on a trolley is shown in Fig. 4. This can either image human retina or be used as a handheld probe to inspect skin or industrial objects for NDT.

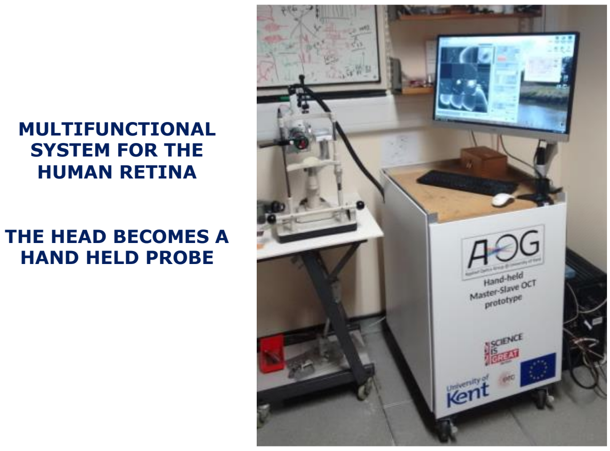

Fig. 4. OCT multifunctional system on a trolley

2. MEDICAL APPLICATIONS

2.1 Ophthalmology

As with any group performing OCT, eye imaging has been central for the group in Kent. From the demonstration of the *en-face* OCT of the human retina[18] and of the OCT/SLO[19] (an instrument that combined the two high resolution modalities for the human retina in a single instrument, OCT and that of scanning laser ophthalmoscopy), research evolved to ultra high axial resolution OCT in the dual OCT/SLO system[20] and combinations of *en-face* OCT and SLO imaging with angiography[21] and 3D imaging applied to the eye and skin[22].

The research in Kent focused on performing *en-face* procedures, initially via time domain OCT, then based on the more modern versions of OCT, spectral and swept source where the FT block was replaced with a Master Slave processor. This operates similar to a correlator recognizing patterns in the channeled spectrum shapes at the OCT interferometer output. Simultaneous display of as many as 40 *en-face* OCT images from the retina have been demonstrated.

2.2 Endoscopy

One of translation exercises refers to collaboration with Northwick Park Hospital London that supported by a i4i NIHR grant, lead to installation of an instrument to investigate the usefulness of OCT imaging in an ear, nose and throat (ENT) department[23]. This was dedicated to *in-vivo* laryngeal investigation, based on an endoscope probe head assembled by compounding a miniature transversal flying spot scanning probe with a commercial fiber bundle endoscope. This dual probe head was used to implement a dual channel nasolaryngeal endoscopy-swept source-OCT system at 1300 nm (Fig. 5). The two probe heads were used to provide simultaneously OCT cross section images and *en-face* fiber bundle endoscopic images. The dual channel instrument was initially tested on phantom models and then on patients with suspect laryngeal lesions in a busy ENT practice. This feasibility study demonstrated the OCT potential of the dual imaging instrument as a useful tool in the testing and translation of OCT technology from the lab to the clinic.

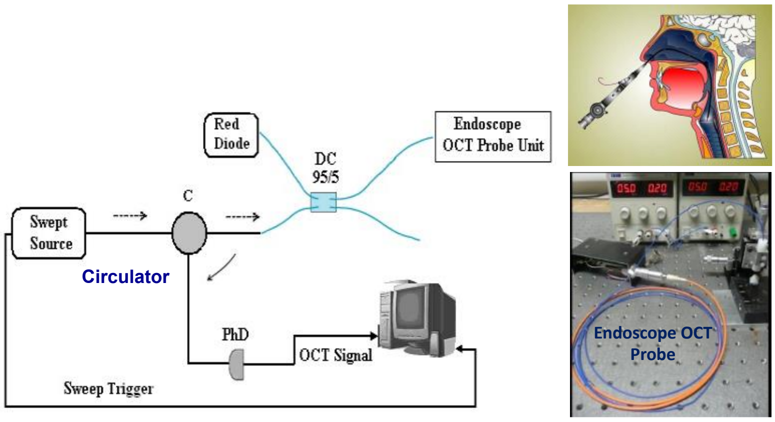

Fig. 5. Optical configuration (left), illustration of probe insertion (top – right) and electronic box (bottom-right) {adapted with permission of Optica from[23]].

3. NON- DESTRUCTIVE TESTING

A first OCT application oriented towards NDT started based on a collaboration with Nottingham Trent University, British Museum and National Gallery, to investigate the OCT utility for guiding conservation of paintings[24,25] and imaging of objects of art, such as Roman pendants.

More recently, activity was expanded towards assessing functionality of needle arrays[26] to deliver drugs, a preliminary investigation on serving agriculture by imaging berries to predict the most optimum moment of harvesting, imaging tattoos[27] in order to recognize victims of war and disasters, and exploration on the utility of ultra high resolution OCT for document inspection[28,29]. In collaboration with DTU, long wavelength OCT (4 μm)[11] was proven capable to image the chip and RF antenna in bank cards.

4. OCT IN ROMANIA

There is an active area of research in Romania, centered on Timisoara and Arad, the place of the conference and of its organisers. These two university towns are leading research in OCT in two fields, respectively in dentistry and NDT. The Chair of the conference has been promoting a pole[30] of interest in the fields of opto-mechatronics, optical mechanics and optical metrology for quite a few years and this conference ending with a SPIE conference volume is proof of evolution of research on OCT and its applications in this part of Romania, under a more general title of 3OM. Due to their efforts over the years, Romania is in the 31th place by the number of reports on OCT in the list of countries in the web of knowledge. The group in Kent maintained a continuous collaboration with the two OCT teams at the Victor Babes University of Medicine and Pharmacy, Timisoara and at the Aurel Vlaicu University Arad that led to numerous joint reports. Apart from a review on using OCT for characterization of dental constructs[31], topics addressed by joint publications so far refer to quality assessment of dental treatments[32], monitoring the quality of sintering processes using OCT[33], investigation of apical microleakage after laser-assisted endodontic treatment[34] , quantification of abfraction and attrition using swept source OCT[35] and assessment of the sealant/tooth interface[36]. A special direction was that of development of scanning devices[37,38] and of low cost hand held OCT probes[39]. Novel applications include using MS-OCT to calibrate ovens for sintering metal ceramic prostheses[40], using MS-OCT to evaluate bone regeneration after low level laser radiation[41], nanoparticles for contrast enhancement of OCT images, detection of fractures in metals[42] and OCT guidance on Xray imaging systems[43]. The research setting the agenda of training of next generation of researchers has been highlighted in a symposium[44]. The three groups, in Arad, Canterbury and Timisoara are currently collaborating in training future specialists on fields straddling the border between non invasive high resolution imaging and clinical applications. Victor Babes University of Medicine and Pharmacy Timisoara is an active partner in the European Master degree in Oral Laser applications (EMDOLA)[45]. University of Kent has been training future specialists in OCT and its applications with support from the Marie Curie actions[46,47].

A document recently elaborated by UEFISCDI[48] within the SIPOCA542 project, has established the agenda of priorities in research in Romania. This report mentions the biomedical optics field in relation to the priorities for health and gives examples from the diaspora (Virtual Community of Romanians abroad engaged in Biomedical Optics, RoBi-Opt)[49], including links to the research activity in Kent ('Health' priority on page 64 with a link on page 66 on the *en-face* OCT in Kent[50] and on 'Industry supporting health delivery' priority on page 75 with a link on page 76 to the Hub for Light maintained by Kent[51]).

5. CONCLUSIONS

Although OCT entered its 30th years of existence in 2021, it continues to evolve. There is a diversification of its applications with continuous increase in the number of vendors on ophthalmology as well as on different other markets. Recent dynamism has been brought to the field by developments in optical sources. Supercontinuum sources allowed crossing the barrier of submicron axial resolution. Fast tunable lasers allowed multi MHz A-scan rates. The very principle of operation is still evolving, with versions such as Master Slave or Nanoscale OCT. Ultra high resolution OCT has now a future in medical diagnostic and NDT.

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