Combining Photoacoustic and Optical Coherence Tomography Imaging for Non-Destructive Applications

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ABSTRACT

Robust, non-destructive testing imaging instruments, capable to provide valuable information from within the body of materials is important for both quality control and the development of new materials, for industrial and medical applications. Conventional non-destructive testing (NDT) methods, such as radiographic or ultrasound-based techniques, allow for deep axial range imaging, however, they are either using non-safe radiation or/and exhibit low imaging resolutions. The speed at which the standard NDT methods deliver images is also limited. The development of photoacoustic (PA) and optical coherence tomography (OCT) applications in the field of NDT have grown exponentially over the past years, offering faster, higher resolution images. Both techniques, PA and OCT bring a plethora of benefits to the current methods. However, a multitude of challenges still needs to be addressed to truly make either of them the technique of choice for NDT applications. In this manuscript, a short overview of the challenges that these two imaging techniques are facing when used for NDT applications is presented. Illustrative high-resolution images, produced by a dual PA/OCT imaging instrument developed within the Applied Optics Group at the University of Kent are presented. These images demonstrate unique capabilities for NDT applications.

Keywords: Photoacoustic Imaging, Optical coherence tomography, non-destructive testing

1. CHALLENGES IN PA AND OCT

1.1 Limited lateral resolution

The beauty of both PA and OCT technologies is that their axial resolution is decoupled from the lateral one. The axial resolution in PA imaging is basically determined by the electrical bandwidth of the ultrasound transducer (UT) and the speed of the acoustic wave within the material investigated whereas the bandwidth of the optical source employed determines the axial resolution in OCT. The transversal resolution depends on the interface optics, mainly on the numerical aperture of the microscope objective employed to focus light on the sample. Optical sources with a sufficient broad optical spectrum ensure an excellent axial resolution for OCT, whereas large bandwidth ultrasound transducers that of the PA. To improve the lateral resolution, a high numerical aperture microscope objective must be used. The immediate drawback of this approach is a limited axial image restricted to the extension of the confocal gate. A solution suitable for high numerical aperture interface optics can be the Gabor method [1], currently used with OCT, which potentially can be extended to PA instrumentation. Using the Gabor technique, data acquisition is repeated for several focus positions, corresponding to various shifts of the confocal gating profile through the sample. The images obtained are then fused to form a final larger image covering an extended axial range. As the data acquisition must be performed multiple times the real-time operation of the instrument is limited. The axial resolution in PA depends on the imaging depth. The axial resolution decreases from shallow depths, reachable by ballistic photons, to deeper depths due to acoustic attenuation. As the higher acoustic frequencies are stronger attenuated than the lower frequencies, a deterioration of the resolution at large depths occurs. Several numerical and hardware-based techniques [2,3] have been proposed so far to tackle this problem.

In PA instruments, the axial imaging range is limited by the depth at which photons, ballistic or multi-scattered ones can penetrate the sample and the attenuation of the acoustic waves and the bandwidth of the ultrasonic transducer. However, typically PA axial range is larger than that of OCT. Considering the two waves, incident and returned waves, simply in OCT, both waves are optical, while in PA one is optical while the other is a sound wave. Both implementations of spectral-domain OCT, respectively spectrometer based (CB) and swept-source (SS), can be used to produce images with high speed and high sensitivity. The SS-OCT technology seems to be the method of choice over CB-OCT when a long axial range is required. Due to the finite coherence length of the lasers used, the axial imaging range in SS-OCT is still limited, an exception from this being the tunable vertical-cavity surface-emitting lasers (VCSEL) and akinetic light sources, which can provide long axial ranges, exceeding centimeters but are costlier than the microelectromechanical swept sources conventionally used.

As the operation of OCT is based on detecting ballistic photons, the axial imaging capability of OCT is certainly also limited by the characteristics of the sample to be imaged. PA can break the optical diffusion limit as multi-scattered photons can also generate acoustic waves, leading to a better penetration depth than that provided by the OCT instrumentation.

1.2 Real-time imaging capability

The production of real-time images in OCT is very often limited by the complex mathematical operations required to process acquired data. In OCT, to produce a cross-sectional image, interferometric spectra acquired while scanning the probing beam over the sample is subject to a fast Fourier transform (FFT). Before the FFT, several preparatory signal processing steps are needed to achieve high axial resolution and sensitivity. Some of the preparatory operations are extremely time-consuming as can only be sequentially executed, therefore the production of the OCT images in real-time is limited. So far, several techniques involving both hardware and software solutions have been demonstrated to successfully eliminate or diminish the execution time of the preparatory steps.

The most demanding preparatory steps in terms of computation time are data resampling and compensation for dispersion mismatch between the arms of the interferometer. To eliminate the resampling step, in CB-OCT, hardware solutions were proposed. However, this requires careful adjustment of the hardware components and the use of extra optical components in the interferometer or in the spectrometer [4] introduces losses. In SS-OCT, the swept sources are often equipped with a supplementary k-clock that adds to the cost of the source [5]. Other techniques such as using an additional light source that produces several spectral lines in the region of interest of the spectrometer, parametric iteration methods, phase linearization techniques, and automatic calibrations have been also proposed. All these methods are normally computationally expensive and limit the real-time operation of OCT systems.

As the computational requirements for high-speed image processing usually exceed the capabilities of most personal computers, the display rates of OCT images rarely match the acquisition rates. After the preparatory steps, most image generation, analysis, and diagnosis become a post-processing operation. A true, real-time display of processed cross-sectional, and *en-face* images could benefit NDT applications that require instant feedback of image information.

In contrast to OCT, in PA, there is no need for an interferometer, therefore no need for a complex mathematical procedure to decode the information needed from the raw data. A simple Hilbert transform of the detected acoustic signal suffices to generate an A-scan, so fast generation in real-time of the cross-sectional images is possible.

1.3 Contact-less imaging

OCT is well known for its capability of producing images without any need of contact between the microscope objective and the sample investigated, however, PA does require either direct contact between the ultrasonic transducer and the sample or involves the use of ultrasonic gels, which may not be ideal for some industrial applications. There are a plethora of reports demonstrating the use of Fabry-Perot interferometric sensors [6] instead of the ultrasonic transducers not requiring contact with the sample, however, they add complexity to the instrument or do not provide sufficient quality of the images.

2. SOLUTION: COMBINING PA AND OCT

To tackle the limitations of the current PA or OCT instruments, we develop imaging instruments combining these two technologies [7-10]. The PA channel provides better axial penetration and offers excellent spectral capabilities due to the PA signal being dependent on spectral absorption. If the optical source for PA uses a supercontinuum optical source, then the large spectrum of such optical sources allows a wideband spectroscopic analysis. At the same time, a broadband optical source enables high axial resolution OCT imaging. A broadband source demands enhanced signal processing when using a Fourier Transform, which is considerably simplified employing the Master/Slave (MS) technique [11,12] developed by our research group. These combined instruments can meet the demands of various NDT applications such as high lateral and axial resolution, long axial range, and real-time operation. They are also offering flexibility as the MS approach allows for easy, quick adjustments of the OCT channel in the combined instrument if required by a specific application, as well as robustness, and spectral capabilities of the PA imaging channel.

The benefits of the MS method originate from the fact that the method does not use FFTs to generate images [12]. Instead, there is no need for any of the preparatory steps, and as the method is only based on the multiplication of digital signals, is highly parallelizable [13]. As no sequential mathematical operations are needed, the MS method can operate in true real-time. The MS method compares, raw, unprocessed spectra which incorporate all the information about nonlinearities and unbalanced dispersion. As a result, there is no need for data resampling or procedures to compensate for unbalanced dispersion. An enhanced MS-OCT instrument is an instrument free of non-linearities and perfectly compensated for dispersion. The PA imaging instruments do not require any calibration procedures. With no need to decode the raw signals, only a Hilbert transform is needed to generate a PA axial reflectivity profile.

Various MS enhanced PA/OCT imaging instruments were developed in our group and used for different NDT applications, operating at various spectral ranges, and allowing quite long axial ranges [7-10]. In Fig. 1, we present a basic diagram describing how our combined instruments are developed by using the same optical source for both imaging channels. The optical source (OS) is a supercontinuum laser capable to emit pulsed light with a repetition rate of a few tens of kHz, and several ns pulse duration. When combining PA and OCT, each pulse must contain a wide spectral bandwidth to enable good axial OCT resolution, but sufficiently narrow to allow for spectral measurements in the PA channel. PD on the sketch presented in Fig. 1 is a spectrometer devised for the spectral range targeted. The speed at which the two channels are operating is the same, given by the repetition rate of the pulses emitted by the optical source, therefore, like no other multimodality imaging instrument, high-resolution cross-sectional images can be obtained in both channels, eventually simultaneously.

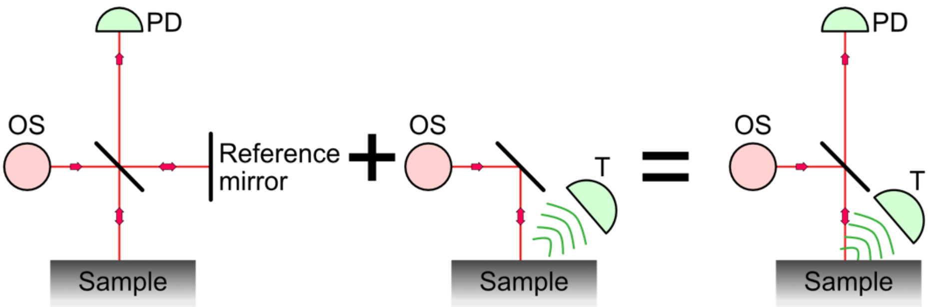


Figure 1. Combining an OCT and a PA instrument within a multimodality imaging tool using a single optical source (OS). PD is a spectrometer operating over the spectral range needed, whereas OS delivers pulses of a duration of a few ns with a repetition rate of tens of kHz. The combined instruments share a single OS, but not the same detection paths.

A more detailed diagram of a combined PA/OCT instrument currently in use in our labs is illustrated in Fig. 2 where light is emitted by a supercontinuum optical source over a spectral range from 450 to 1,800 nm. When the two flipping mirrors FM are in the UP position (i.e. FM1 deflects the optical beam towards the flat mirror M and FM2 towards the galvos), the whole optical power delivered by the source is conveyed towards the sample. The optical bandpass filter F placed between the flat mirror M and the flipping mirror F can be employed to select the spectral range needed to target the chromophores present within the material of the sample under investigation. A transducer T collects the acoustic waves, and an electronic amplifier A amplifies the transducer output electric signal that is directed towards an analogue-to-digital converter ADC1. When the two flipping mirrors are in the DOWN position, the whole optical power is used by the OCT channel. An optical bandpass filter F1 placed between the flipping mirror FM1 and the achromatic lens L selects the spectral range utilized by the OCT channel. Although the operation of such an instrument is sequential, it has the advantage of employing the whole available optical power delivered by OS in each mode of operation. Depending on the requirements of the application, the instrument can be interfaced with optics ensuring a very high lateral resolution.

Using an instrument as that depicted in Fig. 2, images as those presented in Fig. 3 can be produced. To generate such images, a supercontinuum optical source (SuperK Compact, NKT Photonics) is employed. This OS delivers pulses at 20 kHz of 2 ns duration and a sufficient energy per pulse to produce good quality PA images. The OCT channel operates in the 1300 nm spectral range (160 nm spectral bandwidth) with an axial resolution of 5 µm (measured in air). As, at the same time, the instrument is equipped with a high numerical aperture microscope objective, high lateral resolution images can be generated. Typically, the lateral resolution in both channels is 5-7 µm across the entire spectral range, therefore isotropic resolution volumes can be generated in the OCT channel. The axial resolution in the PA channel, measured experimentally, is around 38 µm, value limited by the duration of the pulse, the attenuation of the high-frequency acoustic waves by the sample and the bandwidth of the ultrasonic transducer employed. The lateral field of view of our instruments can extend over several millimeters making them ideal for several NDT applications.

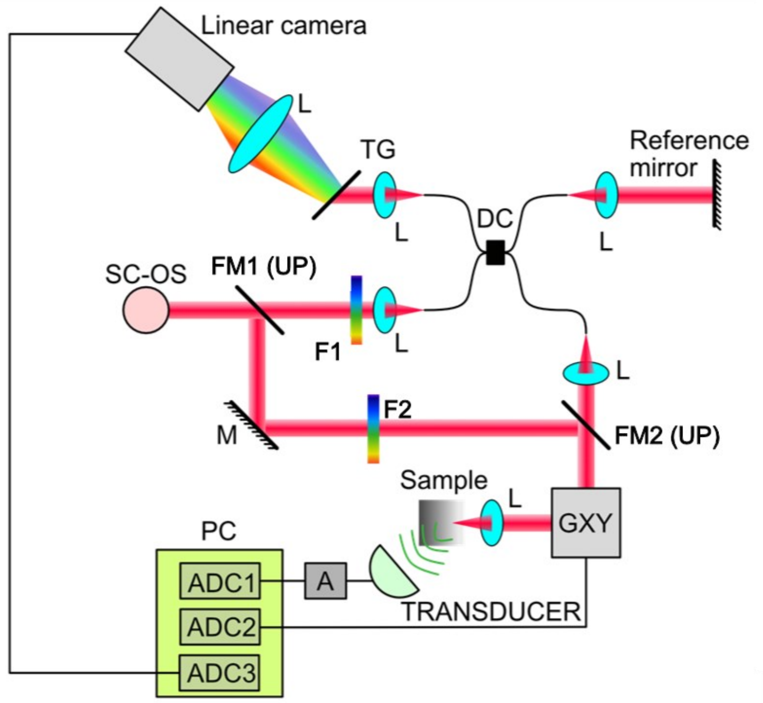
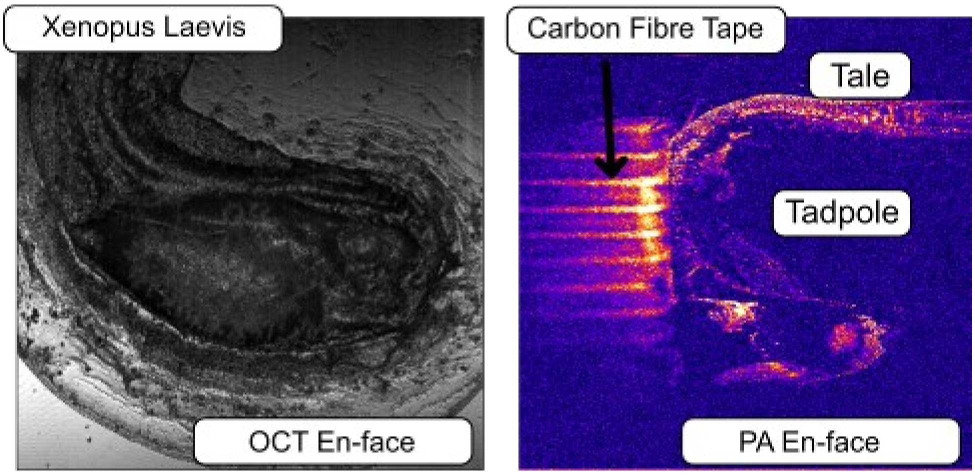


Figure 2. Schematic diagram of a combined sequential PA/OCT imaging instrument. ADC1-3: digitizers or signal generators; A: amplifier; L: achromatic lenses, GXY: galvos-scanners; FM1,2: flipping mirrors (both in the UP position)); F1,2: optical bandpass filters; M: flat mirror; DC: directional coupler, TG: transmission diffraction grating; SC-OS: supercontinuum optical source.

All the instruments developed so far employ the MS technology in the OCT channel, useful for a variety of NDT applications. The *en-face* images shown in Fig. 3 present 400 lateral pixels. Data to produce each volumetric image was collected in 8 s. Taking advantage of the MS method and of the simplicity of the mathematical operations needed in the PA channel, the instrument delivers cross-sectional images in both channels at a rate of 50 Hz, in real-time.



In Fig. 3 (left) an *en-face* OCT image of the Xenopus Laevis tadpole, of isotropic resolution of 5 μm is shown, whereas, on the right, an *en-face* PA image of the same tadpole is presented. Here, a carbon fiber tape was placed in the focal plane of the microscope objective, next to the tadpole, which is also placed approximately in the focal plane of the objective. The amplitude of the PA signal from within the tadpole is sufficiently high to generate a high-quality image, amplitude depending on the optical energy within each pulse. In our case, we managed to obtain an energy per pulse of over 50 nJ over the whole spectral range of the supercontinuum source when a bandpass filter of 25 nm was employed. As a result, it is expected that high sensitivity PA images of the biological samples are possible with sufficient spectral resolution. In NDT applications, the typical amplitude of the PA signals would normally be much stronger than that obtained from biological tissue. This is illustrated on Fig. 3 (right) where the carbon fiber tape is brighter than the body of the tadpole.

3. DISCUSSIONS AND CONCLUSIONS

In this manuscript, a short review of some limitations of the current PA and/or OCT technologies was presented. To overcome them, the use of the Master/Slave approach was proposed in the OCT channel and a combined PA/OCT instrument using a single optical source. Some illustrative images produced using PA/OCT enhanced instruments developed in our group suitable to be used for NDT applications were demonstrated. The advantages of such an enhanced multimodality instrument recommend such technology for NDT applications.

The combined instrument offers great advantages, such as excellent resolution, uses two contrast methods (optical absorption and optical scattering), offers great spectral capabilities (especially in the PA channel), ability to perform widefield scans, uses non-ionizing, safe radiation, does not require heavy computational resources, etc.

The multimodal instrument is ideally suited to measurement of the shape of the surfaces (OCT), detection of micro-cracks in ceramic materials (PA+OCT), stress measurements (OCT), ablation-depth monitoring (PA+OCT), characterization of the multi-layered structures (PA+OCT), tablet coating monitoring (PA+OCT) [14], Li metal batteries imaging (PA) [15], monitoring structural changes such as corrosion (PA+OCT) [16], metal contaminations (PA+OCT) [17], defects, porosity, damage in composite materials (PA+OCT) [18], defects and damage in silicon (PA+OCT), coatings and underdrawings (OCT), analysis of microstructure in various materials (OCT), etc.

In terms of real-time production of the cross-sectional images, current CPUs are capable of data processing as required by the MS approach and by PA data processing with no need to resort to FPGA or GPUs. As our enhanced PA/OCT instruments can produce sequentially or simultaneously cross-sectional, *en-face* and volumetric images in real-time, such combined instruments are appropriate to industrial settings where swift imaging of the samples is required as for example for fast quality control along a production line.

Extra research is needed to overcome limitations of the two imaging technologies presented here, including developments on,

- the size of the transducer and its bandwidth
- non-uniform light fluence effects in the PA channel,
- acoustic attenuation
- sample heterogeneities,
- the need for contact with the sample (not ideal for some industrial applications, but when the OCT channel can be employed
- a limited penetration depth (PA may be used for some applications rather than OCT)
- high cost of the optical source (which is reduced when it is shared by both techniques), etc.

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