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Optical Interferometry – from Astronomy to Art

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Summary

After more than a century, Michelson's interferometer is still at the forefront of scientific investigation. While the first application was in astronomy, it is now used as a novel technique in a wide range of subjects, notably in the form of Optical Coherence Tomography used primarily for biomedical applications. This paper will introduce a new application of the interferometer for the examination of art for conservation purposes.

Interferometry in Astronomy

In 1868, Fizeau suggested that by using an interferometric combination of light from two separated slits '*il deviendra possible d'obtenir quelques données nouvelles sur les diamètres angulaires de ces astres*' [1]. In 1891, Michelson successfully measured the angular diameters of Jupiter's moons using the first optical interferometer in astronomy [2]. Later in 1921, Michelson & Pease developed the first stellar interferometer and successfully measured the size of the supergiant star Betelgeuse with their 20 ft interferometer mounted on the 100 inch Mount Wilson Telescope, thus fulfilling Fizeau's vision [3]. However, the requirements for mechanical stability and sensitive detectors with good time resolution limited the development of the stellar interferometer.

After WWII, the development of radio astronomy pushed interferometry to a new era, where demands in resolution at radio wavelengths resulted in the development of high sensitivity and long baseline inteferometric arrays (e.g. the Very Large Array telescope in New Mexico, USA and the Australia Telescope in New South Wales, Australia) and the development of the ultimate high resolution interferometric technique - Very Long Baseline Interferometry (VLBI) which achieved milliarcsecond resolution by using radio telescopes across the continents simultaneously. Imaging techniques developed in radio astronomy soon found applications in medical science. A notable example is the algorithm developed for reconstruction of astronomical images from radio interferometers by Bracewell [4] that has since been universally adopted for use in Computer-Assisted Tomography (CAT) scans [5] and Magnetic Resonance Imaging (MRI).

In the meantime, the development of optical interferometers in astronomy was not revived until the 1960s when intensity interferometers were developed to measure the size of the brightest stars through recording only intensities (but not phase) of the complex visibility function. It was not until the 1980s that advancement in computer, laser and detector technologies and interferometric techniques developed in radio astronomy resulted in the development of a modern version of the Michelson's interferometer. The first on the drawing board was the SUSI (Sydney University Stellar Interferometer) - a long baseline optical array for the measurements of stellar sizes [6] and COAST (Cambridge Optical Aperture Synthesis Telescope) - an optical stellar imaging array [7]. In the 1990s, a number of long baseline optical interferometers were developed around the world for imaging stars at sub-milliarcsecond resolutions [8].

Michelson's interferometer in various disguises

While in astronomy the aim is to resolve or image the source, the source is used to illuminate the object to be imaged in normal terrestrial applications. In both case we take advantage of the coherence properties of light. Optical Low Coherence Reflectometry (a 1-D optical ranging technique) uses essentially a Michelson's interferometer in a variety of configurations. Once again the coherence properties play an essential role and therefore, to achieve high depth resolution, short coherence length sources are required. Consequently, a range of sources such as tungsten lamps, superluminescent diode (SLD), Kerr lens mode-locked laser and supercontinuum sources were tested and developed. All these deliver light with high spatial coherence but low temporal coherence (i.e. wide bandwidth). Initial applications were of particular interest in the 1980s for the examination of fibre optic cables [9]. The potential application of the technique for examining the eye and other biological tissues was soon recognised. It was the development of a 3-D scanning technique specifically for producing stacks of high-resolution cross-sectional images of the internal microstructure of living tissue that made the technique popular in biomedical studies and gave the name Optical Coherence Tomography (OCT) to the technique [10]. OCT is basically a fast high-resolution 3-D scanning Michelson's interferometer.

Application to art conservation

Since non-invasive techniques are highly sought-after in both medical applications and art conservation, it is not surprising that these techniques are often transferable from biomedical applications to that of art conservation. One such well-known example is the use of X-rays in art conservation.

Here we describe a similar example of a recent application of a biomedical instrument to art conservation. The first applications of Optical Coherence Tomography to the examination of museum paintings were reported recently [11,12]. We used two *en-face* time-domain OCTs at 850nm and 1300nm to examine paintings in depth [11], the other group used a frequency-domain OCT [12]. Unlike a conventional time-domain OCT where a stack of cross-section images are taken one after another to create a 3-D image, an *en-face* OCT takes images in planes parallel to the painting surface one after another in depth [13,14] which is particularly convenient for the examination of paintings. The *en-face* display provides an instant comparison to the familiar look of painting. Figure 1 shows an example of a series of images taken in depth of a small region of a painted board. As images are taken deeper into the painting, underdrawings (preparatory drawings before the application of paint) are revealed. The dynamic range and resolution of these images of underdrawings surpass any conventional infrared images. The high dynamic range is because interferometers register only coherent signals hence only back-scattered light from the layer that matches (within the coherence length) the reference path length is registered. Back-scattered light from the other layers is automatically filtered out. The resolution in the plane of the painting is given by the numerical aperture of the objective lens and the depth resolution is given by the coherence length which is inversely proportional to the bandwidth of the source.

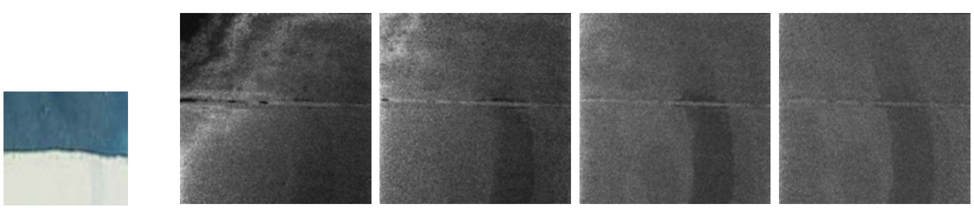

Fig 1. From left to right: 1) colour image of a painted board with underdrawing under the paint layers; 2) to 5) layers of OCT image at 1300nm in increasing depth. The images are 1cm by 1cm in size.

Figure 2 shows cross-section images of two line segments on a painting obtained with an 850nm OCT and a 1300nm OCT showing the varnish layer and the roughness of the paint layer. Figure 3 shows that it is possible to obtain images of paint layer structure from OCT images. The images show the optical thickness of the paint and varnish layers. We have conducted preliminary measurements and found that it is possible to measure the refractive index and the thickness of the varnish layer simultaneously using a focus-tracking method pioneered by Tearney et al. [15].

Fig 2. From left to right: 1) A cross-section image from a 1300nm OCT showing two layers of varnish above the paint layer; 2) a colour image of the painting; 3) a cross-section image from a 850nm OCT which has a higher depth resolution and X-Y resolution than the 1300nm, owing to the larger bandwidth source and higher numerical aperture used.

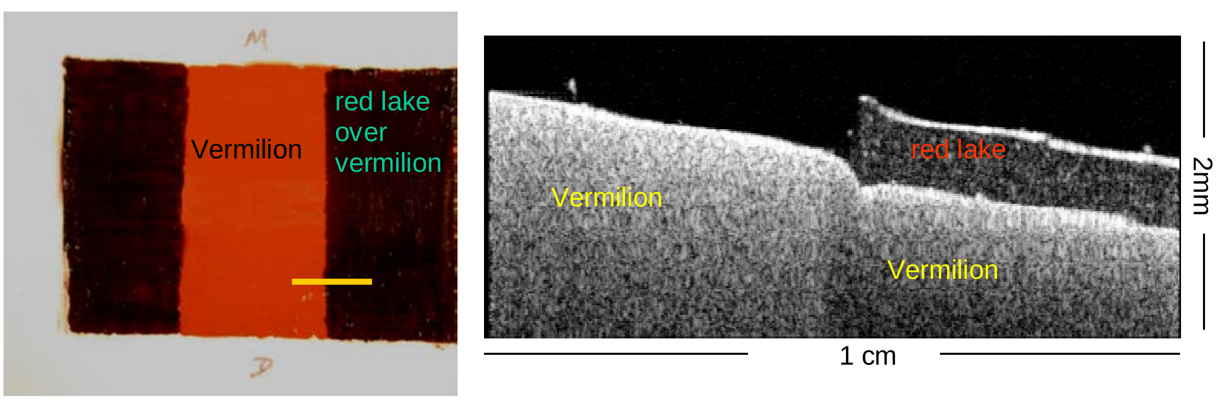

Fig 3. Left: a colour image of a painted board, the central strip is painted with vermilion, the strip on the right is painted with a red lake layer on top of a vermilion layer; Right: a 1300nm OCT cross-section image of a line segment cut across the boundary between the central and right hand strip showing the layer structure.

Conclusions

Optical Coherence Tomography – a fast 3-D scanning low coherence Michelson's interferometer has great potential in non-invasive examination of museum and gallery paintings. Infrared OCT is capable of providing 3-D infrared images of paintings that would not only show the underdrawings underneath the paint layers, but also show the layer structures of paint and varnish layers. We have started quantitative measurements of the optical parameters of paint and varnish layers using the data collected from OCTs.

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