Optical Coherence Tomography

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Imaging & Sensing for Archaeology, Art history & Conservation (ISAAC)

• Instrument development & data analysis (hardware + software)

Remote spectral imaging (PRISMS)
Portable automated microfading spectrometry

Overview

• What is OCT?
• How does it work?
• How to interpret an OCT image?
• Example applications of OCT to different conservation, art history & archaeology problems
• Types of OCT
  – Time domain versus Fourier domain
  – Raster scan versus full field/parallel scan
  – Functional OCTs: Polarisation sensitive OCT, Spectroscopic OCT, Doppler OCT
• Which OCT is right for your application?
What is OCT? How does it work?

Optical Coherence Tomography (OCT) – an imaging Michelson interferometer

• Designed for in vivo 3D scanning of the eye
• Needs a broadband laser for high depth resolution
• Capable of imaging subsurface microstructure of transparent and semi-transparent material in the NIR

Interference of monochromatic light
Fringes due to two monochromatic light sources of different wavelengths

Black curve is the sum of the two

Optical path length difference

Fringes of 3 monochromatic light sources of different wavelengths

Black curve is the sum of the three fringes

Optical path length difference

The broader the spectral bandwidth of the source, the narrower the fringe envelope

Metrology - distance measurements

- White light interferometer
  - Replace one of the mirrors with the object to be measured
  - Allow the second mirror to scan back & forth

Optical path length difference
Optical Coherence tomography (OCT)
- Imaging white light interferometer
- Free space or fibre based Michelson interferometer using special light sources – broadband lasers (e.g. a superluminescent diode = SLD)
- Virtual cross-section or 3D subsurface volume imaging
- The name OCT was coined in 1991 and applied to the 3D imaging of the eye
- OCT has been applied to conservation/heritage science since 2004*

Resolution
- Advantage of OCT: depth resolution decoupled from transverse resolution
- Transverse resolution determined by
  \[ \Delta x = \frac{\lambda}{D} f \]
  where D is the diameter of the beam, f is the focal length
- Depth (axial) resolution given by
  \[ \delta z = \frac{2 \ln 2 \lambda^2}{\pi n} \frac{\lambda_0}{\Delta \lambda} \]
  where \( \lambda_0, \Delta \lambda \) are the central wavelength and bandwidth of the laser, n is the refractive index of the sample

How to interpret OCT images?

* Yang et al., Archaeometry, 2004
Targowski et al., Studies in Conservation, 2004
Liang et al., SPIE, 2004;
Liang et al. Optics Express 2005

OCT image of ancient Egyptian core formed glass

British Museum reference collection
Layers of blue glass
Air bubble
Brown crystals

A microscopy image of the cross-section at the broken edge

OCT virtual cross-section images

Liang et al. SPIE 2008
Physical & optical thickness - refractive index of paint layer

- OCT measures the optical thickness = (Refractive index) x (thickness)

Madder lake in linseed oil painted on a glass slide

Raw OCT cross-section image

True cross-section image after correction for refractive index

Spring et al. ICOM-CC 2008

Optical scattering & absorption properties of paint limitation to penetration depth

Single scattering

Madder lake in oil

Single scattering ~ multiple scattering

Madder lake in egg tempera

Multiple scattering dominates

Ti White in oil

Absorption

Charcoal

Liang et al. Applied Physics B 2013

Ghost images or image artefacts

Artifacts due to interference between interference in the sample and interference between interfaces

A transparent plastic sheet with a finite thickness placed above a flat glass surface

OCTs in ISAAC lab (those developed in our lab are in red)

<table>
<thead>
<tr>
<th>λ (nm)</th>
<th>Δx (μm)</th>
<th>Δy (μm)</th>
<th>Speed (fps)</th>
<th>Penetration depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>810</td>
<td>1.2</td>
<td>7</td>
<td>50</td>
<td>Moderate</td>
</tr>
<tr>
<td>930</td>
<td>4.5</td>
<td>9</td>
<td>2</td>
<td>Moderate</td>
</tr>
<tr>
<td>1300</td>
<td>4</td>
<td>7-13</td>
<td>100</td>
<td>Moderately deep</td>
</tr>
<tr>
<td>1960</td>
<td>6</td>
<td>17</td>
<td>3</td>
<td>Deep</td>
</tr>
</tbody>
</table>

Ultra-high resolution (UHR) OCT at 810 nm

Commercial OCTs at 930 nm, 1300 nm

Long wavelength OCT at 1960 nm
Conservation applications

- Conservation assessment
- Monitoring cleaning of varnish
- Monitoring drying of varnish
- Detecting extent and area of loss
- Paint cross-section and degradation
- Early warning of glass degradation
- Degradation of enamel
- Revealing cracks in different depth
- Measuring speed of water transport in rocks

Gaspard DUGHET
Landscape with a Storm (NG 36)
Date: c.1653-54
Date entered National Gallery Collection: 1824

Monitor cleaning of varnish

=> monitoring the cleaning of varnish with OCT

Liang et al. Conservation Science 2007
New mastic varnish
Old discoloured varnish
Pale blue paint
Mastic and boiled linseed oil varnish (1991)

OCT imaging of layers of new and degraded varnish

Quantitative analysis of solvent cleaning of varnish
OCT can perform multilayer profilometry to 50 nm accuracy depending on surface roughness

before
after
before
after

Liang et al., SPIE, 2008

Dynamic monitoring of drying of varnish
– the quest for the perfect varnish
An ideal varnish
• has the right material properties (rheological properties) to form a dry layer with the right smoothness
• does not degrade easily

Monitoring the drying of varnish (blue profile) over a rough substrate (black profile)
Lawman & Liang, Applied Optics, 2011

Power spectrum of two varnish surfaces compared with models

Two varnishes:
I. AYAT polymer in toluene
II. Regalrez monomer in toluene

Applied to a rough substrate & measured with OCT (solid curves)

Model based on the lubrication approximation of the Navier-Stokes equation (dashed curves)

Lawman & Liang, Applied Optics (2011)
Dynamic monitoring of drying varnish
refractive index change as a measure of evaporation rate & concentration change

\[ n = \frac{t}{t_0} \]

Lawman & Liang Applied Optics 2011

Aelbert Cuyp, The Large Dort (NG961), oil on canvas, about 1650

OCT cross section

normal light ultraviolet light

Spring et al. ICOM-CC 2008

normal light ultraviolet light
UHR OCT imaging of modern painting: The Mellow Pad (1945-1951) by Stuart Davis

Brooklyn Museum
02/2016

Ford et al., AIC, 2016 (in press)

OCT imaging of Mogao cave paintings in the Gobi desert along the Silk Road (UNESCO world heritage site)
- Depth resolved crack patterns

OCT in situ imaging of Mogao cave paintings in the Gobi desert along the Silk Road (UNESCO world heritage site)

OCT Imaging of Wall Painting at Tower of London

OCT scanning of Tower of London painting
The probe is fixed on a XYZ stage

Liang et al. SPIE, 2011
Monitoring water transport in rocks – probing vulnerability of rock art panels

Rock art panels in Northumbria, UK

Bemand & Liang, Applied Optics 2013

Deterioration of ancient Egyptian glass

British Museum Collection

Liang et al, SPIE 7139, 2008

Degradation of cover glass for Daguerreotype – UHR OCT image

- 1839 Daguerre invented Daguerreotypes
- Down House displays six Daguerreotypes of the Darwin children with their original cover glass from 1842-1851

English Heritage

UHR OCT virtual cross-section image of enamel in English Heritage collection at Ranger House

Imaging degradation of Limoges enamel

4 mm
Art history applications

- Underdrawings
- Paint sequence
- Paper identification

OCT imaging of underdrawings

Liang et al. Conservation Science 2007
After Francesco Francia, *Virgin and Child with an angel* (NG 927). Detail of the angel’s eye

Spring et al. ICOM-CC 2008

Near Infrared image at 880nm


Paper classification

Royal Horticultural Society Reeves Collection of Chinese export watercolours

OCT depth profile

OCT cross-section image

OCT surface image

Manuscript on parchment from the Fitzwilliam Museum

- UHR OCT cross-section imaging of the paint thickness & sequence

OCT in situ imaging of Mogao cave paintings in the Gobi desert along the Silk Road (UNESCO world heritage site)

Archaeology applications

- Jade tool marks
- Faience microstructure
- Glass manufacturing
Identification of tool marks

BM 1947,0712.515, c. 2600-2200 BC, late Shijiahe culture (石家河文化), photo courtesy of British Museum.

OCT virtual cross-section image

OCT imaging of ancient jade - tool marks

• Concave longitudinal profile => wheel cut

BM collection, 1973,0726.130, Ming/Qing dynasty, photo courtesy of British Museum.

OCT as profilometer – surface profile plot

Identification of tool marks

BM 1947,0712.515, c. 2600-2200 BC, late Shijiahe culture (石家河文化), photo courtesy of British Museum.

OCT virtual cross-section image

OCT imaging of ancient jade - tool marks

BM 1947,0712.107, Han dynasty.

SEM image

OCT image
Method of manufacturing Egyptian Shabti

BMRL16322 – Egyptian Shabti Late Period

Non-invasive investigation of ancient manufacturing technique

Manuscripts – Fadden More Bog bible leather cover (imaged while it was wet)
OCT laser safety

• The most light sensitive pigment realgar (fades in <1 min with microfade) was tested when the laser (central wavelength at 810nm) dwelled at the same spot for 400 times longer than it takes to collect an OCT image => no change in reflectance spectrum

• OCT is safe BUT make sure you block the laser when not imaging

<table>
<thead>
<tr>
<th></th>
<th>P (mW)</th>
<th>Spot size (μm)</th>
<th>t dwell (s)</th>
<th>I (W/cm²)</th>
<th>Fluence (J/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microfade</td>
<td>2</td>
<td>500</td>
<td>60</td>
<td>1</td>
<td>60</td>
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<tr>
<td>OCT</td>
<td>1</td>
<td>10</td>
<td>1e-5</td>
<td>1.3e3</td>
<td>0.013</td>
</tr>
<tr>
<td>Raman</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>5.1e3</td>
<td>5100</td>
</tr>
</tbody>
</table>

Which OCT suits your application?

Consider
• Central wavelength
• Axial resolution
• Transverse resolution
• Speed of capture

Types of OCT

➢ Raster scan, parallel or full field OCT
  • Raster scan – most commonly used
  • Parallel scan/full field – faster but problem with cross-talk

➢ Time or Fourier domain
  • Time Domain OCT (TD-OCT)
  • Fourier Domain OCT (FD-OCT)

➢ Functional OCT
  • Spectroscopic OCT
  • Polarisation sensitive OCT
  • Doppler OCT

Time domain OCT

• Time Domain OCT (TD-OCT) – scanning in depth by moving the reference mirror

SLOW    Sensitivity constant with depth
Fourier domain OCT

Reference mirror fixed
- Spectral Domain OCT – the interference signal is registered as a function of wavelength through a spectrometer => FFT => image
- Swept Source OCT – the interference signal is collected by sweeping through the source spectrum => FFT => image

FAST high sensitivity
Sensitivity decreases with depth

Resolution
- Advantage of OCT: depth resolution decoupled from transverse resolution
- Transverse resolution determined by
  \[ \Delta x = 1.22 \frac{\lambda}{D} f \]
  where \( D \) is the diameter of the beam, \( f \) is the focal length.
- Depth (axial) resolution given by
  \[ \delta z = \frac{2 \ln 2 \lambda_0}{\pi n} \frac{1}{\Delta \lambda} \]
  where \( \lambda_0, \Delta \lambda \) are the central wavelength and bandwidth of the laser, \( n \) is the refractive index of the sample.

Depth range
- To achieve higher transverse resolution means shorter depth of field – depth range reduced
  \[ z_{\text{max}} = \frac{\pi \Delta x^2}{\lambda} \]
  \[ \Delta x = 1.22 \frac{\lambda}{D} f \]
- For Fourier domain OCT, the depth range is further limited by the spectral resolution of the spectrometer or the line width of a swept source.
- Opacity of the sample is more often the limiting factor for depth range than instrumental depth range.

Fourier domain OCT
Spectral resolution limits effective depth range

Top interface
Bottom interface
Bottom interface with limited spectral resolution => fringe contrast reduced.
Special feature of OCT

- Depth resolution decoupled from transverse resolution
  - Transverse resolution determined partly by the objective lens
  - Depth resolution determined by source spectral bandwidth
- Most layer structures are smooth but thin

\[ \Rightarrow \text{high depth (axial) resolution is important} \]
\[ \Rightarrow \text{no need for very high transverse resolution} \]
\[ \Rightarrow \text{better to have large } x-y-z \text{ field of view} \]

Varnish and paint layers

10 mm

1.6 mm

Speed of capture

- Fourier domain OCT is much faster than time domain OCT for the same sensitivity, current speed for capturing an image cube of 500 x 500 depth profiles => 10s to 3s
- BUT for the same OCT the longer exposure time (slower) images are better quality than the images captured with faster speed
- For Fourier domain OCT the maximum speed of capture is determined by the camera readout speed
- For most applications in heritage science speed of capture is a secondary consideration

New Generation OCT for Heritage Science

- Increase depth resolution towards 1 \( \mu \)m while maintaining high sensitivity & dynamic range
  - Axial resolution \( \Delta z = \lambda^2 / (4 \Delta \lambda) \) = broadband laser (BW~200 nm) at short central wavelength (~800 nm)
- Increase depth of penetration
  - OCT at longer wavelength (~2\( \mu \)m) to reduce scattering

Ultra High Resolution (UHR) Fourier Domain OCT at 810nm

- Depth resolution 1.2 \( \mu \)m in varnish and paint
- Transverse resolution 7 \( \mu \)m
- Speed of acquisition ~40 \( \mu \)s per depth profile
  \[ \Rightarrow 20 \text{ ms per cross-section image} \]
  \[ \Rightarrow 5 \text{ mm} \times 5 \text{ mm} \times 2 \text{ mm volume in 10s} \]
- Power incident on object ~1 mW

Chung, Spring, Liang, Optics Express, Vol. 23(8), pp. 10145-10157 (2015)
Ultra-high resolution OCT

- Ultra-high resolution OCT ~1 micron resolution
- An image cube in 10s

UHR OCT virtual cross-section image of enamel in English Heritage collection at Ranger House

- Difficult to see the gel layer without high axial resolution

Importance of resolution

- 815nm UHR OCT
- 930nm commercial OCT

After Raphael, The Madonna and Child (NG 929)
probably before 1600, Oil on wood, 87 x 65.3 cm

Cheung, Spring, Liang, Optica Express, Vol. 23(8), pp. 10145-10157 (2015)
Importance of Sensitivity

Ultra-high resolution 810nm OCT

930nm OCT

=> not all the layers are seen

(3 instead of 5 layers)

Top surface

5 mm

Multi-layers with different scattering properties

Bottom surface

What resolution do you need?

• Depends on the features you want to image
• High resolution is not always the best - if the features of interest is diffuse, high resolution may not be the best

Importance of wavelength for depth of penetration

• Need to find optimum spectral band for OCT

930nm OCT image overlaid

InGaAs NIR camera (900-1700 nm)

After Raphael, The Madonna and Child (NG 929) probably before 1600. Oil on wood, 87 x 61.3 cm


Multiple Scattering masks layers

Transparent at 1300nm, but multiple scattering masked the layer
Optimum Spectral Window for OCT imaging: 2.2 μm

- Scattering coefficient decreases with increasing wavelength
- Copper-based pigments, azurite, malachite and verdigris, have minimum transparency corresponding to absorption troughs between 0.7 and 1.0 μm;
- Cobalt pigments have minimum transparency corresponding to the broad absorption trough at 1.3–1.6 μm.

High resolution Fourier domain OCT at 1960 nm

- FDOCT using FLIR InSb camera (640x512 pixels) as detector
- Axial resolution ~ 6 microns (in polymer)
- Incident power 1-2 mW
- Fast frame rate (2.7kHz) using 4x640 pixels

=> 6mm x 6mm area in 2 mins


Mediam spectral transparency normalized at 2.2 μm for pigments in use before the 19th century but excluding lake pigments.

Blue – oil paint
Red – egg tempera paint

Liang et al. SPIE Vol. 9527, 952705 (2015)
Cobalt blue in oil

Indigo

Long wavelength OCT for deeper penetration

2 micron OCT – best underdrawing image

Composite textile

Working distance of 4cm

1960nm OCT

930nm OCT

Which wavelength do you need?

- Long wavelength for deeper penetration into highly scattering material
- Shorter wavelength for transparent material that require high resolution

References

- Free download of full text for all the papers published by my group
  [http://rd.ntu.ac.uk/rdp/researchpublications.php?pubid=1866abac-8395-4d09-b763-637da94f532a](http://rd.ntu.ac.uk/rdp/researchpublications.php?pubid=1866abac-8395-4d09-b763-637da94f532a) or go to my web profile
  [https://www.ntu.ac.uk/staff-profiles/science-technology/haida-liang](https://www.ntu.ac.uk/staff-profiles/science-technology/haida-liang) and click on ‘go to Haida Liang’s publications’
- For all OCT publications in heritage science see

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