9th International Conference on NDT of Art, Jerusalem Israel, 25-30 May 2008
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OPTICAL COHERENCE TOMOGRAPHY FOR NON-DESTRUCTIVE INVESTIGATIONS OF STRUCTURE OF OBJECTS OF ART

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ABSTRACT

In this contribution the Optical Coherence Tomography (OCT), as a novel tool for non-invasive structural imaging of selected objects of cultural heritage, will be reviewed. This technique relies on multispectral interference of infrared light and therefore is well suited for investigation of transparent and semi-transparent structures. The technique originates from medical imaging and has been present in conservation science since 2004. Until now it has been successfully utilized in imaging of varnishes, glazes and underdrawings of paintings, glazes on porcelain and faience, structure of archaic jades, stained and archeological glass, parchment and recently for revealing the surface details of varnished punchwork. Authors of this paper are active in this field from the very beginning and will report their own results obtained with OCT technique.

The physical background of the OCT method will be shown in an accessible manner. Then advantages and disadvantages of various modalities of the technique will be discussed. However, the major emphasis will be laid on applications. Examples of imaging of the layers of varnish and semi-transparent glazes of paintings will be presented. The thickness of these layers may be directly measured with OCT in completely nondestructive, quick and convenient way as many times as necessary. The application of these images for real-time monitoring of conservation treatments as well as for authentication of signature will be shown. Another important and perspective application of OCT is examination of stained and archeological glass. We use this technique for nondestructive evaluation of in-depth range of atmospheric corrosion and in our contribution we present results obtained from various samples of stained glass.

INTRODUCTION

Non-invasive methods for examination of artworks have been in focus of interest of conservators and art historians since over a century – X-rays were used for inspection of underneath layers of paintings (Bridgman 1974) shortly after being discovered. At present many other methods, also often originating from medicine, are used for non-invasive examination of objects of art. In addition to standard radiography, 3D imaging with an aid of computed tomography (CT) is used in examination of various art objects successfully. However the resolution offered is not sufficient for examination of paintings. Among other methods X-ray fluorescence (Woll, Bilderback et al. 2005), neutron-induced autoradiography (Taylor, Cotter et al. 1975), high-energy proton-induced X-ray emission (PIXE) (Griesser, Denker et al. 2000) and most popular IR reflectography should be mentioned (Boutaine 2006). Unfortunately, these methods lack in-depth resolution: although they permit identification of certain components of the object, their precise location within the piece remains unknown. This disadvantage is significant especially in examination of objects composed of thin layers e.g. easel paintings.

The optical sectioning offers resolution in micrometer range due the short wavelength of radiation used. Confocal laser scanning microscopy (CLSM) enables obtaining three-dimensional images of the internal structure of oil paintings even with submicron resolution.

It can utilise both visible and ultraviolet light (Jane, Barker et al. 1995), (Wei, Frohn et al. 2007). However, the depth of imaging is limited by the range over which light can propagate in the media examined and the investigated field is very small.

Another method utilising light for structure examination is Optical Coherence Tomography (OCT). In this case the in-depth (axial) resolution is obtained by means of interference of light of high spatial (to ensure sensitivity) and low temporal coherence. The broader light source is used, the higher axial resolution is achieved. In practice, IR sources of bandwidths from 25 to 150 nm are utilised. Resolutions obtained ranges from 10 down to 2 μm in the media of refracting index equal 1.5. All OCT instruments fall into two general groups: Time domain (TdOCT, developed firstly) and Fourier domain (FdOCT, most popular at present). Time domain systems require in-depth scanning with an optical delay line of mechanically changed length and therefore are rather slow. In FdOCT systems, the information on the location of all scattering centres along the probing beam is encoded in fringe pattern superimposed on the spectrum of the light source. This results in lack of mechanical in-depth scanning elements and thus about a hundred fold increase of data collection speed. FdOCT instruments utilising spectrographs as detectors are usually referred to as Spectral OCT systems. In this case, due to the multiplexing advantage, the sensitivity is significantly (about 20 dB) increased.

The obvious limitation of the method lays in the transparency of medium being investigated to infrared light (Szkulmowska, Góra et al. 2007), (Liang, Peric et al. 2007). Therefore OCT is mostly used for the examination of transparent and semi-transparent structures like varnishes and glazes in easel paintings (Targowski, Rouba et al. 2004), (Liang, Cid et al. 2005), (Arecchi, Bellini et al. 2006). It is possible to measure thickness of these layers non-invasively in as many places as desired. If the axial resolution permits, the superimposed layers of different varnishes (e.g. retouching and original) can be discerned. The method may be also used for identification of position of certain pigmented layers, like signatures, within the varnish-glaze structure (Tymińska-Widmer, Targowski et al. 2007). The penetrating power of the infrared light in combination with the high contrast of coherent imaging was also successfully used to imagine underdrawings (Liang, Cid et al. 2005). Recently the high resolution OCT instrument was utilised for revealing the surface details of varnished punchwork (Adler, Stenger et al. 2007). Among other applications an increasing attention is given to imaging of the structure of both archaeological and stained glass (Liang, Peric et al. 2007), (Targowski, Rouba et al. 2008). In case of well preserved objects taking samples is not possible and OCT permits non-invasive inspection of their internal structure, including the range of corrosion processes.

Another interesting application for imaging of internal structures of archaic jades was described in 2004 (Yang, Lu et al. 2004) but not developed further unfortunately. Other objects investigated with OCT were samples of parchment with iron gall ink (Góra, Pircher et al. 2006) and porcelain and faience (glaze layer only) (Targowski, Góra et al. 2006b).

High speed variation of OCT technique permits real-time imaging of certain conservation process like varnish laser ablation (Góra, Targowski et al. 2006), (Targowski, Rouba et al. 2008) and tracking deformation of paintings caused by changeable environmental conditions (Targowski, Góra et al. 2006a).

EXPERIMENTAL

All the tomograms presented in this paper have been obtained with a prototype SOCT instrument based on an optical fibre Michelson interferometer set-up (Fig. 1), constructed at the Nicolaus Copernicus University in Toruń (Poland). The instrument utilises as the light source a broadband (Δλ = 50 nm, central wavelength 845 nm) superluminescent diode (LS). The light of high spatial but low temporal coherence is launched into a single mode 3dB fibre coupler (FC). To protect the light source from the light back-reflected from the elements of the interferometer, an optical isolator (OI) is inserted between the source and the coupler. After passing the coupler light propagates in two arms of the interferometer: an object and a reference ones. In the reference arm light passes through a polarization controller (PC) to provide optimal conditions for interference, the neutral density filter (NDF) for adjustment of the power of light to achieve the shot-noise-limited detection and a block of glass acting as a dispersion compensator (DC). The light is then back-reflected from the stationary reference mirror (RM) to the reference arm fibre and coupler (FC). The object arm comprises transversal scanners (X-Y) and lens. The light beam is scanned across the object and backscatters and/or reflects from the elements of its structure and returns to the coupler FC. Light returning from both arms of the interferometer is brought to interference and further analyzed. In the instrument described here, the Fourier domain detection of spectral signal is employed. Therefore, to collect this signal a spectrometer is utilised. It comprises a volume phase holographic grating (DG) with 1200 lines/mm and an achromatic lens (SL) which focuses the spectrum on a 12 bit single line CCD camera (2048 pixels, 12 bit A/D conversion). The spectral fringe pattern registered by this detector is then transferred to the personal computer (COMP). This signal after the Fourier transformation yields one line of the cross-sectional image (A-scan). Scanning across the sample with transversal scanner (X-Y) enables collecting a 2-D cross-sectional image (B-scan). Additional scanning in the perpendicular direction gives 3-D information about the spatial structure of the sample.

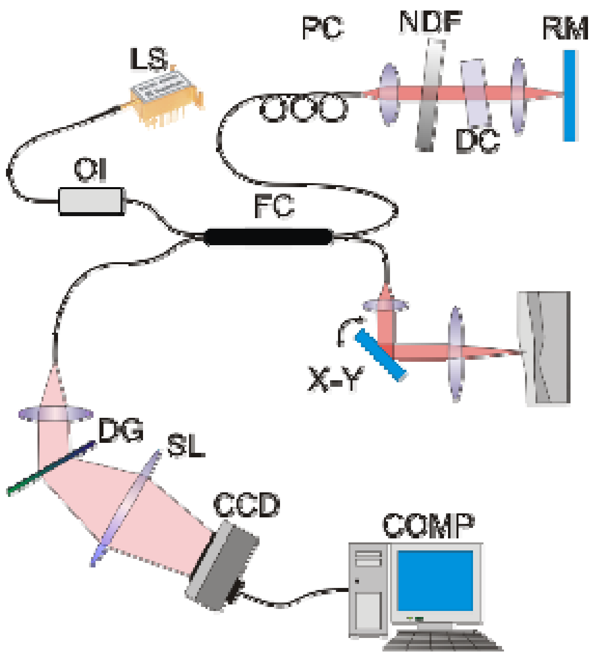

Figure 1. Schematic of the SOCT instrument. LS – light source; OI – optical isolator, FC – fibre coupler, PC – polarisation controller, NDF – neutral density filter, DC – dispersion corrector, RM – reference mirror, X-Y – transversal scanners, DG – diffraction grating, SL – spectrograph lens, CCD – single line CCD camera, COMP – computer

In the forthcoming section examples of utilisation of the SOCT instrument will be given. All tomograms are shown in falsecolour: red and green colours indicate regions revealing a high level of the backscattering of the penetrating light, while blue points to low-scattering areas. Tomograms in figures are oriented accordingly to the direction of scanning - light approaches from the left (for vertical scanning) or top (for horizontal scanning). Thus the first strong line represents the air-material interface. For better legibility of structure details, tomograms have in-depth scale expanded. The scale bars in figures represent distances in the air and may be directly used for estimation of the surface roughness. However, all in-depth distances below the surface are expanded by the factor equal to refractive index n_R of the examined medium. This expansion is occasioned by the fact that all measured distances are optical ones. Therefore, if the scale bar provided is used, all distances obtained in-depth should be divided by n_R (number 1.5 may serve here as an acceptable estimation). It is worthwhile to note that the axial resolution in medium is increased by the same factor n_R if compared to the resolution in the air.

RESULTS

Easel Paintings

The first example under consideration is an oil painting on canvas of unknown origin titled *Virgin and Child* (Fig. 2). The picture is well preserved and thus the possibility of sampling is strictly limited.

Figure 2. 'Virgin and Child' – oil on canvas. Letters correspond to macrophotograps in Fig. 3

The problem to be resolved was the authenticity of a thick and uneven brown glaze layer applied in some areas of shadows with characteristic beads-like structures on its surface. To investigate this, a series of OCT tomograms has been collected. In Fig. 3 exemplary tomograms are shown in an upper row, whereas corresponding photographs in the bottom indicate the fragments of the painting where examination was carried out. In the tomogram in Fig. 3a the brightest line (first from the left) indicates picture's surface. In the highlight area of the painting (upper part of the tomogram) a low-scattering varnish layer is clearly visible as a darker band directly underneath the surface line. In the area of shadow (bottom of the tomogram) this structure is not recognizable. Instead, a thick moderately scattering layer of different optical properties is visible directly under the surface line. Beneath this layer, a thin transparent layer (possibly original glaze or varnish) is discernible. Similar structure and sequence of layers can be observed in Figs 3c, although the image was recorded in a different area of the picture. In both cases tomograms suggest that the uppermost thick layer present in shadows may be not original as it is not covered with varnish layer observed in the areas of highlights. On the contrary, the structure of painting registered at the Child's eye (Fig. 3e) that seems to be original, is clearly different: the thick semi-transparent layer in dark parts is not present. Both lights and shadows are homogeneously covered with a continuous varnish layer. In shadows an additional glaze layer beneath the varnish is clearly visible.

The analysis of all tomograms allowed one to draw a conclusion that in the studied painting there are at least two different types of outward layer in shadows: one thick and pigmented – present at some areas of deep shadows at the Virgin and Child's figures, and another one, thin, transparent (like a varnish) covering a separate dark glaze layer together with highlights of the painting present at areas of models' complexions.

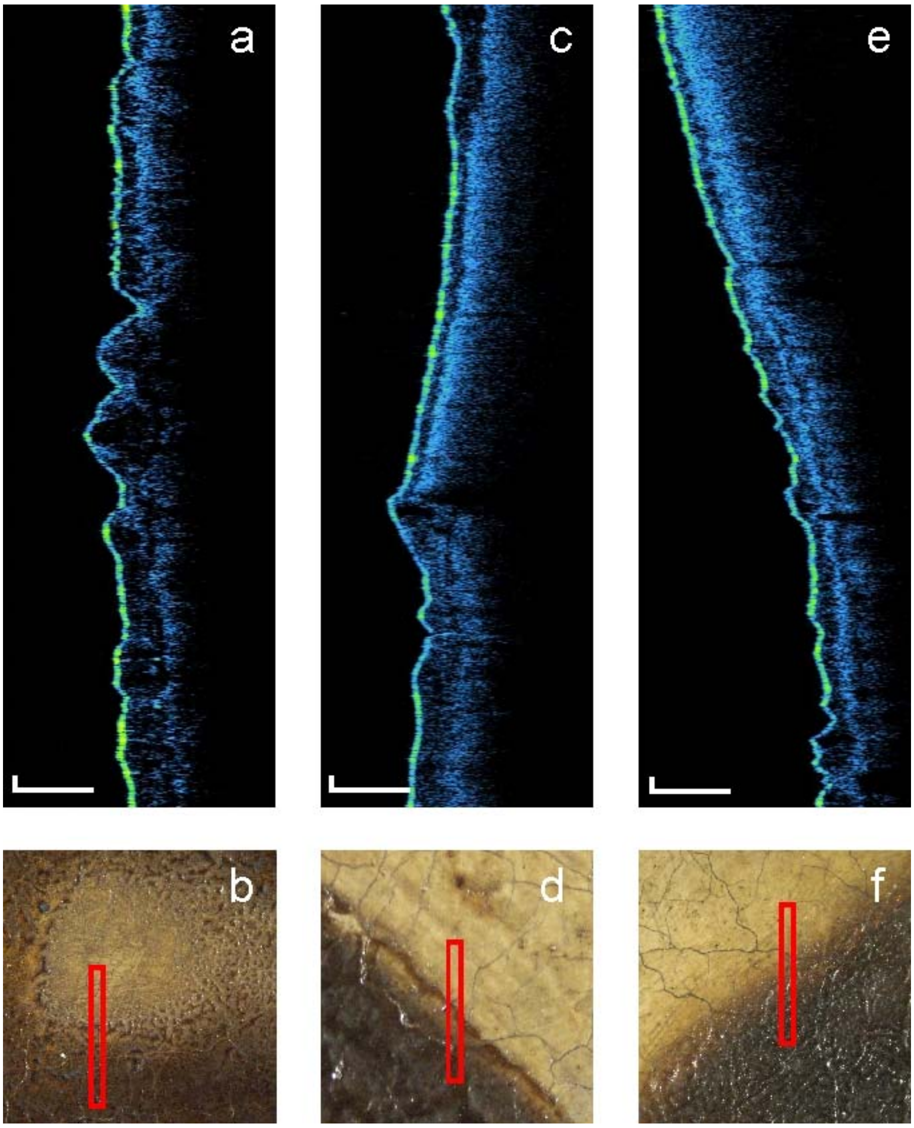

Figure 3. (a) OCT tomogram from the Child's leg and its location (b); (c) OCT tomogram of the Child's hand and its location (d); (e) OCT tomogram of the Child's eyebrow and its location (f). Bars indicate 200 μm

In the examination of this picture, OCT was also applied to the analysis of its physical condition. In Fig. 4 the tomogram taken from an area of surface abrasion is presented. It is quite evident that the damage is limited to the uppermost, thick and brownish layer.

Furthermore, an internal crack (arrow) at boundary between this layer and the underneath opaque paint layer is clearly visible.

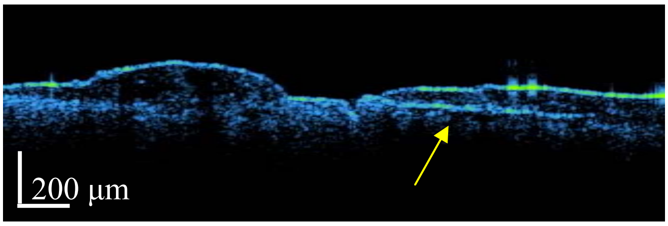

Figure 4. OCT tomogram from the proximity of the defect localised at the boundary between shadow and light areas of the painting

In addition to collecting single 2D images (Fig. 3-4) the instrument used in this study is also capable of accumulating a series of parallel slices (B-scans). These slices may be then combined together to obtain 3D (volume) information of the examined sample. In the case of data presented in Fig. 5, 200 parallel B-scans were collected over 15 x 15 mm area of varnished paint layer. Then the automatic edge recognition procedure was used at every B-scan to localise the picture surface and subsequently the boundary between varnish and paint layer. As one can see from the tomogram, the shape of both surfaces is distorted somehow by optical aberrations. However, the thickness data, as a differential result, are free from this artefact. From these data the varnish thickness may be easy calculated and combined into the false colour map (Fig. 5b).

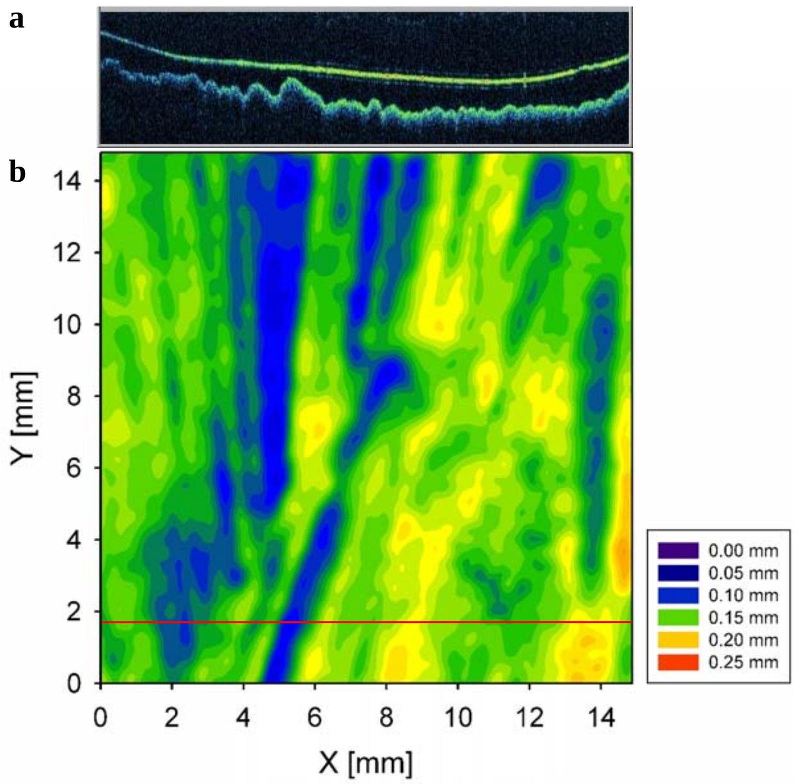

Figure 5. (a) One of 200 OCT tomograms of the varnish layer over the fragment of oil paint. (b) A thickness map of the varnish layer obtained from a series of tomograms. The thickness is coded in false colours, red line indicates position of the tomogram shown in fig. a

Data presented in Figure 5 illustrate significant heterogeneity of the varnish layer: within this small area thickness varies from 0.1 to 0.25 mm and the negative of brush strokes of paint layer levelled by varnishing is clearly visible. The advantage of non-invasive OCT measurements over usual technique utilising a microscopic analysis of the cross-section of the sample collected from the picture is thus evident. It is never possible to take so many samples and the information obtained is not fully representative. The OCT examination is fast, relatively inexpensive and may be repeated as may times as necessary due to non-invasive character. Therefore results obtained with this method are much more reliable.

Historic Glass

The examination of the condition of historic glass is important for both conservation and inventory purposes. The major ageing process that any historic glass undergo is water corrosion of its surface. It usually leads to hydration of the surface layer of the glass. The knowledge of its range and extent of this decay is important for planning of conservation treatment and for adjustment of the storage conditions. The problem is particularly important for medieval stained glass which for centuries was exposed to very hostile environment. Rains and lately acid rains from outside and moisture condensation from inside are the major sources of progressive destruction of stained glass windows in churches in Kraków (Cracow), Poland. In Fig. 6 an OCT tomogram of the inner surface of the 14th c. glass window from St. Mary's church in Krakow is shown. In the picture the range of corrosion process in clearly visible and may be estimated to 0.11 mm. In a few places glass chips flaked off the glass surface leaving holes of the 40-80 μm depth. In the area where corrosion is not visible, the glass surface was covered with the deposit non-transparent to the IR light used for examination.

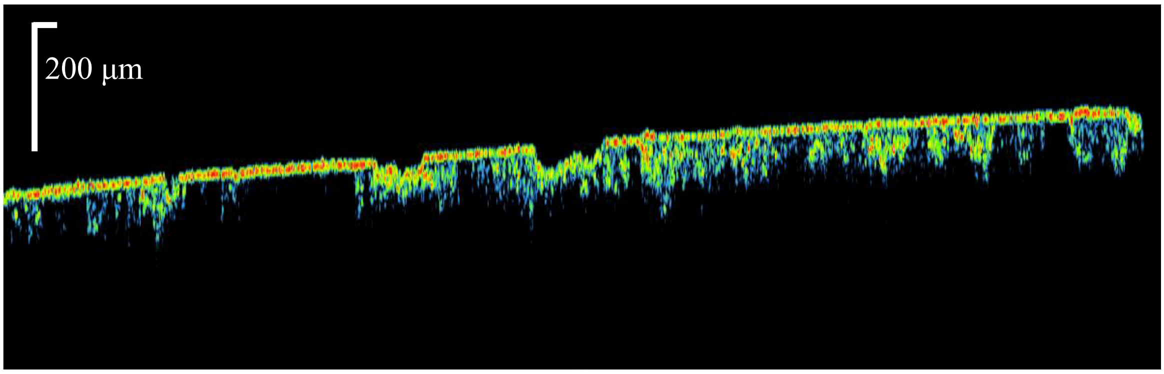

Figure 6. OCT tomogram of the inner surface of 14th c. window glass from St. Mary church in Kraków, Poland. Glass corrosion is clearly visible

Since the technique is non-destructive, it may be applied directly to objects in any desirable place whilst the most popular sampling techniques are limited to glass edges both natural or caused by damage.

CONCLUSIONS

Optical Coherence Tomography when used to examination of easel paintings may be helpful in determination of the structure of its outward, semi-transparent layers. Since the method may be applied many times and at many locations, the information gained is more representative than obtained from traditional sampling. However, for the univocal identification of structures imagined, it is recommended to compare tomograms with a microphotograph of a cross-section of the sample taken in painting's region allowed by conservation ethics.

In certain cases, when the identification of clear varnish layer is obvious, the method may be used with strong confidence even without sampling, also for monitoring of restoration treatments concerning this layer.

In case of examinations of glass, the major advantage of using OCT lies in practically unlimited number of cross-section images which may be collected in a short time. If the glass surface is clean and glass is transparent to IR light, no further sample preparation is necessary. This is especially important for museum collections of archaeological glass, usually composed of hundreds of pieces. In such case sophisticated methods, like back-scattered electrons (BSE) in scanning electron microscopy are too slow and thus too expensive. A quick, inexpensive method for estimating condition of glass artefacts may help to establish proper storage environment and thus to avoid dehydration of objects. Similarly, this convenient technique for estimating condition of stained glass, in nearest future portable and thus applicable *on-site* in the church, should be useful as an supplementary tool for the art conservator. However, to fully benefit from this technique, further investigation especially towards proper interpretation of results obtained, is necessary. The preliminary data were collected and analysed by authors of this contribution and results has been reported already (Kunicki-Goldfinger, Targowski et al.).

As for both applications of the OCT technique described in this contribution, a further effort is necessary to improve in-depth resolution of imaging. This mostly depends on implementation of new technologies, especially new broadband light sources. Resolutions of about 6 μm are already on-hand for semi-portable devices, but 2 μm resolution in the medium of $n_R = 1.5$ looks like a reasonable target for future designs. It is expected that this will finally permit taking a full advantage of the OCT technology for artwork diagnostics and other conservation purposes.

ACKNOWLEDGEMENT
This work was supported by Polish Government Research Grants through the years 2003-2006 and 2008 -2011.

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