

Application of graphically oriented programming to imaging of structure deterioration of historic glass by Optical Coherence Tomography

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ABSTRACT

Optical Coherence Tomography (OCT) is an interferometric method utilising light of low temporal coherence for non-invasive structural imaging of objects weakly absorbing and scattering light. In this contribution, using various examples of images of objects made of glass affected by the atmospheric corrosion and/or by crizzling, we demonstrate a software developed in our laboratory specifically for 3D OCT imaging of samples with a fine structure. For this task we employed the OpenGL platform (Open Graphics Library), an Application Programming Interface (API) for writing applications dedicated to interactive 3D computer graphics. In our application we have utilized texture rendering with a modulation of transparency and a colour as a function of elevation.

Keywords: Optical Coherence Tomography, structural analysis, non-invasive testing, glass, crizzling, OpenGL, computer graphics

1. INTRODUCTION

Structural imaging of three-dimensional objects needs specific methods of data collection and processing. Despite of application of the most adequate method of data acquisition, proper way of data presentation is also very important for taking full advantage of the examination technique chosen.

Optical coherence tomography (OCT) is a tool for non-invasive structural imaging by sectioning with infrared light. In this method, the location of scattering centres within the internal structure of the object is determined by means of interferometry and visualized. The technique originates from diagnostic medicine but its application to any object, which weakly absorbs and/or scatters light, is straightforward [1]. The OCT has been used in conservation science since 2004 [2,3,4,5] for structural imaging of objects at least partially transparent to infrared light [6,7]. Therefore, structures in easel paintings such as varnishes and glazes were examined with OCT mostly, especially for identification of position of certain pigmented layers [8], imaging of underdrawings [2,9] and revealing the surface details of varnished punchwork [10]. Modern OCT instruments, fast enough to work in real time, are utilized for monitoring such conservation processes as laser ablation of varnish [8,11,12] and LIBS analysis [13]. Recently the OCT has been applied to structural imaging of glass artefacts [6,8,9].

In optical imaging of structure of glass the major advantage is in its bulk transparency. It usually permits investigating the phenomena occurring at one glass surface from the another side, through its volume. However, imaging of the structure of glass creates some specific problems which need addressing.

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In this contribution we demonstrate various examples of OCT imaging of objects of historic deteriorated glass. The major attention will be given to samples of stained glass affected by an atmospheric corrosion and to glass with crizzling. These glass ‘diseases’ need not only specific methods of data collection but also dedicated techniques of presentation of obtained results.

2. METHOD AND INSTRUMENTATION

The OCT method utilises light of low temporal (to ensure high axial resolution) and high spatial (to ensure high sensitivity) coherence. Thus broadband light sources with a spectrum span from 50 to 150 nm are implemented in OCT tomographs. There are two variants of this method: time domain OCT (TdOCT) [14] and Fourier domain (FdOCT) [15]. At present, the second approach is more popular. In this case structural information is extracted from the spectrum of the interference signal by means of Fourier transformation. The two-dimensional image of the cross-section of the object is usually called a B-scan, by analogy to ultrasonography. Depending on the spectral parameters of the light source, the Spectral OCT devices have different resolutions and in-depth measuring ranges. However, the practical imaging depth in an object depends on the depth of its penetration by examining light. Therefore the transparent and semi-transparent objects, like glass, are very well-suited for OCT investigation.

All results to be presented have been obtained with a Spectral (Fourier domain) OCT instrument constructed at the Nicolaus Copernicus University in Toruń (Poland) [16]. The instrument utilizes two coupled together superluminescent diodes as a broadband light source ($\lambda = 845 \text{ nm}$, $\Delta\lambda = 107 \text{ nm}$). The axial and transverse resolutions of our OCT tomograph are equal $4 \mu\text{m}$ and $30 \mu\text{m}$ respectively with theoretical imaging depth of 2.5 mm.

3. SOFTWARE

3.1 Software tools utilised

The special software, dedicated to imaging with OCT of demanding data has been developed in Borland’s Turbo C++ Explorer, in C++ programming language. For three dimensional rendering OpenGL (Open Graphics Library) platform was chosen. It is an Application Programming Interface (API) for writing applications dedicated to interactive 3D computer graphics. The major idea, quite common nowadays, was to transfer rendering of screen graphic from computer’s general purpose main processor to specialized circuits embedded into a graphic card. This approach, due to a great variety of hardware implementations, needs a specialized programming interface allows for use universal commands, regardless of the architecture of the graphic card. Installation of OpenGL API takes place together with a graphic driver, specific to the computer graphic card, present in the system. This process is completely transparent for the end-user of the final software: neither specific action nor special versions of drivers are necessary during initial system configuration.

Since its introduction in 1992, OpenGL has become the most popular interface for generating 3D graphics for PC-class computers. It was developed from IrisGL, a similar API elaborated for workstations produced by SGI (Silicon Graphics). An independent organization, Architectural Review Board (ARB), governed the future of OpenGL proposing and approving changes to the specification until 2006 when OpenGL Working Group was incorporated into the Khronos Group [17].

Nowadays, OpenGL has only one main rival – DirectX (Microsoft graphics library). It was introduced in 1995, but the competition between them has increased strongly since DirectX 8 appeared in 2001. At present DirectX has a better position on video game market, but Open GL, thanks to its logical construction, is still a crucial tool in scientific imaging and technical simulations.

A three-dimensional computer graphic is based of a few general concepts. One on them is a working space (Fig. 1). To show an object in the 3D virtual space, it is necessary to define the working space or the scene. It is a space after the flat rectangular, the screen. It may be identified with the computer display and every object from the scene is projected on the screen along lines originating from the common focal point, equivalent to a camera position.

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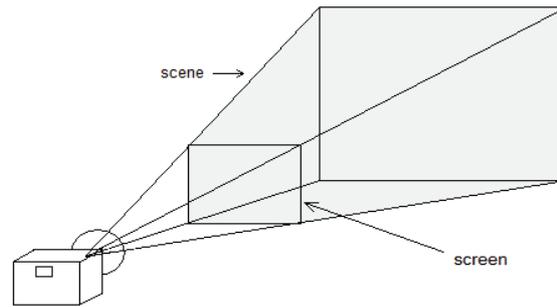


Fig. 1. Defining the working space – the scene

In this contribution, the HSL (Hue, Saturation, Lightness) colour scale is utilized. It is a common model describing perceptual colour relationships. To explain how these three parameters of colour space define a colour it is convenient to consider two cones (Fig. 2) with their bases facing each other with white at the top, black at the bottom vertexes, and the fully-saturated colours around the edge of bases with grey at its centre.

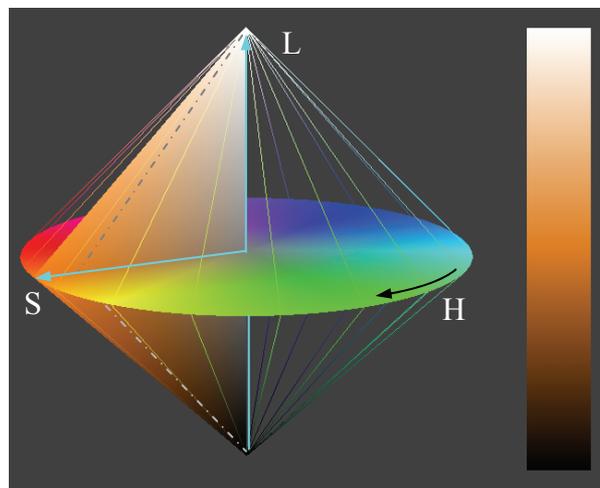


Fig. 2. HSL model for colour rendering, to the right: a lightness scale: $H = 30^\circ$, $S = 80$, $L = 0..100$

Thus, on any horizontal circle there is a colour scale, where hue is defined by the angle around the central axis, saturation is defined by the distance from the central axis and lightness is described by the position of this circle regarding to the upper (white) and the bottom (black) apexes. Therefore, the “Hue” parameter changes from 0° for red, through 120° for green, and 240° for blue to come again to 360° for red. Fully saturated colours have “Saturation” parameter equal to 100. Gray scale is located at cones’ axis with “Saturation” = 0 and “Lightness” = 100 for white and = 0 for black. Similarly, for any established “Hue” and “Saturation” different from 0, it is possible to generate a luminance scale for that colour by changing one parameter: the “Lightness”.

3.2 Developed software

The 3D examination with optical coherence tomography generates huge amount of data. Modern systems collect hundreds of slices (2D cross-sections) each composed of thousands lines comprising usually 1024 points of in-depth information. For instance, system used in this study is capable to collect $150 \times 2000 \times 1024 = 307\,200\,000$ data points. This made unpractical the simplest method of simultaneous interactive visualization of such amount of the data: to place them as cubes (voxels) into

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3D scene (Fig. 1) with modulation of transparency, and project them one by one to the screen. For this kind of visualisation method every translation or turn of the whole object would demand the separate recalculation of coordinates of all voxels.

To make whole process faster, it is necessary to work with smaller amount of object to be rotated or translated. To do so, in the developed software space of voxels is replaced with two dimensional textures. The cube of whole data is divided into sets of rectangles (parallel to the cube's walls – Fig. 4b). Such a rectangle is covered with a bitmap texture generated from OCT data and placed on the scene. Its location in 3D scene is thus described by coordinates of it's four vertexes only.

To obtain desirable visibility of the structure from any point of view it is necessary to generate such flat textures in three perpendicular (Fig. 4b) planes and ensure their proper interpenetration and the transparency. The textures should represent scattering properties of given slice of examined object. To do so, two mapping systems are usually used. In the case of monochrome mapping (Fig. 4c), scattering intensity I is associated with the Lightness, whereas Saturation is kept equal to 0:

$$S = 0 \quad L = \begin{cases} 0 & \text{for } I < I_{Min} \\ 100 \frac{I - I_{Min}}{I_{Max} - I_{min}} & \text{for } I_{Min} > I > I_{Max} \\ 100 & \text{for } I > I_{Max} \end{cases} \quad (1)$$

Where I_{Min} parameter is freely adjusted, to eliminate the background noise from the image. In the case of multicolour mapping (Fig. 4b) all HSL parameters are scaled in such a way, that strong scattering intensities are shown in warm colours and low intensities in cold colours down to black for non-scattering media:

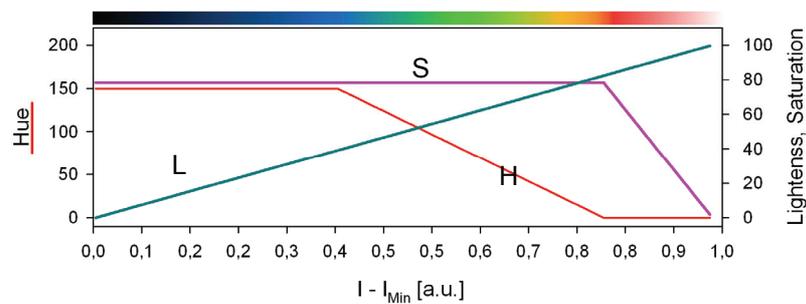


Fig. 3. Colour mapping of scattering intensity in standard OCT imaging

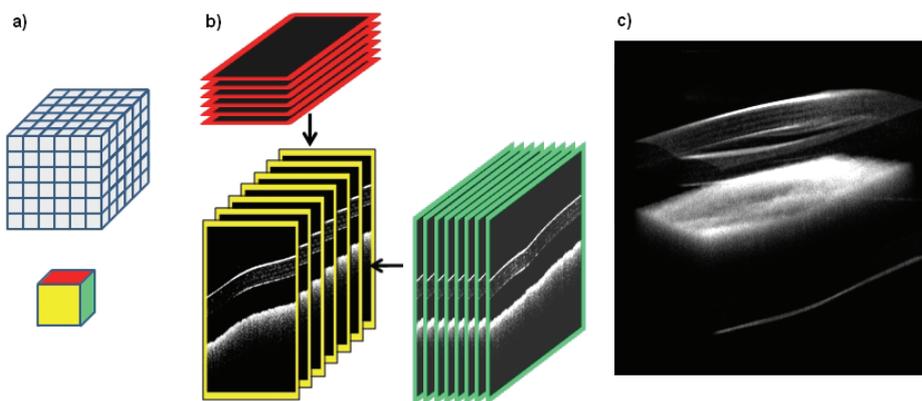


Fig. 4. Methodology of creating visualization; a) one voxel from the 3D tomogram; b) 3 sets of rectangles covered with a bitmap textures generated from OCT data; c) result obtained with enabled partial transparency of textures

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Another way of presentation developed for this study, is three dimensional visualization of non transparent cross-section with clear presentation of the topography of the measured object's surface (Fig. 5b). The cross-sections are presented with standard colour mapping of scatter intensities (Eq. 1 or Fig. 3). To properly show the details of the topography of the complicated surface it is usually better to colour code its elevation then using light reflection rendering. The later method is more useful for computer-generated objects.

Therefore, for the software described the former way was chosen. To do so a colour map has to be defined. The most commonly used and obvious solution is to associate elevation with the hue: high elevations ("mountains") are usually shown in red, whereas low elevations ("valleys") are coded in green and blue. However, according to psychological studies of S. Smith Stevens [18] this method is not optimal from the point of view of the perception of colours. Stevens found that "hue" was not a good parameter for encoding a magnitude of scalar quantity. According to his power law of perception, the perceived intensity of lightness is linearly proportional to its physical stimulus described by L parameter in HLS model. Therefore mapping the elevation with Lightness gives more natural perception of its magnitude.

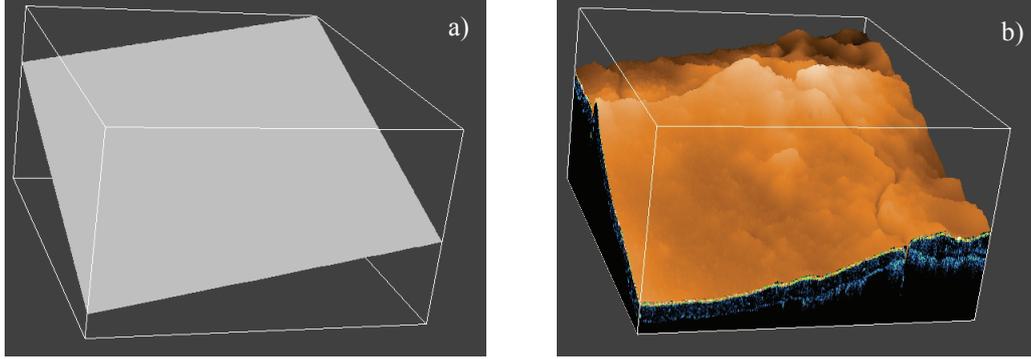


Fig. 5. a) virtual reference surface; b) OCT volume data with surface visualised by mapping of distance from reference surface to Lightness; cage dimensions (Width, Depth, and Height) are: 7 x 8 x 1 mm

In order to properly map the surface shape it is necessary to make it independent on general tilt, caused by sample orientation. To do so, a new virtual reference plane (Fig. 5a) was estimated from the real surface data by linear fitting and used as a reference for elevation mapping. To do so, the distance between real surface s and reference plane r was converted into the "Lightness" parameter of the surface, whilst parameters "Hue" and "Saturation" remain constant and may be adjusted for the best visual effect. Thus the Lightness L at every point i,j of the surface may be estimated from the linear function:

$$L_{i,j} = L_0 + (s_{i,j} - r_{i,j}) \cdot \frac{\Delta L}{2 |s - r|_{Max}} \quad (2)$$

where L_0 and ΔL are two freely adjustable parameters ensuring the best visibility of the surface details.

In specific case of imaging of glass deterioration when all important information is located very close to surface, there is a need for an another presentation mode. In such a case the distance from the surface is the most important parameter and thus is more convenient to code it with hue. Consequently, the lightness parameter is used to code the scattering intensities. This way of presentation is especially useful for analysis of crizzling phenomenon when it helps in recognition of the in-depth range of the destruction process.

$$H = H_0 + \Delta H \cdot \frac{s - r}{(s - r)_{Max}} \quad S = const \quad L = \begin{cases} 0 & \text{for } I < I_{Min} \\ 100 \frac{I - I_{Min}}{I_{Max} - I_{Min}} & \text{for } I_{Min} > I > I_{Max} \\ 100 & \text{for } I > I_{Max} \end{cases} \quad (3)$$

where H_0 and ΔH are freely adjustable parameters, I_{Min} is used to eliminate background noise.

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4. RESULTS

In case of imaging of glass with pitting, it is important to present surface destruction precisely. To do so, surface data were extracted from the OCT scattering data. In case shown in figure 6 the sample was illuminated from the top and the glass surface is visible well. However, due to the multi-scattering events the thickness of the gel layer is overestimated (arrow) in some places. This is because in such a case the real optical path in gel layer is longer than in case of single scattering and thus the layer is artificially down elongated [9].

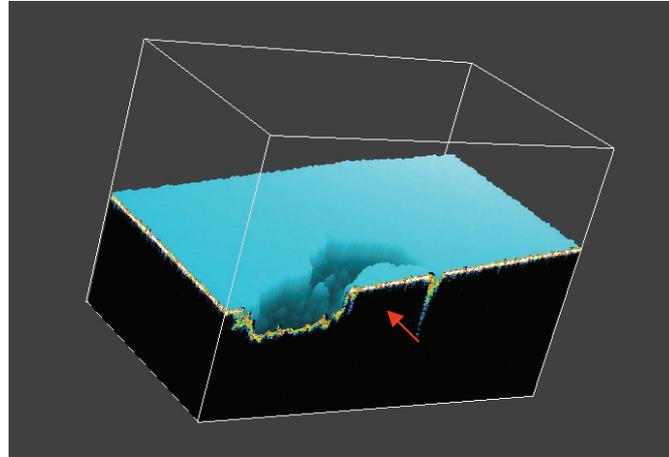


Fig. 6. Pitting of historic glass of unknown origin. Surface destruction is shown together with OCT slice. Arrow points to the multiscattering artefact; cage dimensions (W,D,H) are: 4 x 2.4 x 0.7 mm

If the range of deterioration is the major factor to be presented, sample must be examined from the bottom and the surface with pitting is reached from the other side – through glass. In this case multi-scattering affects the outer surface reproduction but has no effect on the gel – glass interface. This effect is shown in Fig. 7 where depth mapping with hue were used. In such a case the surface data extraction was not necessary, but one must keep in mind that this simplistic attempt was possible only because in this case the rest of sample was completely transparent. For volume scattering samples like paint layers for instance (Fig. 5b) this way of presentation doesn't give acceptable results.

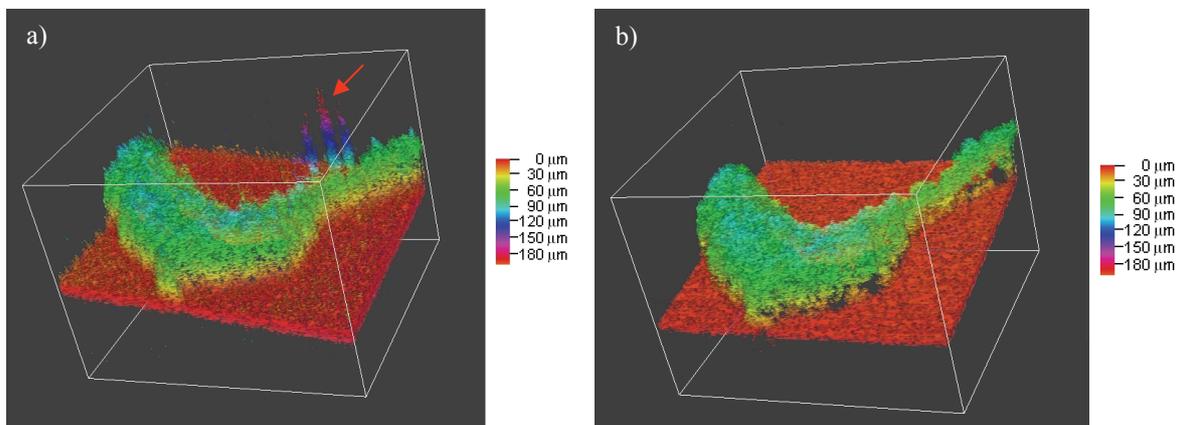


Fig. 7. Detail of glass with pitting: the glass-gel interface as seen from the opposite side of the glass plate; a) examining light approaches structure from the surface side (from the bottom in the figure) – multiscattering artefacts distort the gel-glass interface (arrow); b) examining light approaches structure from inside the glass (from the top in the figure) – the gel-glass interface recovered properly; in both cases colour indicates the distance from the glass surface according to eq. (3) and cage dimensions (W,D,H) are: 1.7 x 1.7 x 0.4 mm

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Another subject under investigation is a crizzling phenomenon. This kind of glass deterioration is caused by an imbalance in the ingredients in the bath, during the glass manufacture when excess of alkali and deficiency of stabilizing calcium oxides occurs leading to the unstable composition of glass [19,20]. Crizzling takes form of a network of cracks, perpendicular to the glass surface and penetrating a short distance (several micrometers) beneath it. Specular reflections from crack walls almost parallel to the probing beam make OCT imaging of the crizzling especially difficult. Again, for univocal and convenient visualization of crack network the 3D visualization is necessary. Special false colour coding must be applied to emphasize delicate structure of crizzling cracks.

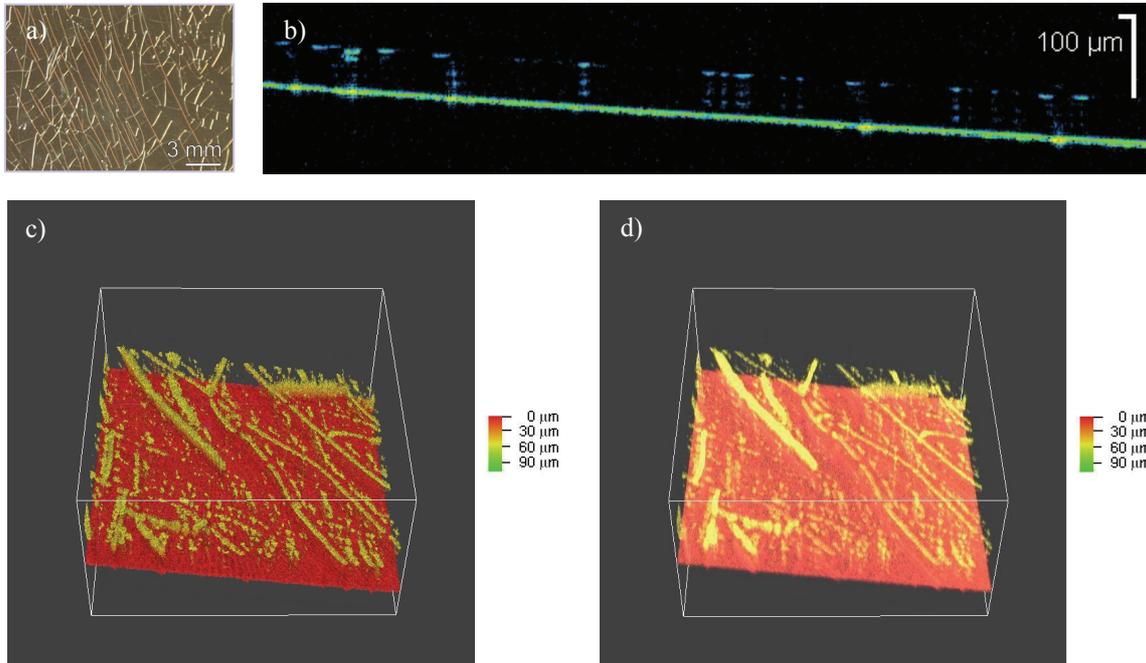


Fig. 8. Example of using depth colour coding for imaging of crizzling; a) sample photo in raking light; b) standard OCT tomogram (B-scan) examined through glass – light approaches from the top, signal from cracks is visible above strong signal from the surface; c,d) volume OCT data presented in distance from the glass surface to colour mapping mode, in two modalities of colour mixing and transparency, cage dimensions (W,D,H) are 4.8 x 4.8 x 0.34 mm

In case of crizzling it is very important to examine the in-depth range of cracks. In Fig. 6 the structure of severely crizzled glass is shown with colour coding of in-depth information. It is clearly seen that all cracks have the same depth.

5. CONCLUSIONS

Optical Coherence Tomography provides information on internal structure of objects of cultural heritage in non-contact and non-invasive way. Since the applicability of the OCT method is limited to objects weakly absorbing and scattering light, it is well suited for examination of glass. Taking a full advantage of the imaging capability of OCT, especially in case of volume examination, needs developing special tools for convenient demonstration of results. Imaging with surface presentation and in-depth colour rendering are especially appropriate for glass examination.

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REFERENCES

- [1] Stifter, D., "Beyond biomedicine: a review of alternative applications and developments for optical coherence tomography". *Applied Physics B Lasers and Optics* 88(3), 337-357 (2007).
- [2] Liang, H., Cid, M., Cucu, R., Dobre, G., Podoleanu, A., Pedro, J. and Saunders, D., "En-face optical coherence tomography—a novel application of non-invasive imaging to art conservation". *Optics Express* 13(16), 6133-6144 (2005).
- [3] Targowski, P., Rouba, B., Wojtkowski, M. and Kowalczyk, A., "The application of optical coherence tomography to non-destructive examination of museum objects". *Studies in Conservation* 49(2), 107-114 (2004).
- [4] Yang, M. L., Lu, C. W., Hsu, I. J. and Yang, C. C., "The use of Optical Coherence Tomography for monitoring the subsurface morphologies of archaic jades". *Archaeometry* 46, 171-182 (2004).
- [5] A complete list of papers published on application of OCT to artwork, retrieved 15 May 2009, from www.oct4art.eu.
- [6] Liang, H., Peric, B., Hughes, M., Podoleanu, A., Spring, M. and Saunders, D., "Optical coherence tomography for art conservation and archaeology". *Proceedings of SPIE* 6618, 661805 (2007).
- [7] Szkulmowska, A., Góra, M., Targowska, M., Rouba, B., Stifter, D., Breuer, E. and Targowski, P. 'The Applicability of Optical Coherence Tomography at 1.55 μm to the Examination of Oil Paintings'. in *Lasers in the Conservation of Artworks, LACONA VI Proceedings, Vienna, Austria, Sept. 21 - 25, 2005*. Nimmrichter, J., Kautek, W. and Schreiner, M. (ed.). 487-492. Berlin-Heidelberg-New York: Springer Verlag, 487-492 (2007).
- [8] Targowski, P., Rouba, B., Góra, M., Tymińska-Widmer, L., Marczak, J. and Kowalczyk, A., "Optical coherence tomography in art diagnostic and restauration". *Applied Physics A: Materials Science and Processing* 92, 1-9 (2008).
- [9] Liang, H., Peric, B., Hughes, M., Podoleanu, A. G., Spring, M. and Roehrs, S., "Optical Coherence Tomography in archaeological and conservation science - a new emerging field". *Proceedings of SPIE* 7139, 713915 (2008).
- [10] Adler, D. C., Stenger, J., Gorczynska, I., Lie, H., Hensick, T., Spronk, R., Wolohojian, S., Khandekar, N., Jiang, J. Y. and Barry, S., "Comparison of three-dimensional optical coherence tomography and high resolution photography for art conservation studies". *Optics Express* 15(24), 15972-15986 (2007).
- [11] Góra, M., Targowski, P., Kowalczyk, A., Marczak, J. and Rycyk, A. 2008. "Fast spectral optical coherence tomography for monitoring of varnish ablation process". *Lacona 7 - International conference on Lasers in the Conservation of Artworks, Madrid, Spain, September 17 -21 2007*, Taylor & Francis Group, 23-26 (2008).
- [12] Targowski, P., Góra, M., Marczak, J., Rycyk, A. and Rouba, B. J. "Optical coherence tomography holds promise for conserving art" *newsroom.spie.org*, (2009) DOI: 10.1117/2.1200904.1589
- [13] Kwiatkowska, E. A., Marczak, J., Ostrowski, R., Skrzeczanowski, W., Sylwestrzak, M., Iwanicka, M. and Targowski, P., "Absolute LIBS stratigraphy with Optical Coherence Tomography". *Proc SPIE* 7391, 739114 (2009).
- [14] Huang, D., Swanson, E. A., Lin, C. P., Schuman, J. S., Stinson, W. G., Chang, W., Hee, M. R., Flotte, T., Gregory, K., Puliafito, C. A. and Fujimoto, J. G., "Optical coherence tomography". *Science* 254(5035), 1178-1181 (1991).
- [15] Fercher, A. F., "Optical coherence tomography". *Journal of Biomedical Optics* 1(2), 157-173 (1996).
- [16] Targowski, P., Ostrowski, R., Marczak, J., Sylwestrzak, M. and Kwiatkowska, E. A., "Picosecond laser ablation system with process control by Optical Coherence Tomography". *Proc SPIE* 7391, 739115 (2009).
- [17] <http://www.opengl.org>, retrieved 16 May 2009
- [18] Rogowitz, B. E. and Treinish, L. A. "Why Should Engineers and Scientists Be Worried About Color?" retrieved 16 May 2009, from <http://www.research.ibm.com/people/l/lloyd/color/color.HTM>.
- [19] Brill, R. H. "Crizzling - a problem in glass conservation" in *Conservation in Archaeology and the Applied Arts - Congress of the International Institute for Conservation*, ed. by N. S. Brommelle, and P. Smith, Stockholm, 121-134 (1975).
- [20] Hogg, S., McPhail, D., Oakley, V., and Rogers, P., "Cracking crizzling: eight years of collaborative research" *Conservation Journal of Victoria & Albert Museum* 29, 10-12 (1998).

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