Optical Coherence Tomography for Examination of Art Workshop

Abstracts

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Invited lectures

Contributed papers

OCT
STATE OF THE ART AND ITS FUTURE DEVELOPMENT

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Optical coherence tomography can perform micron-scale, cross-sectional imaging of microstructure in tissues *in situ* and in real time. Cross-sectional images are generated by scanning an optical beam across the tissue and measuring the echo time delay and intensity of backreflected light from internal tissue microstructures. The resulting two-dimensional data array represents the optical backreflection within a cross-sectional slice of the tissue. OCT is based on an interferometric technique with light sources emitting temporal partially coherent electromagnetic radiation, known as white light interferometry. Classic OCT systems use a mechanically scanned reference arm delay.[1] In these OCT systems imaging speeds are limited to several hundreds of lines per second. Recently, there have been important advances in OCT technology which enable dramatic increases in imaging speed over standard time domain OCT systems. These new techniques are known as "Fourier domain" OCT because time delays of light echoes are measured using the interference spectrum of light reflected back from the tissue.[2] OCT with Fourier domain detection can be performed in two ways: Spectral OCT using a spectrometer with a multichannel analyzer or swept source OCT using a rapidly tunable laser source. The first demonstration of biomedical imaging using OCT with spectral detection was reported in 2002.[3] The Spectral OCT system uses a spectrometer and high speed, high dynamic range CCD camera. Because Spectral OCT does not require moving parts, data acquisition speeds can be extremely rapid. Furthermore, since all of the reflected light is measured at once rather than light which returns from a given depth, this is a dramatic increase in detection speed and sensitivity up to 100times higher than in classic OCT instruments.

There are many possibilities offered by OCT with Fourier domain detection, which are still unexplored and which can be applied either to biomedical imaging or to metrological applications. Further modifications of the Fourier domain OCT techniques can enable measuring additional physical parameters like: spatial (in-depth and transverse) distribution of the absorption/scattering coefficient, or flow velocities. These measurements can be performed in weakly scattering media with high speeds up to 200kHz of line rate, with more than 100dB sensitivity and with micron-scale resolution.

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TOWARDS FUNCTIONAL APPLICATION OF OCT TO ART HISTORICAL STUDIES AND CONSERVATION

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Optical Coherence Tomography (OCT) is a fast scanning Michelson interferometer capable of 3D imaging of transparent or semi-transparent material. It was first designed for the in vivo examination of the eye. The application of OCT to the examination of art is fairly recent with the first papers published in 2004.[1-3] Since the initial demonstration of non-invasive imaging of cross-sections of paintings and other historical objects of art, OCT is gaining acceptance as a non-invasive, non-contact alternative to the examination of subsurface structures of art works. It is now a fast growing area of research.[4-6]
This talk focuses on moving OCT research in art conservation and art historical studies towards functional applications that is beyond qualitative imaging. The importance of the use of image processing techniques to post-process OCT images will be demonstrated. Examples of OCT examination of paintings in assisting conservation and art historical studies for western European paintings from the National Gallery as well as examples of how OCT can be used to assist archaeologists in identifying material and the manufacturing process for objects from the British Museum will be discussed.

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IMAGING AND SPECTRAL INFORMATION WITH TIME-DOMAIN OCT

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Paintings are stratified systems made of a ground layer covered by one or more coloured layers. The composition and the thickness of each layer is of great interest for conservation, restoration and art history. Until now, these are obtained by electronic microscopy after sampling. In order to carry out a non-destructive technique without contact, we develop a time-domain Optical Coherence Tomography (OCT) in the visible range which combines tomographic imaging and Fourier transform spectroscopy.

OCT is an optical device developed since the 90's. It allows to obtain three-dimensional images in the near infrared domain at different depths on biological tissues.[1] More recently OCT is applied to works of art to observe and to measure the thickness of varnishes and of paint layers.[2-3] The present device extends the previous results to the visible range. It provides imaging with a resolution about 2 µm in the three directions.[4] Imaging is realised on several samples to determine the field of application and its limits (pigment volumic concentration, thickness). Works of art will be studied such as paintings, music instruments and glasses.

Moreover, with an appropriate signal processing based on Fourier transform, it is then possible to calculate spectral information. The spectra obtained for dyes are validated by comparison with spectroscopic measurements. First results obtained on scattering media like pictorial layers containing pigments will then be presented.

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IMAGING OF GOLD RENAISSANCE PUNCHWORK USING THREE - DIMENSIONAL OPTICAL COHERENCE TOMOGRAPHY

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Introduction

Optical Coherence Tomography (OCT) is an imaging modality which enables reconstruction of the spatial structure of examined objects.[1] It uses low power, near infrared (NIR) light to interferometrically measure distances between layers inside the sample. OCT is a non-contact and non-destructive technique which achieves micron-scale imaging resolutions. Therefore, OCT is well-suited for examining fragile works of art which often have fine layered structures, possess unique historical value, and inherently require safe analysis methods to avoid damaging the sample.[2-12]

In our report, we show examples of three dimensional OCT (3D-OCT) imaging of gold punchwork in Renaissance panel paintings.[13] Punchwork is an art decoration technique which uses small tools with different shapes to adorn various works of art with ornamental motifs. One example is the impressions of punches in gilded panel paintings from the early Italian Renaissance. The techniques of embellishing halos and garments with punches were developed in different workshops, spreading from Italy to Bohemia and France. Analysis of punchwork is important for studying the development of workshops, origination of paintings or attribution of specific works to different artists.[14,15] 3D-OCT imaging of punchwork may provide valuable information for studying the history of paintings.

Experimental setup

For imaging of gold punchwork, we used a 3D-OCT instrument with a Fourier domain mode locked (FDML) laser as a rapidly tunable light source.[16-17] The laser operated at sweep repetition rates of 42,000 sweeps/s. The center wavelength of emitted light was 1287 nm. The tuning range was 118 nm, providing an axial imaging resolution of ~6 µm in varnish or paint. With ~10 mW of power incident on the sample, we achieved an imaging sensitivity of 100dB. As an imaging platform, we utilized a modified OCT microscope (Thorlabs, Inc.). The beam spot size was ~30 µm which defines the transverse imaging resolution. The working distance of the microscope was ~3 cm.

Results

We imaged punchwork in two Renaissance panel paintings created by the Master of the Orcagnesque Misericordia active between 1375 and 1400 AD ("Marriage of the Virgin" and "Coronation of the Virgin") and in one copy of a Renaissance painting "San Marco", produced by Daniel V. Thompson Jr around 1920 using the punch tools of Frederico Ioni, a well known restorer and notorious forger of Italian Renaissance art.[18] We imaged several punch marks characteristic of these paintings. The three dimensional data sets acquired in these regions consist of 800 x 800 x 512 pixels in horizontal, vertical and depth (or axial) directions. The imaged volumes are 4 mm x 4 mm x 3 mm. We utilized a commercial 3-D rendering software (ResolveRT, Mercury Computer Systems, Inc.) for visualization of the OCT data. We used several data display methods for visualization of features characteristic of the punch marks. For example, projection OCT images generated by axial summation of the 3-D data sets are used for identification of the imaged areas in the painting. In addition, they can be correlated with photographs and therefore allow for registration of cross-sectional images with the details visible in the surface of the painting. Cross-sectional OCT images enable measurement of the depth of punches. Volume rendering can be used to generate three dimensional virtual models of the punchwork. Such visualization allows for intuitive assessment of spatial distribution of punches, their shapes and depths. *En face* slices selected at different depth-locations of the 3D data sets at increased depths reveal the shape of punches and therefore also the form tools used for their creation.

The results of our study show that 3D-OCT instruments are well-suited for applications in imaging of the gold punchwork. Infrared light used in the OCT technique has the ability to penetrate through different materials used for creating works of art. Although the gold foil used as the base material for punchwork is nearly 100% reflective for a very wide range of wavelengths (including NIR), it is not uncommon to find layers of aged varnish or paint on the top of the punch marks. 3D-OCT enables correct recognition of the gold layer located beneath other materials. The high imaging speeds of swept source 3D-OCT instruments using FDML lasers enable high-density transverse optical scanning of fine punchwork structures in short times. This allows reconstruction of high definition three dimensional virtual models of examined objects. Punch marks can be analyzed quantitatively. Their contours can be examined for presence of defects in tools used for their execution. Such microscopic imperfections could serve as “fingerprints” allowing for tracking the tools as they were shared or handled down by different workshops or artists.

Conclusions

In conclusion, the results of our feasibility study show that 3D-OCT can be used for examination of paintings containing gold punchwork. OCT may enable the recognition of specific tools used for execution of different works and therefore give insight into the origination of paintings. Attribution of different works to the same artist may be possible after more detailed analysis of multiple paintings and punches. Verification of possible forgeries could be also attempted using systematic 3D-OCT study of punchwork.

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LOW COHERENCE SPECKLE INTERFEROMETRY (LCSI) – A TOOL FOR DEPTH RESOLVED DEFORMATION MEASUREMENTS

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In recent years electronic speckle pattern interferometry (ESPI), has become a powerful tool in the real-time observation of object vibrations and micro-deformations. Since a long time our group uses this technique e.g. for the investigation of deterioration processes in works of art and for the development of procedures for their preservation.[1]

One very exciting application of the method was the monitoring of deformations on coloured fragments of the famous 2000-yrs-old terracotta army of the first Chinese emperor. One problem in the preservation of these objects is that the multilayered colour, which partly exists on the terracotta, is very fragile. They show immense sensibility to humidity changes and since the excavation led to a desiccation of the terracotta figures, the remnants of the paint layers were extremely endangered to fall off. In order to develop suitable methods of conservation ESPI measurements were performed during cycles of humidity changes to estimate the influence and suitability of several conservation agents and procedures.

During the investigations we realized that it is of great interest to measure the behaviour of the individual layers of the multi layered painting separately. For this purpose, a modified ESPI system was designed with a low-coherent superluminescent diode (SLD) instead of a laser. By changing the path length of one of the interfering beams it is thus possible to select a region limited in depth where deformations should be measured even if it is located below the surface. The use of well adapted evaluation procedures like spatial phase shifting in combination with the Fourier transform method allows the separation of the coherent from the incoherent part of the reflected light, which is very helpful for a reliable evaluation of the deformation maps.

The basic of this modified LCSI method is the measuring of the echo time delay and magnitude of backscattered light and one well-known representative of this technique is optical coherence tomography (OCT). Typically, the latter method is used to get cross-sectional topographic images from the internal microstructure in materials and biological systems. In contrast to these applications our aim is not (only) to get absolute topographic information about the internal structure but to measure their deformations.

In this contribution the modified system will be presented and some deformation measurements on an artificial test object and on terracotta fragments will be demonstrated.

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POLARISATION-SENSITIVE OPTICAL COHERENCE TOMOGRAPHY: PRINCIPLES AND APPLICATIONS OUTSIDE THE BIOMEDICAL FIELD

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By extending conventional optical coherence tomography (OCT) – for which only the intensity of the backscattered light is recorded – towards polarisation sensitivity, additional contrast is obtained in the depth resolved images of semitransparent materials: polarisation-sensitive OCT (PS-OCT) maps the polarisation state of light reflected from the interior of the sample material[1], thus giving access to additional physical parameters, like birefringence, and enhanced structural information, that is difficult to resolve with other imaging techniques. Measurements of birefringence, of full Stokes vectors and Mueller matrices, the simultaneous determination of intensity, retardation and orientation of optical axes as well as measurements of diattenuation have been reported to date.

We will give a short overview on these different PS-OCT techniques together with their original applications in the biomedical field and focus in the following on alternative applications related to material research and non-destructive testing and evaluation. Starting from conventional time-domain PS-OCT imaging of polymer and composite materials[2], we will demonstrate the potential of PS-OCT combined with ultra-high resolution imaging and *en-face* scanning capabilities.[3] Especially *en-face* scanning, i.e. acquiring an image parallel to the surface at a certain adjustable depth, proves to be useful for a quick evaluation of complicated, planar structures without the need of acquiring full 3D datasets derived from multiple cross-sectional scans. With the extension towards polarisation sensitivity, UHR-birefringence imaging allows depth resolved stress measurements in materials and is exemplified on photoresist mould structures as well as on fibre composites as used in aerospace parts: simultaneous determination of the fibre structure, defects (like cracks and delaminations) and residual stress becomes now feasible in a contact-free and non-destructive way. These applications shall serve as instructive examples of the type and quality of information which is obtainable from standard and advanced PS-OCT methods for future applications in the field of non-destructive art examination.

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OCT IN THE CONTEXT OF OTHER TECHNIQUES FOR EXAMINING AND ANALYSING WORKS OF ART

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While the OCT technique provides a useful tool for the non-invasive examination of museum objects, it is not yet capable of analysing the materials that compose the structure which it images. This paper examines how OCT compares with other examination methods and can be used in tandem with those methods to give a more complete analysis of works of art.

OCT is compared with non-invasive imaging techniques such as visible imaging, ultraviolet fluorescence imaging and infrared reflectography, which largely provide two-dimensional images of objects, and with three-dimensional methods such as X-radiography and neutron radiography.

Non-invasive vibrational methods such as Raman and infrared spectroscopy and other non-contact analytical techniques, including X-ray fluorescence, give information about single points, usually on the surface. The information provided by these methods can be enhanced if the choice of sampling positions can be informed by mapping techniques, and the role of OCT in this process is explored.

Finally, the information from OCT is compared to that provided by invasive analysis, particularly the preparation of cross-sections from areas also examined by OCT. The correlation of information between the techniques is explored and the potential for extrapolating information obtained from a single point over a larger area is discussed.

APPLICATION OF OPTICAL COHERENCE TOMOGRAPHY TO MONITORING OF LASER ABLATION OF VARNISH

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Varnish layer removal is a crucial operation during the conservation of paintings. It has to be conducted with extremely high precision and selectivity. Preserving the original paint layers without modifying their original colours and structures is essential for this task. Despite of well established mechanical and/or chemical methods it is still a need for new solutions, dedicated to especially difficult cases. For instance, when the varnish layer is more chemically resistive then underlying paint layers, laser ablation of varnish seems to be very promising alternative. Prior to introduce this technique, which is still at experimental stage, to the common conservation practice, one of the most important issue to be resolved is an effective monitoring method of this process. The tracking method should be precise, fast, non-contact and should allow thickness estimation of remaining varnish layer in the region of ablation. This last requirement derives from the fact that thickness, topography and physical properties of both varnish and paint layers can vary rapidly from point to point.

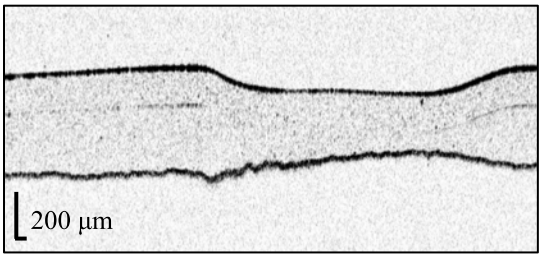

Figure 1. Frame from the OCT movies registered during ablation of the Maimeri Dammar varnish layer ablated with 8 Hz repetition. Laser pulses were applied at the centre of image, during the process sample were translated to the right.

Spectral domain OCT (SOCT) as a fast, sensitive, and non-invasive modality of structural imaging can be considered as a useful tool for real-time monitoring of various conservation treatments. In this contribution an overview of preliminary studies on application of OCT for monitoring of laser ablation will be summarised. Since this method gives both qualitative and quantitative information it is possible to visualise varnish layer structure as well as to generate surface profiles and varnish thickness maps. In this application OCT can be utilized in two steps. Firstly *in situ* estimation of process conditions like ablation rate for given laser – varnish combination is used for planning of whole treatment. Then the real time monitoring of ablation makes this process safer for the object under treatment (Fig. 1).

The review of the recent results obtained can be a good introduction to the discussion about the potential of this method. The technical requirements like optimal resolution, imaging range, imaging speed, etc. will be addressed. On the base of the results obtained and the experience gained we will try to foresee the future of this application.

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NON-DESTRUCTIVE AND PORTABLE METHODS TO IDENTIFY THE COMPONENTS OF WORKS OF ART AND THE ARTISTIC TECHNIQUES

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Non-destructive techniques, without any contact with the studied surfaces, able to be implemented without moving the work of art from its place of exhibition and leading to results in real time in the presence of the restorer or of the conservator are developing subjects. Qualitative and quantitative results obtained with different instruments will be presented and compared with OCT results.

The first portable instrument that we developed in order to study works of art is a gonio-spectro-photo-colorimeter in a back-scattered configuration. The recording of diffuse reflectance spectra allows the identification of pigments and dyes embedded in the upper layer of the works of art, by comparison with spectral databases.[1] The pigments can be of the same nature or mixed. The previous spectra also allow to calculate the corresponding trichromatic co-ordinates and to underline a glaze technique, compared to a pigment mixture one.[2] The same instrument can also be used as a goniophotometer where the luminance is recorded as a function of the back-scattered angle and the different gold applying techniques, such as gold leaves on a bowl, on a mixtion or gold embedded in a binder, can then be discriminated.[3]

When the white light of the previous instrument is replaced by UV-LED, UV-fluorescence emission spectra can be recorded. The comparison with a spectral database of reference varnishes then allow to identify the resin, the recipe and the state of degradation of an unknown varnish.[4] This identification can be implemented in the same time than pigment recognition on the same work of art.

Finally, confocal microscopy has been explored to image varnishes applied on paint layers. The surface state of both interfaces air/varnish and varnish/paint are simultaneously recorded and stratigraphic images are deduced. The varnish thickness is then easily measured, as with OCT. Moreover, it is possible to quantify the roughness, the correlation length of each interface and the leveling of the paint surface by the varnish can be visualized and studied according to the properties of the ground layer and of the varnish.[5]

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NEAR-INFRARED CONFOCAL LASER SCANNING MICROSCOPE FOR THE ANALYSIS OF PAINTINGS

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The use of confocal microscopy for artwork diagnostic, and in particular for the analysis of paint layers in ancient paintings, is strangely confined to some recently reported white-light applications[1]. For this type of analysis, optical coherence tomography (OCT) is widely preferred and its use is indeed well documented[2,3]. Laser-scanning near-infrared confocal microscopy (LSCM) can however be applied to optical sectioning, to 3D imaging, and to the measurement of surface roughness of ancient paintings. The paint layers are almost transparent to near-infrared radiation beyond 1.1 microns, and the scattering power of pigments in the same range is low, allowing for a good imaging of paint sections. This technique can thus be used as a simpler replacement of optical coherence tomography (OCT) for the analysis of varnish and paint layer thicknesses.

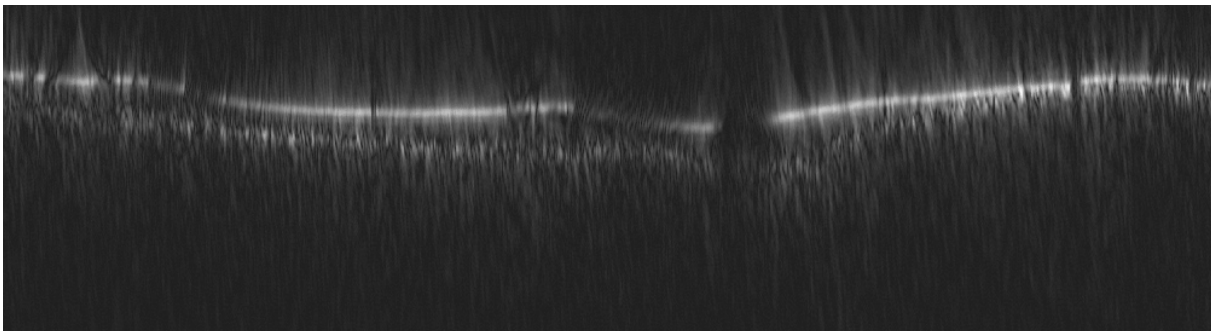

Figure 1. Optical (LSCM) section of the surface of a painting, 1000 x 270 μm^2, showing the varnish thickness profile.

To demonstrate the applicability of NIR confocal microscopy to artwork diagnostics, we designed and built a simple fibre-optic confocal laser scanning microscope operating in the near-infrared at 1.55 microns. The instrument has been tested on reference targets and then applied to the analysis of ancient paintings at the INOA Optical Metrology Lab at the Opificio delle Pietre Dure in Florence. Examples are provided on several paintings showing the imaging capabilities of this laser-scanning technique. The system could be easily upgraded to a multi-spectral NIR confocal microscopy. This approach, which we plan to exploit in the near future, makes this technique an interesting and promising tool for non invasive optical sectioning of paintings and of painted surfaces of artworks in general.

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SURFACE ROUGHNESS AND THE APPEARANCE OF OBJECTS IN CULTURAL HERITAGE

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The appearance and perception of objects of art and cultural heritage is essentially subjective in nature. Among other factors, it depends on the viewer's state of mind in the broadest sense of the word, the person's background, and the environment in which he or she is observing the object. However, a viewer's perception of an object is triggered by the physical interaction of light with the object and its arrival at the viewer's eye. The interaction of light with the object is determined by the surface and near-surface properties of that object. The absorption and reflectance properties of the surface, combined with the lighting conditions, determine the what enters the viewer eyes.

On the technical side, much research has been conducted in the optics and related industries into how objects appear, how they are perceived, and how they can be realistically reproduced (rendered). Many of the research methods and results have been applied in the cultural heritage world, such as in traditional studies of pigments and dyes in paintings and polychrome objects, studies and theoretically modeling of the effects of varnishes and other coatings on object appearance, and more recently, "true colour" documentation and reproduction objects.

While colour perception is an important aspect in the appearance of objects, the surface roughness of objects plays an equally important role in how light interacts with objects. This goes beyond the simple determination of whether an object is glossy or matte. Information about roughness has already been theoretically considered in scattering models describing the effects of varnishes. [e.g. 1-2] However, restoration treatments, in particular cleaning, can cause significant changes to the roughness of objects, altering their appearance from what originally was intended. Further, roughness is an important parameter in light scattering models used to "realistically" reproduce (render) objects. It is thus rather surprising that little experimental work has been done to actually incorporate real roughness data into such models, or to perform simple measurements to determine the effect of treatments on the surface roughness and appearance of objects.

Equipment for measuring roughness has been commercially available for decades, developed initially for use in the science of tribology, the study of friction, wear, and lubrication of materials. Such equipment is now commonly used in many industries for quality control, not only for tribological applications, but, in fact, to guarantee the consistent appearance of products.

Several years ago, the Netherlands Institute for Cultural Heritage (ICN) began using rough-ness measurements, profilometry, for studying surface changes in paintings, and for the rendering of objects.[3-6] Non-contact confocal white-light profilometry is used to allow investigators to directly study the objects themselves. It provides high resolution, quantitative data with the spatial resolution of a light microscope, under 1 μm, and depth (roughness) resolutions down to the nanometer range. The application of this technique has since been expanded in the European FING-ART-PRINT to its use in "fingerprinting" objects for tracking and tracing, and protection against theft and illegal trafficking. The purpose of this communication is to review the concept of (micro) roughness measurements, and their possible applications in the conservation of cultural heritage.

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TRACKING CANVAS DEFORMATION WITH OCT – METHOD AND POSSIBILITIES

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The main application of optical coherence tomography (OCT) is non-contact and non-destructive imaging of stratigraphy of semi-transparent objects. In conservation practice, it permits investigating the arrangement, continuity and thickness of varnishes and glaze layers. Nevertheless, even if the painting structure is non-transparent to the light used for examination, OCT may still be used for profilometry of its surface. One of possible applications of this approach, used for tracking distortions of the painting's surface caused by climatic changes in its surroundings, will be presented.

The research project applying Spectral domain OCT for profilometry combined with marker position tracking as well as experimental set-up designed for this application by the Institute of Physics in collaboration with the Institute for the Study, Restoration and Conservation of Cultural Heritage of Nicolaus Copernicus University will be described.

On examples of experiments carried out on model paintings it will be shown that the method is capable of continuous monitoring simultaneously in- and out-of-plane deformations of the painting surface in response to environmental fluctuations with micrometer precision. One of major advantages of using the OCT for this application lie in the absence of problems characteristic for optical methods relying on measurements of phase differences, such as phase ambiguity and phase unwrapping. Moreover, the method is suitable for *in situ* and long-lasting examination since it is not sensitive to micro-displacements of the investigated object with respect to the measuring head.

The current research project utilising SOCT aims at the gathering detailed data for a better understanding of the relationships between the painting technique employed, the age and storage conditions of the painting, and its susceptibility to dimensional deformation influenced by fluctuations of relative humidity and temperature, as well as quantifying the range and direction of the changes. To interpret processes taking place in the structure of the painting and the role of particular components in the behaviour of the overall structure, model paintings prepared using different techniques, and samples at different stages of preparation are being examined with the SOCT in conditions designed according to climate parameters usually experienced in museums and historic interiors.

SEQUENTIAL COHERENT INTERFEROMETRIC RECORDING: A KEY TO MONITOR STRUCTURAL ALTERATIONS IN INTERVENTIVE RESTORATION

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In Cultural heritage preservation there are many interventive procedures which affect in short and long term the structural integrity of artworks under restoration. The effect of excimer laser ablation utilized in paintings restoration, consolidation processes and cleaning treatments are currently mostly performed based on operator's experience. However modern practices utilising laser optical coherent interferometry have been proved promising candidates to reveal inborn defects, stressing areas and material fatigue in terms of structural deterioration, destabilisation of structures and disintegration of interfaces with subsequent loss of adhesion and detachment generation.
In this presentation an exemplary review of applying optical holographic interferometry and holographic speckle interferometry are presented.
They are applied to monitor in semi-real-time or real-time the dimensional changes which may be generated during artwork interventive conservation. A study by means of sequential recording of holographic interferograms on model samples is provided. In ablation processes, reversibility is assessed versus a reference displacement before ablation established by means of a controlled experimental methodology. This is determined according each distinctive initial state of sample prior to ablation.
The long-term sequential recording enables comparison between temporally resolved optical wave fronts scattered before, after and during the selective ablation of material. Thus, comparative structural monitoring of laser-induced photomechanical effects that may result in potential damage is accomplished. Results and discussion of consolidation treatments in paintings and environmental stimulations on humidity sensitive materials are also included.

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OPTICAL AND SURFACE METROLOGY APPLIED TO THE STUDY OF PHOTOGRAPHIC SURFACES

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The field of optical surface metrology is well suited to the study of cultural heritage. Advances in electronics, optics and faster computing in the past ten years have revolutionized the fields of 2D contact surface profilometry and optical and surface metrology. The antiquated surface metrology contact methodologies, which irreversibly perturb surfaces, were never considered by cultural heritage institutions and although still useful in industry are quickly becoming a tool of the past. New optical surface metrology tools such as confocal surface topometry use light to probe surfaces rapidly and risk-free, and yield a wealth of areal data unachievable with 2D contact methods. Such instrumentation enables non-perturbing (non-contact, non-destructive and non-invasive) examination of delicate and sensitive surfaces of the wide range of historic and artistic works encompassing the cultural heritage accumulated by mankind. Confocal surface topometry joins the growing cadre of non-perturbing techniques such as optical coherence tomography, which provide new approaches and possibilities for the study of surfaces of individual historic and artistic works as well as art historical collection based studies.

The Conservation Department at George Eastman House International Museum of Photography and Film has been testing the value and practicality of tools from the field of optical metrology since 2005. Collaboration with NanoFocus, AG, developer and manufacturer of confocal surface topometry systems, has allowed for the successful testing of the μsurf confocal topometer to probe and examine the delicate and sensitive surfaces of numerous types of historical and fine art photographic images. Confocal surface topometry provides quantitative data of the surface geometry; an array of (xyz) points in 3D space that reflects the topographical nature of the photograph surface. This paper focuses on the application of confocal surface topometry to the study of daguerreotypes, the first commercially viable photograph making its debut in 1839, and the 20th century silver gelatine photographs. Confocal surface topometry is ideally suited for the examination of the surface geometry of the daguerreotype image – a metallic surface structure and topography of silver, mercury and gold – independent of the illumination and optical properties, thereby providing quantitative metrics of the daguerreotype's surface ultra-fine structure; measure surface and any changes in structure affected by deterioration mechanisms and/or evaluate restorative conservation treatments.

This presentation will discuss the confocal principle, briefly cover the early history of photography and daguerreotypy, and provide examples of confocal topometry applied to the examination and assessment of conservation treatments of daguerreotypes and silver gelatine photographs.

SIMULTANEOUS MONITORING OF DRYING VARNISH WITH UNILATERAL NMR AND OCT

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Recent work has shown that the most important contribution to the optical appearance of varnishes on a paint surface is the ability of the varnish to give a smooth top surface.[1] It has been shown that different types of resin have different surface levelling ability and it has been proposed that the ability of the resin molecules to flow with increasing concentration as it dries is responsible for the difference in appearance.[2,3] Unilateral Nuclear Magnetic Resonance (NMR)[4] can be used to non-invasively measure the self diffusion coefficients in the drying varnish. The self diffusion coefficient of the resin is closely related to the dynamics of the resin drying process. This technique can, therefore, tell us how "wet" the varnish is. Optical Coherence Tomography measures not only the changing thickness of the varnish, but also the large scale roughness of the surface of the varnish and how it relates to the surface profile beneath simultaneously.[5,6] The combination of these techniques allows us for the first time to relate directly how wet the varnish is as it dries and potentially identify at which point different varnishes solidifies and how it correlates with surface roughness.

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ELECTRONIC SPECKLE PATTERN INTERFEROMETRY (ESPI) IN ANALYSIS OF THE CLIMATE-INDUCED DAMAGE OF PAINTED WOOD SURFACES

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Electronic Speckle Pattern Interferometry (ESPI) is an effective tool for the detection of sub-micrometer surface movements to indicate and localize material defects. This method is used to map the formation and development of damage to decorative layers on wood induced by variations in relative humidity (RH) in its environment. Specimens of wood coated with gesso and paint imitating the historic objects are subjected first to real RH fluctuations in a climatic chamber, then to cycles of mechanically produced dimensional changes simulating the responses to climatic fluctuations. The interference patterns recorded before and after deformation of the specimens yield a characteristic fringe pattern containing full required information. The measurement of the absolute phase and absolute deformation is possible by the implementation of the phase shifting technique. The goal of the investigations is to identify the critical RH levels dangerous for the polychrome wood as a function of the amplitude, duration and starting level of the RH change and number of such changes. The ESPI method was found to trace precisely cracks and delamination of the paint layer. Sound-induced vibration of the surface proved very effective in characterizing the extent and mechanical properties of the delaminations.

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POLARIZATION SENSITIVE OCT FOR SCATTERING MATERIALS EXAMINATION

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Optical Coherence Tomography (OCT) is a unique technique of cross-sectional and three-dimensional visualization of inner structure of different type of materials. This method is based on low-coherence interferometry, and the OCT enables in situ investigation in non-contact and non-destructive way. With the aid of OCT one can analyze a structure of investigated materials with measurement resolution reached a few µm, high sensitivity and high dynamic range. Nowadays, this method is highly applied in medical treatment especially in dermatology and ophthalmology [1] and also in industry and science [2][3]. Recent researches on OCT expand its applications to materials characterization, multilayered structure investigation [4], art conservations [5] and many other fields beyond medical applications. Our research interests have been concentrated on polarization sensitive OCT (PS-OCT) for investigation of highly scattering objects. The polarization sensitive analysis, based on polarization diversity detection, expands the OCT measurements by selective investigation of anisotropic structure in an investigated material. Therefore, it is possible to determine birefringence principles of the device, as well as study the phenomenon causing materials anisotropy. An example of such examination might be birefringence determination of PLZT ceramics or strain field mapping in composites materials. Until now, we concentrated our studies on investigation of PLZT ceramics, polymer composites and painted anticorrosion protecting coatings. By the use of PS-OCT, the homogeneity of PLZT ceramics and polymer composites structure were examined. The study of polymer composites subsurface layer gives information about their rheological properties. For anticorrosion coatings, a corrosion progress and process of painted coatings delamination were monitored. Obtained results show the usefulness of PS-OCT system for surface and subsurface defects examination of wide range of highly scattering materials. Unique features of PS-OCT, like no-destructive and no-contact measurements, polarization sensitivity, high measurement resolution, make this system an interesting tool for inspection of multilayered scattering devices.

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EXAMINATION OF INSCRIPTIONS ON EASEL PAINTINGS WITH OCT

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Recently, potential of optical coherence tomography (OCT) has become more and more explored in heritage science since it is a one of unique techniques for non-contact and non-destructive imaging of inner structures of transparent and semitransparent elements of artworks.
Due to the ability to differentiate layers of various optical properties in the cross-sectional images of oil painting structure in fully non-invasive way, OCT has been applied by our team for specific practical applications such as estimation of the sequence of varnish and paint layers in the region of signature.[1-3] The analysis of this region, which cannot be sampled, is important both for attributing the artwork as well as for confirming its authenticity. The experiments show that OCT examination can be helpful when the signature is suspected to lay on original varnish or overpaintings but it is not apparent e.g. surface of the picture is covered with a secondary varnish with very strong UV-visible fluorescence.
The second application that will be presented relies on the utilisation of OCT for three-dimensional imaging of surface and inner structures of art works. Spectral OCT instruments collect a large quantity of data in a short time and thus are well suited for obtaining volume information. If the procedure of recognition of interfaces between layers of different optical properties (eg. air–varnish and varnish–paint layer) is applied to the volume data collected with OCT from the multi-layered structure of the varnished painting, it is possible to recover virtually profiles not only of the surface of the object but also of convex or concave details of its inner layers.[2,4,5] Experiments carried out on models and examination of original paintings prove that OCT method can be useful for revealing textural painted inscriptions or marks increased in fresh paint layer levelled by a thick discoloured and hazy varnish or overpintings permeable for near infrared utilised by OCT examination. The technique can be particularly helpful in cases when the inscriptions are not clearly recognisable with other methods e.g. observation in raking light.
Applicability of OCT for examination of inscriptions on oil paintings will be presented on results of examination carried out on models and real artworks.

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CHARACTERIZATION OF GLASS CORROSION PROCESSES BY OPTICAL COHERENCE TOMOGRAPHY

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It this study the applicability of optical coherence tomography (OCT) in identification and characterisation of leached and hydrated glass surface layers has been assessed. The goal is to provide glass conservators and researchers with simple, convenient, quick and non-invasive method of monitoring and predicting of evolution of glass surface.

The reaction of glass with water of any form is called a corrosion process. Although this multi-phase processes is well documented, it is often very difficult to predict evolution of particular artefact. This is because the behaviour of a glass depends on many factors like its chemical composition, the manufacture conditions, the environmental history of the object, the quality of glass in terms of its homogeneity and the occurrence of various technological defects. If environmental parameters (RH, temperature, and the acidity or alkalinity (pH) of surrounding water) are stable, many kinds of even partly hydrated glass can remain stable in equilibrium with this environment for a quite long period of time. However, in some cases of so called unstable glass, reaching such an equilibrium is not possible. But even then, by careful planning and controlling the microenvironment and being aware of the glass surface state, it is possible to significantly slow down its further decomposition. Otherwise, the alteration of glass can even be enhanced.

Optical Coherence Tomography may be useful for frequent monitoring of such objects and for a quick screening of museum collections as well as stained glass windows to identify possible threat from the storage conditions.

In this contribution examples of OCT cross-sectional images of leached glass will be presented and compared with results obtained with other, more conventional (destructive) techniques. The composition of leached layer was assessed with Electron Probe Micro-Analysis (EPMA) whilst its thickness was visualised on cross-section with back scattered electrons (BSE) technique. It will be shown with historic samples, that the leached layer recognized on cross-sections with these techniques may be also found with OCT, but on non-destructive way. Consequently the advantages and limitations of the method will be discussed.

REMOTE MULTISPECTRAL IMAGING OF PAINTINGS AND PIGMENT IDENTIFICATION

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PRISMS (Portable Remote Imaging System for Multispectral Scanning) is designed for *in situ* high resolution multispectral imaging of paintings at inaccessible heights from the ground level.[1] It can also be placed in the centre of a gallery and scan any painting in the room at high resolution without moving the imaging system. PRISMS currently operates in 10 spectral channels between 400 and 900 nm. Sub-millimetre resolutions of up to 25 pixels/mm are achievable for distances up to 25-m. The imaging system stays at ground level during operation. Future plans for PRISMS include hyperspectral imaging capabilities in the near infrared (0.9 – 1.7 μm). Application of PRISMS for multipspectral imaging and spectral pigment identification will be demonstrated.

It has long been recognised that spectral reflectance can be used as a signature of a pigment to offer non-invasive identification of pigments.[2] For the last 10 years, multispectral imaging which offers an efficient measurement of spectral reflectance over a large area simultaneously has been used for spectral pigment identification.[3,4] However, this non-invasive technique has not been met with enthusiasm in the conservation community partly because the identification of mixtures of pigments is unreliable and it cannot identify a pigment if it has deteriorated. The difference between spectral pigment identification and the examination of a sample under a microscope is that the latter offers not only colour but shape information whereas spectral pigment identification does not give any shape information on the pigment particles, but gives not only colour but also spectral information. We demonstrate how OCT can be used to assist spectral pigment identification by measuring the relative absorption and scattering properties of a paint.

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OPTICAL COHERENCE TOMOGRAPHY FOR EXAMINATION OF STRATIGRAPHY OF EASEL PAINTINGS

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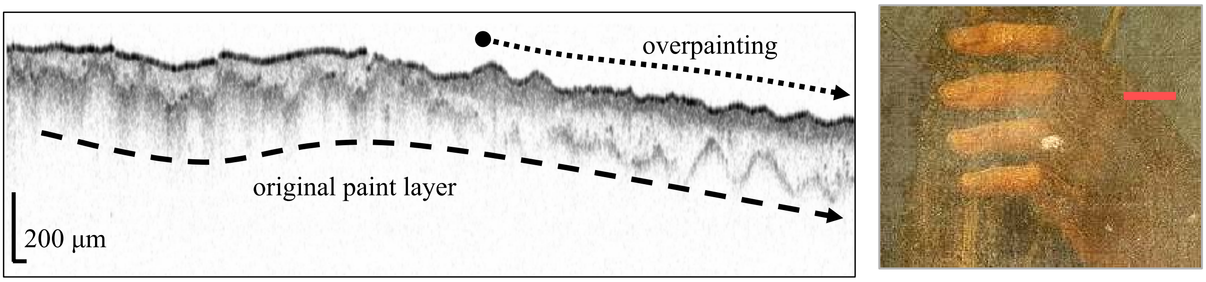
Over the last few years it has been known that the OCT technique may be utilised for examination of inner structure of artworks, especially layers of varnish and semi-transparent paint.[1-7] The crucial point seems to be the implementation of the technique into the conservation practice. That would mean solving specific problems emerging from conservation and restoration of real objects of art. Therefore, in this contribution, the major emphasis will be laid on practical applications.

Examples of imaging of varnish layers and semi-transparent paint layers of old paintings will be presented. The thickness of these layers may be directly measured with OCT in completely non-destructive, quick and convenient way as many times as necessary. Comparison of OCT tomograms obtained from easel paintings with microphotography of a cross-section of the sample taken nearby will enable the evaluation of the OCT analysis' reliability. Furthermore, the question of representativeness of the sample will be discussed.

The solution of the problem of authentication of some regions within the painting by means of the OCT will be also presented. Images of multiple varnish layers (up to four) and overpaintings laying on the varnish layer will be shown (Figure). Additionally, a tomogram of an internal crack at boundary between two varnish layers helps to prove the inauthenticity of the upper layer, besides the evaluation of the painting's state of preservation.



OCT tomogram (on the left) showing partial overpainting (region of background) of an oil painting (on the right)

Images of original, well preserved glaze layer in comparison with discolored glazes will be shown. In the latter case the UV/VIS inspection gives confusing results. Nevertheless, the OCT examination may help the restorer create virtual reconstruction of the painting's original appearance.

The OCT tomograms will be presented both as 2-D cross-sectional images and tomographic movies which enable 3-D analysis of the work of art's spatial structure. Also, the application of these images for real-time monitoring of conservation treatments will be shown.

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