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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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.

Support

This research was sponsored in part by the Air Force Office of Scientific Research FA9550-040-1-0011 and FA9550-010-0046 and the National Science Foundation BES-0522845 and ECS-0501478.

<u>A part of this study is published in Optics Express</u>:

D. C. Adler, J. Stenger, I. Gorczynska, H. Lie, T. Hensick, R. Spronk, S. Wolohojian, N. Khandekar, J. Y. Jiang, S. Barry, A. E. Cable, R. Huber, and J. G. Fujimoto, "Comparison of three-dimensional optical coherence tomography and high resolution photography for art conservation studies," *Opt. Express*, vol. **15**, pp. 15972-15986, 2007

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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.

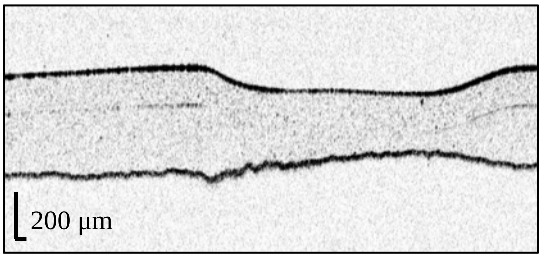

Figure 1. Frame from the OCT movies registered during ablation of the Maimeri Dammar varnish layer ablated with 8 Hz repetition. Laser pulses were applied at the centre of image, during the process sample were translated to the right.

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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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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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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APPLICATION OF OCT TO ART HISTORICAL STUDIES AND CONSERVATION IN THE UK

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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. It is now a fast growing area of research. We report the progress of a Levehulme Trust funded project on the application of OCT to art involving Nottingham Trent university, The National Gallery, the British Museum and the University of Kent. 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 a variety of objects from the British Museum will be discussed. Progress on the application of functional OCT to art will also be reported.

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.

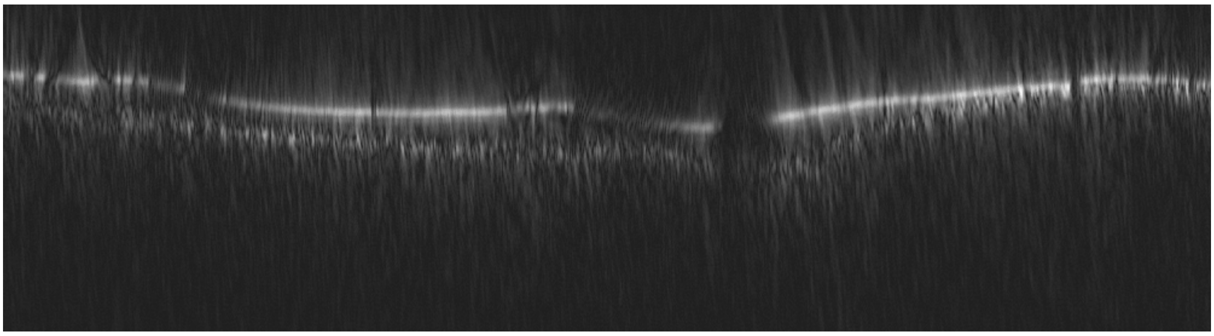

Figure 1. Optical (LSCM) section of the surface of a painting, 1000 x 270 μm^2, showing the varnish thickness profile.

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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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.

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.

Acknowledgements: This work has been supported by the Austrian Science Fund FWF (Projects L126-N08 and P19751-N20).

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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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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.

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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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.