MULTI-THREAD REAL-TIME DATA PROCESSING FOR AN IMAGE-BASED PARTIALLY COHERENT LIGHT INTERFEROMETER

Claudio Pernechele, Simonetta Chinellato, Federico Manzan

INAF – Italian National Istitute for Astrophysics
Astronomical Observatory of Cagliari, Strada 54, I-09012 Capoterra (CA), Italy
phone: + (0039) 070.71180250, fax: + (0039) 070.7180222, email: claperne@oa-cagliari.inaf.it
web: http://www.srt.inaf.it/metrology/index.html

Monica Galeotti

Opificio delle Pietre Dure, Scientific Department, via Alfani, 78, 50121 Firenze (Italy)

ABSTRACT

A parallel multi-channel partially coherent light interferometer has been built and optimized for 3D surface measurements of artworks at a depth resolution of one micrometer. The technique is based on the well known low coherence interferometry (LCI) principle and it is largely described in literature. Usually it uses a single point measure plus a bi-dimensional scanning system to acquire data from an area. Our instrument is equipped with a bi-dimensional image sensor (CMOS) instead of a one-dimensional photodetector and is able to directly acquire images, i.e. matrices of points, and make 3D measures with a single scanning along the depth direction, avoiding the use of any lateral scanning system. The data from the CMOS are read-out and the frames are sent to the PC via a USB2 connection. In order to perform the measure as fast as possible, data processing is performed in parallel with data acquisition, exploiting multi-thread capabilities of the C++ code. Despite the great data flow, the processing time is limited mainly by the USB2 transferring rate and data are acquired, in this framework, in real-time. We present results on a terracotta artwork under restoration revealing quantitatively the 3D structure of the surface, i.e. volumetric and topographic results. With this contact-less approach, and thanks to the IR radiation used as light source, it is moreover possible to achieve tomographic results, visualizing and actually measuring, the layered structure of a terracotta sculpture.

1. INTRODUCTION

The use of partially coherent light interferometry (LCI – low coherence interferometry) for contactless 3D measurements of artworks is becoming of interest in the art diagnostics community. The LCI technique is largely described in literature [1], some applications for artwork diagnostics include measures of canvas deformations [2], painting diagnostic [3], varnish ablation control [4], jades monitoring [5] and parchment degradation [6]. Good reviews may be found in [7-8]. At present the most widespread instrumentation using this technology is based on fiber interferometers where only one pixel per unit time is acquired; the scan speed limits the acquisition rate for high-resolution two-dimensional images to a few hertz. This limitation restricts the method to essentially single-point or cross-section images. To improve the frame rate of the imaging system a parallel detection scheme is used. This approach allows one to get rid of the transverse scanner used in standard OCT setups and to acquire a complete image during only one depth scan. The use of two-dimensional CCD cameras has already been used as detection devices for this purpose [9]. The introduction of a fast frame-rate CMOS camera allows the acquisition of depth cross-sectional images at a high velocity and in real time. The small dimensions of the instrument are advantageous for its portability, thus making it appropriate for in situ measurements of artworks, whereas image analysis is quickly turned out by the processing software. Our instrument is described in some details in paper [10], while its accurate depth and spatial calibrations are described in [11].

2. INSTRUMENT SET-UP

The system is based on the optical concept known as low coherence interferometry (LCI), which is also referred to as partial coherence interferometry. In this context, the term “partial” refers to a source with low temporal coherence and high spatial coherence. The system works as a comparator of optical group delays. The group delay along the optical axis in the probe interferometer arm containing the object to be measured is compared with the group delay along the optical axis of the reference interferometer arm containing a delay line. We realize a traditional-based Michelson optical set-up and develop a fast frame-rate CMOS camera allowing us to acquire depth cross-sectional images at a fast rate. A sketch of the instrument set-up is shown in the Figure 1. A near infrared super-luminescent diode (SLED working @ 820 nm) exits from a fiber-end and is collimated. A 50%/50% beam-splitter splits the collimated beam sending an arm toward a reference plane (a mirror) and the other toward the surface to be measured (the artwork under study). The light is scattered by the object under test and is imaged through an objective into the CMOS area. The reference arm is back-reflected from the flat (λ/8) mirror. A neutral density filter (NDF in figure) is inserted into the reference arm in order to balance the light intensity between the two arms. The distance between the reference mirror and the beam splitter is changing by means of a micrometric motor and the CMOS acquisitions are synchronized with it. When the reference length L is near ("near" depending on the SLED coherence length, tens of µm in our case) to the object length L_0, then the interferometric pattern appears on the CMOS pixels and the distance may be extracted from the motor position. The optics are bound all in once and move together along the L_0 direction with respect to the surface under study. In this way the depth of imaging is virtually unlimited, thus depending only on the permitted range of movement.

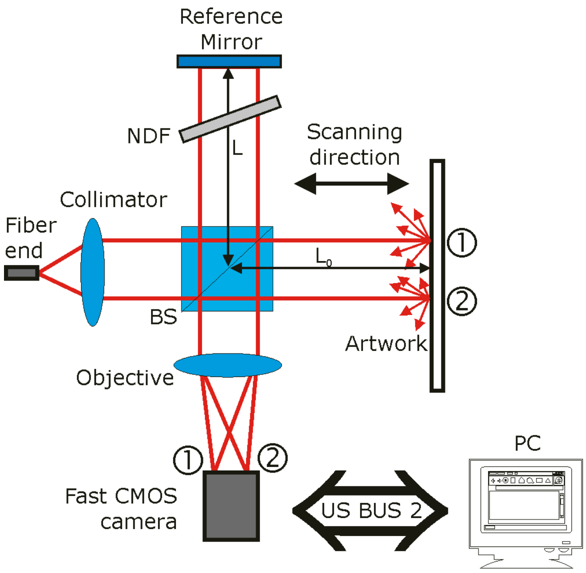

Figure 1 – Instrument set-up concept.

Although acquisition time is generally not the most important feature in artwork diagnostic applications, a measuring time as low as possible avoids the problems linked to possible movements of the bench and of the air, making the measure more accurate. Our interferometer uses a bi-dimensional (1280x1024 square pixels of 5 µm side) CMOS as detector which can be full frame (more the 1.3 Mega channels) downloaded at a speed up to 15 fps (frame-per-second). Each channel corresponds to the single pixel at a depth of 2 byte. The sensor can be read out choosing a sub region thus increasing the data flow velocity. For example, if a 256x256 (65536 parallel channels) region is read out, the frame rate may be increased up to 150 fps, reaching higher velocities for smaller areas. The data are downloaded into the PC via a USB2 connection. Once the data arrive in the PC memory a multi-thread code starts the elaboration simultaneously with the downloading process. The code is robust and simple and permits to have the data analysis completed immediately after the downloading process, making the measure limited only by the USB2 speed (about 240 Mbit/s in download direction).

3. MULTI-THREAD AND CODE TASKS

The core of the elaboration is the use of multi-thread capabilities of the code. Three threads are running in parallel, as shown in Figure 2. The former manages the data flow in acquisition (ACQ thread), the second one applies the single-pixel derivative-based algorithm (DERIV thread) for finding out the interferometric beat and hence the distance L_0 (see Figure 1) and the latter (MOVMEAN thread) is used to find out the maxima and save the results.

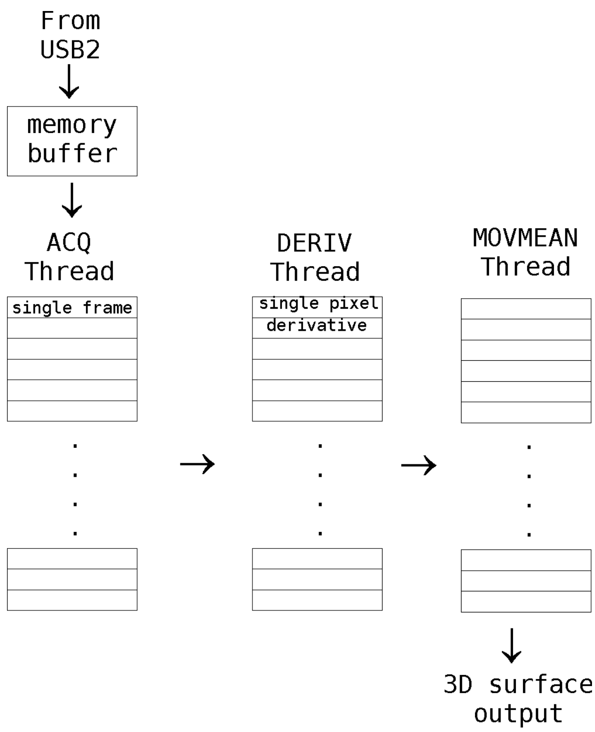

Figure 2 – Multi thread architecture.

A typical elaboration layout for a single channel is shown in the Figure 3. The top panel shows the single-pixel light curve recorded during the acquisition. The whole acquisition is of about 0.5 mm in depth (the abscissa). In the case reported in Figure 3 a single frame consists of 512x512 pixels and the downloading frame rate is of 50 fps. The motor is driven at a speed of 5 µm/s and so the single images are acquired every 0.1 µm in the depth direction (the total number of frames is around 5000). An interferometric pattern in the light curve is already visible in this panel. In order to increase the signal-to-noise (SNR) ratio a derivative task is applied to the light curve, the output of this process is shown in the middle panel. The interferometric pattern is composed of the interferometric sinusoidal curve (with wavelength of 820 nm) plus the low coherence Gaussian envelope. The ACQ thread starts and after a given number (of the order of some hundreds) of images have been loaded in the stack, the

DERIV thread begins the processing of the acquired images by means of a derivative algorithm.

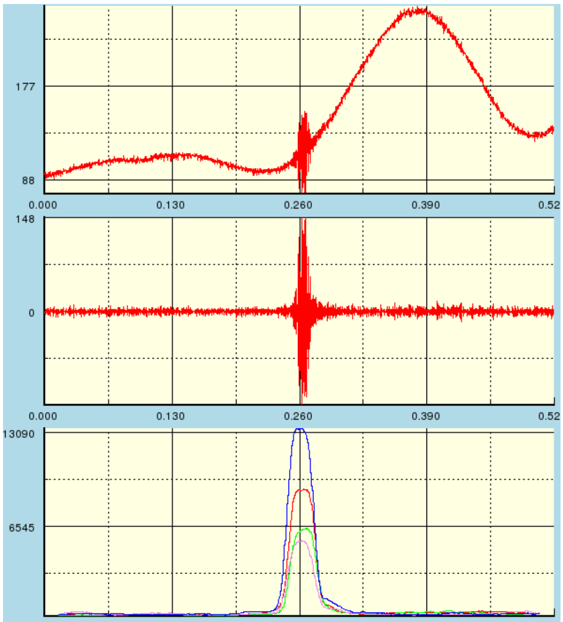

Figure 3 – The elaboration thread tasks on a single channel.

The latter algorithm is suitable when passing from the light + background profile (upper panel in Fig. 3) to a background-free light profile (derivative curve in middle panel in Fig. 3). Being the interferometric pattern sampled each 0.1 µm, the derivative algorithm works properly in fitting the sinusoidal pattern and any aliasing problem is avoided. The following task (MOVMEAN thread) finds out the maxima in the derivative curve. This is performed by means of a variable mean algorithm which consists in summing the absolute values in the curve within a window of fixed width and then moving it along the thread. The result is visible in the bottom panel of Fig. 3, hence the maximum is extracted from this profile. The units shown in the ordinate axes for all the panels are arbitrary. The four curves visible in the bottom panel are relative to four different selected channels (pixels) along the frame. All threads run simultaneously making the system work in a relative "real-time" process. Accurate calibration of the instrument has been achieved and the results are described in detail in our paper [11]. The required precision of 1 µm in depth for the present application is well reached.

4. MEASURES WITH LCI

We present results on a terracotta sculpture attributed to the Della Robbia workshop. The statue is an early XVI century Madonna with Child, partially polychromed and partially glazed. It comes from S.Francesco's church in the village of Citerna (Perugia, Italy) and is now in Florence, at the Opificio delle Pietre Dure, where it is undergoing a conservation treatment. We mounted a 0.5x telecentric objective giving a plate scale of 10 µm/pixel. We chose a frame of 512x512 pixels equivalent to an area of about 5x5 square mm on the polychrome carnation of the Child. The whole depth of scanning was of 1.3 mm. The frame rate was of 50 fps and the motor speed was selected at 5 µm/s. The total measure time was of 260 seconds (limited by the USB2 speed). With this technique is possible to quantitatively measures both the volume of the missing matter and moreover to look at under-surface matter by means of tomography, as will be better explain in the paragraph.

4.1 Volumetry

From the analysis of the data is possible to measure quantitatively the volume of the mssing matter. The result of the measure is shown in the following Figures 4-6

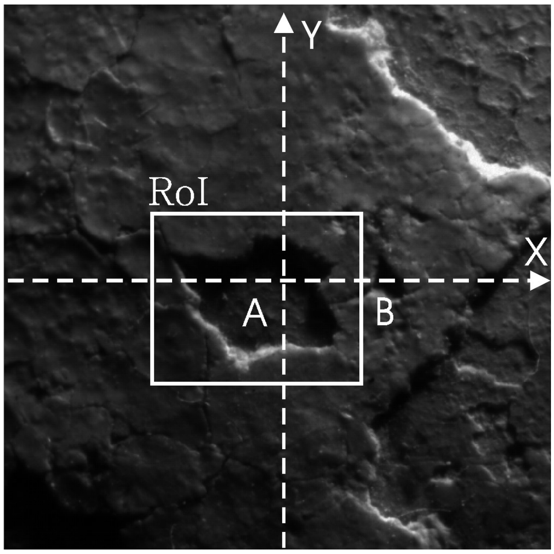

Figure 4 – A picture of the measured area.

In Figure 4 is shown a picture of the measured area: two features and a chosen region of interest (RoI), which has been studied in detail, are highlighted respectively with letters A and B and with a white box. With X and Y are indicated two axes in correspondence of which profiles of the surface are extracted (see Figure 6 below). In Figure 5 the area of the surface, as measured by the interferometer, is shown and features A and B indicated in Figure 4 are clearly visible.

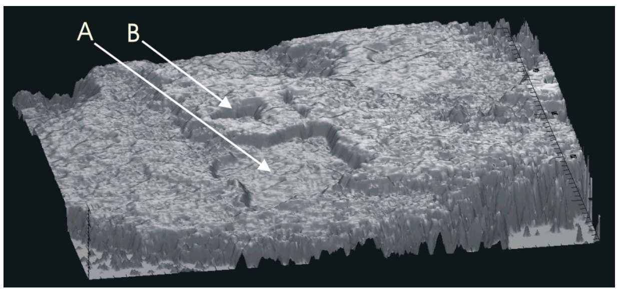

Figure 5 – The 3D surface relative to the 2D area in Figure 4.

Profiles along the X and Y axes drawn in Figure 4 are shown in the next Figure 6 (top and bottom panels respectively).

The features A and B are clearly identified. It has to be emphasized that the accuracy of the curve is of 1 µm in accuracy. From these profiles can be recovered the thickness of the coating and determined quantitatively the volume of the damaged region. In the next picture (figure 7) an enlargement of the RoI in Figure 4 is displayed.

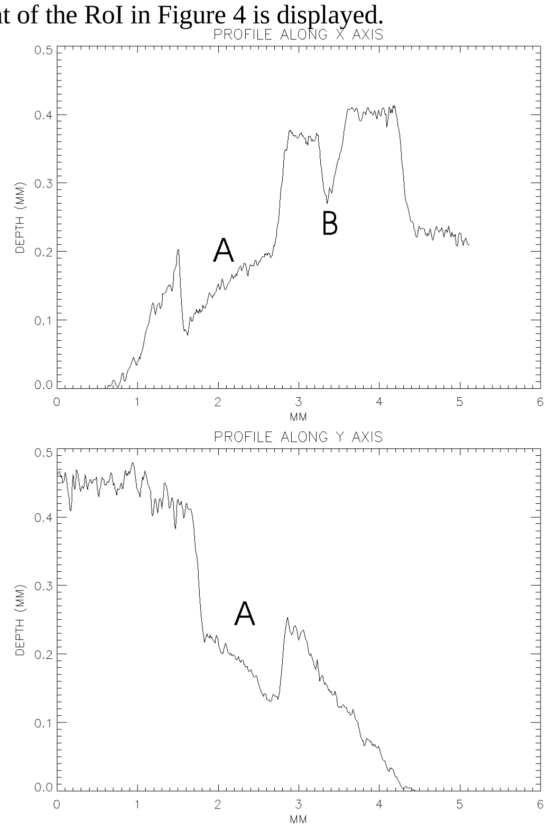

Figure 6 – Profiles along the X and Y directions (see Figure 4).

As a quantitative analisys we calculate the depth of 50 adjacent points in the hole region (along green line in figure) and in the coating one (along the red line) from which we are able to estimate the relative depth between each other.

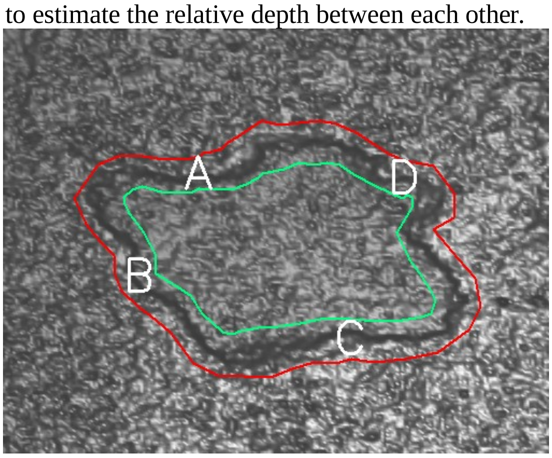

Figure 7 – An elargement of the RoI in figure 5.

In Figure 8 are shown the profiles of the two described lines (the lower curve referring to the green one, the higher one to the red one) and we mark in both figures (7 and 8) four regions, namely A, B, C, and D. The profile in Figure 8 is a polar one starting from region A and following counter-clockwise the lines in figure 7. A variable thickness is measured along the profile, going from about one hundred microns in regions A and D regions up to about 160 µm in region C.

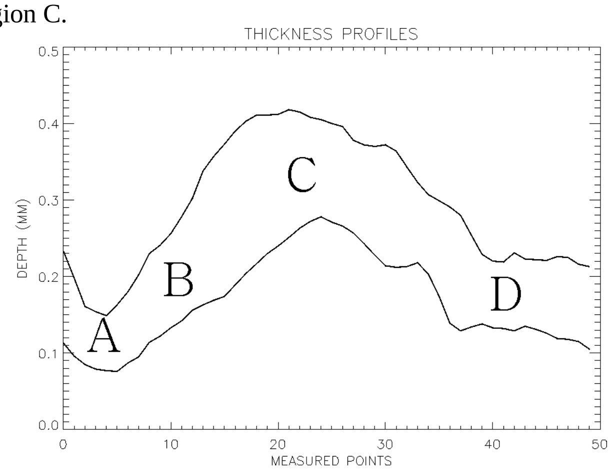

Figure 8 – Profiles of the green (lower) and red (higher) lines shown in Figure 7.

4.2 Tomography

Maybe one of the most powerful potentials of this technique is to look at the structure of the matter lying under the visible surface, with a contact-less non-destructive approach. This analysis is quite challenging and currently under study. One example of acquired data is shown in the Figure 9, in the top panel the depth profile (derivative curve) is shown and three peaks are clearly visible. After the processing of the data by the third thread (the finding of the maxima, see description above) it is possible to recover quantitatively a measure of the under-surface material substrate. It is in fact well known that IR radiation, like that of the 820 nm light source used, is capable of passing through varnish and paint layers [3, 8].
The reported values are comparable with stratigraphic measurements performed on the sample, which are reported in the following Figure 10. In the picture a cross-section of a micro sample from the same region of the interferometric analysis is shown. The sample has been taken after measurements, embedded in a polyester resin, polished, observed by an optical microscope under visible and UV light and submitted also to SEM/EDS analysis to check the elemental composition. Unfortunately, due to sampling difficulties, the sequence of layers from the terracotta support is not complete and the full depth of the pictorial cover is not to be inferred from this sample. Above the residue of *gesso* ground, two layers of white lead with few vermillion particles are clearly visible in the image, each of them being about 50 µm height. Above all, a varnish layer of about 25 µm of depth is well observable in the UV fluorescence image of the figure. The three main peaks visible in the tomographic analysis (fig. 9) are to be referred to the main 3 layers composing the

sample: from bottom to top: the preparation layer (gesso ground), the paint layer and the varnish layer. The distance between the peaks gives us the measure of the optical path between the overlapped surfaces, from which the distance can be recovered knowing the refractive index of the materials.

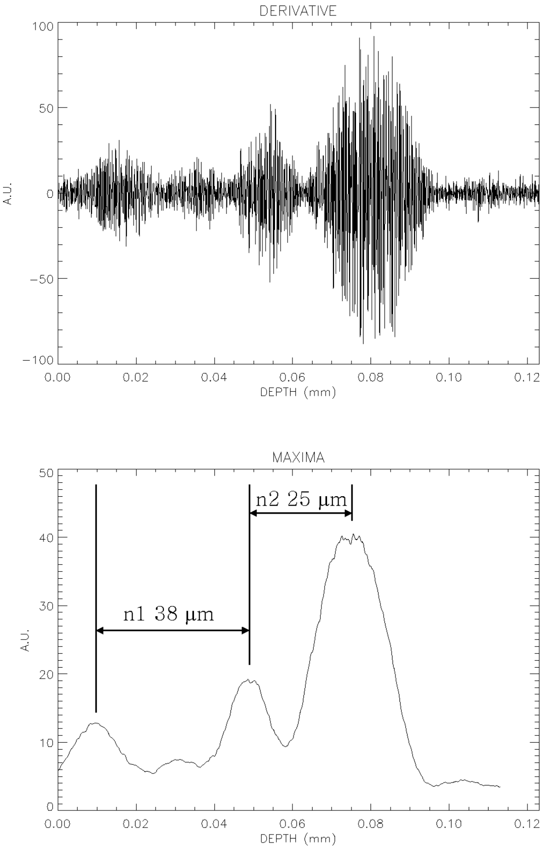

Figure 9 – Multi.peak found of under surface strates.

At present we are able to recover the optical path length but not the geometrical one that needs the knowledge of the refractive indexes of the materials (n1 and n2 in Figure 9). A direct comparison between Figures 9 (optical path length) and 10 (geometrical length) cannot be directly compared. However, taking into account that refraction indexes are greater than one, the two quantities are comparable.

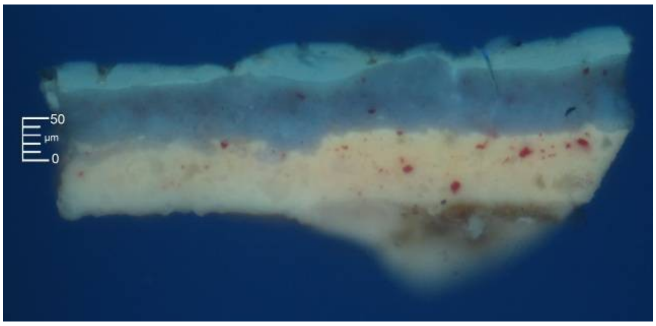

Figure 10 – Cross-section of a micro fragment observed under the optical microscope using an UV lamp.

5. CONCLUSION

A partial-coherence light interferometer based on a traditional Michelson optical set-up and a 2D silicon array (CMOS) that allows parallel detection has been realized for image-based artwork diagnostics. The system is able to measure surfaces topography with interferometric resolution, high depth of field (up to several millimeters), adjustable spatial resolution and parallel multi-channel recording, avoiding the use of any 2D scanning system. Measures taken on a polychrome terracotta artwork show the usefulness of the technique in quantifying its surface structure. The most powerful potentiality of the technique resides in its contact-less non-destructive tomographic capability to perform quantitative measurments of the under-surface materials.

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