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Real-Time Diagnosis of Historical Artworks by Laser-Induced Fluorescence

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Abstract Laser-induced fluorescence (LIF) is a powerful remote analysis tool that has been successfully applied to the real-time diagnosis of historical artworks, allowing the observation of features invisible to the naked eye, as pigment composition, biological attack and restoration technique. This paper presents a LIF-based optical radar and reports on the results of its deployment during a field campaign conducted in February 2010 in Seville, Spain.

Keywords: Laser-induced fluorescence, optical radar, historical artworks, real-time diagnosis

Introduction

In a typical laser-induced fluorescence (LIF) instrument, an ultraviolet (UV) laser beam irradiates a sample and an optical system measures the fluorescence spectrum that contains information on the target composition. LIF is fast, remote, non-invasive, sensitive and specific. These advantages have encouraged its application in the real-time monitoring of historical frescos, mosaics, paintings and stones. These studies showed its high potential as a diagnostic tool for cultural heritage.

The Laser Applications Section (Aristipini et al. 2010) of the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) has worked in this field since 2003 and has developed various prototypes. The system presented here (LidArt) is a lidar fluorosensor (optical radar based on LIF) and its first version was patented in 2007 (Aristipini et al. 2006). It is compact (contained in a cylinder of radius 29 cm and height 18 cm), scanning (the artwork surface is probed remotely aiming the laser beam), hyperspectral and time resolved (the fluorescence spectrum is measured with a wavelength resolution of few nm and a time resolution of few ns). Moreover, it is light, robust, transportable, user-friendly and cost-effective.

Thanks to sophisticated data processing techniques as false-color imaging, principal component analysis (PCA) on spectra and spectral angle mapping (SAM) on images, LidArt has detected characteristics invisible to the naked eye, as pigment compositions (e.g. titanium white vs. zinc white), pigment diffusions (lime and casein), biological attacks (algae and fungi), consolidants (usually resins), deteriorations, depigmentations, retouches and varnishes (Colao et al. 2008).

Instruments and methods

LidArt has widely proven its capability to collect hyperspectral fluorescence images of large artwork surfaces (e.g. frescos, paintings, decorated facades, etc.). A new compact set up has been recently built, with the aim to increase its performances in terms of detection sensitivity, space resolution, time resolved measurements and data acquisition speed. Major achievements have been reached by a critical review of the optical design: the beam transmitter has been substantially modified, the light receiver is now based on an imaging spectrograph (Jobin-Yvon CP240) and the linear array detector has been replaced with a square intensified charge coupled device (ICCD) sensor (Andor iStar DH734) with a pixel size of 13 μm . With these upgrades, an image of $1.5 \times 5 \text{ m}^2$ is now scanned in less than 2 minutes (assuming that the system is at 25 m from the target).

This arrangement is characterized by having the spatial and spectral information on two mutually orthogonal directions imaged on the detector, with submilliradian angular resolution and spectral resolution better than 2 nm. Moreover, it is possible to implement time resolved measurements on the nanosecond scale by controlling the electronic detector gate.

Another interesting feature of LidArt is the possibility of acquiring a red-green-blue (RGB) reconstructed image from a reflectance scan in the visible range: the laser is switched off, a halogen/tungsten lamp is turned on and the optical detector shutter remains opened for a time needed to acquire the image.

The main specifications of LidArt are listed in Table 1, its actual set up is shown in Fig. 1.

Table 1: Main specifications of LidArt.

<i>Transmitted wavelength</i>	266 nm
<i>Horizontal resolution</i>	0.2 mrad
<i>Vertical resolution</i>	1 mrad
<i>Field of view</i>	5.7°
<i>Acquisition time</i>	200 ms (per line)



Figure 1: Actual set up of LidArt: laser (left), ICCD (top right) and imaging spectrograph (bottom right) are mounted on a circular optical table

Results and discussion

From 1 to 5 February 2010, LidArt collected hyperspectral fluorescence images of some artwork surfaces in various churches of Seville, Spain. The results obtained in the Saint Telmo's Church will be shown. In particular, the data analysis of scans A31 and A33 will be presented and discussed in detail. During these acquisitions, LidArt was placed at 3.2 m from a fresco (Fig. 2a). The image was

128 pixels wide and 300 pixels high, resulting in a spatial resolution of approximately 3 mm. 250 spectral channels from 250 to 800 nm were recorded per each pixel.

Although a careful examination of the reflectance scan (Fig. 2b) already shows some details invisible to the naked eye (e.g. the bluish vertical line just under the collar of the Saint), some peculiarities of the image can be only retrieved by a detailed analysis of single pixel spectra. In order to reach this goal, two approaches have been used: the first one makes use of spectra averaging in selected areas characterized by an apparent uniform color; in the second one, PCA components are computed. On one hand, with the first technique, it is possible to document the use of pigments, on the other hand, PCA – although giving spectral components without a direct chemico-physical meaning – could identify emission bands not recognized by the first technique. Eventually, once the more important spectral features are identified by spectral averaging or PCA, SAM similarity maps can be used in order to circumscribe the areas affected by the chemico-physical processes linked to those features.

Fig. 3 is an example of application of spectra averaging. Some areas of the fresco show a strong emission at 310 nm. This UV emission could be ascribed to a varnish or a consolidant. In fact, the presence of this emission, made more evident by a band ratio analysis (the band at 310 is normalized to the band at 450 nm) is distributed on all the surface, confirming that this spectral feature could be more likely linked to an extended film rather than to a punctual retouch.

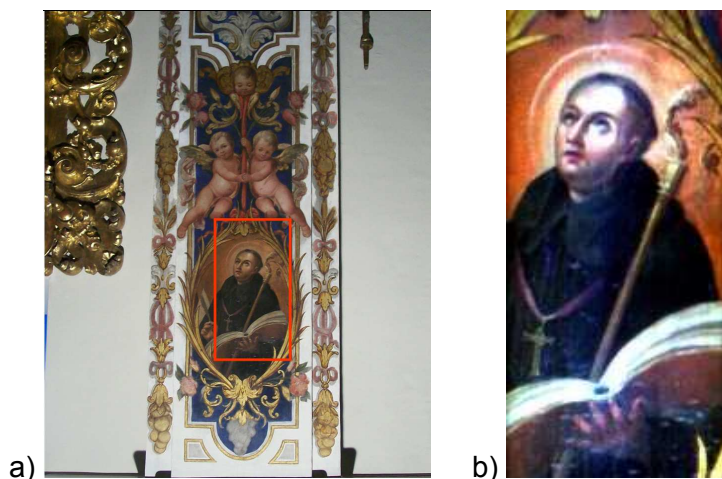


Figure 2: a) Fresco analyzed by LidArt with scans A31 and A33 in the Saint Telmo's Church, Seville, Spain (the red rectangle indicates the scanned area). b) RGB reconstruction from the reflectance scan (A31) with the spectral channels at 609, 508 and 405 nm

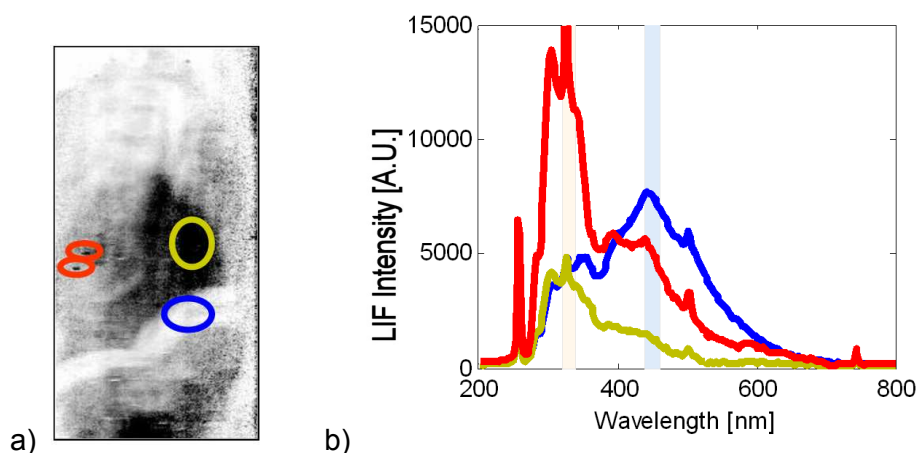


Figure 3: a) Band ratio analysis of the fluorescence scan (A33): the band at 310 is normalized to the band at 450 nm and grey levels indicate the band ratio values (dark/light grey corresponds to high/low values), b) Spectra averaging in the areas on the left identified by the color-line correspondence

Fig. 4a shows the principal components of scan A33. The elastic backscatter at 266 nm is clearly visible (the structures at 532 and 798 nm are its second and third diffraction order, respectively). The most important spectral feature is a strong emission at 360 nm (the peak at 720 nm is its second diffraction order). At present, it is not possible to identify the chemical compounds related to the strong emission observed at around 360 nm. However, comparing Fig. 2b and Fig. 4b, it can be concluded that this emission could originate from retouched areas. Although a precise chemical identification has not been achieved, it is worth noting that an extremely accurate localization of their distribution on the fresco has been attained.

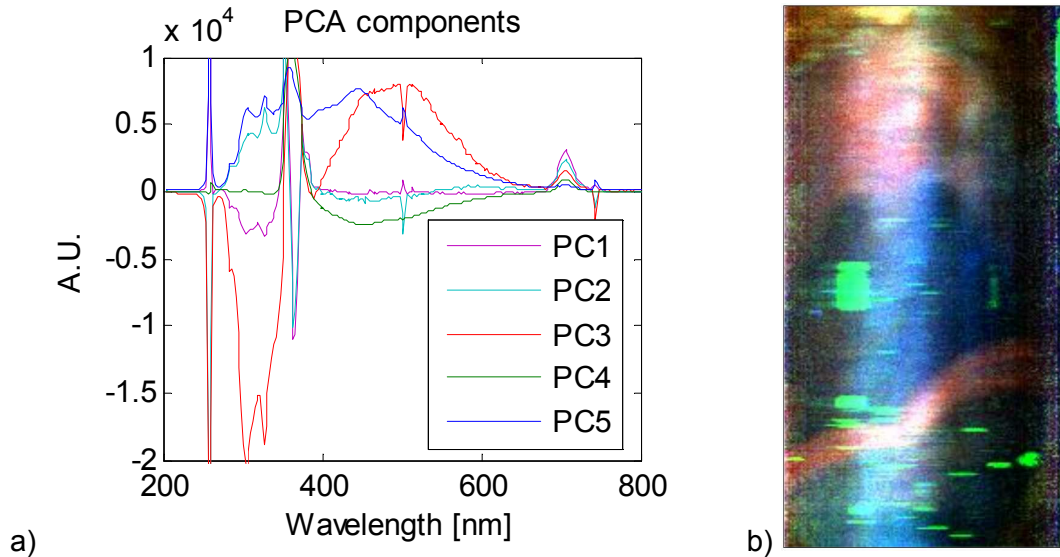


Figure 4: a) PCA analysis of the fluorescence scan (A33), b) RGB reconstruction from the fluorescence scan (A33) with the spectral channels at 450, 360 and 325 nm; the predominance of green indicates the presence of a compound strongly emitting at 360 nm

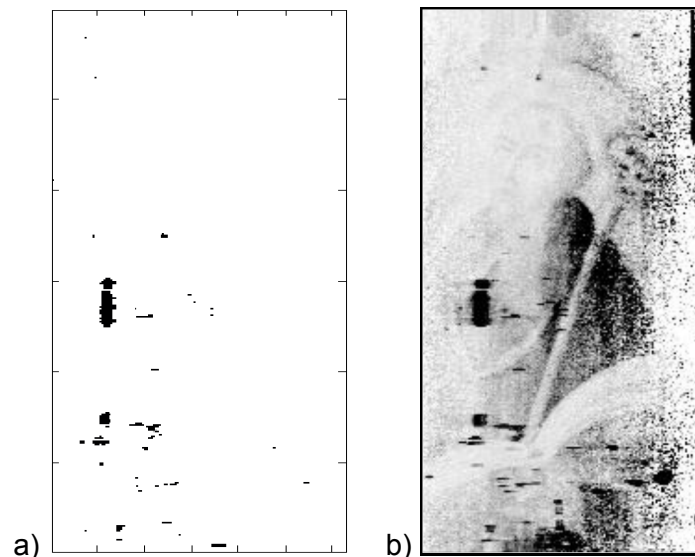


Figure 5: a) SAM similarity map identifying areas with strong emission at 360 nm from the fluorescence scan (A33); b) Band ratio analysis of the fluorescence scan (A33): the band at 360 is normalized to the band at 450 nm and grey levels indicate the band ratio values (dark/light grey corresponds to high/low values)

Eventually, SAM was applied in order to retrieve a similarity map identifying areas with strong emission at 360 nm (Fig. 5a). Comparing the results of SAM to the corresponding RGB reconstruction (Fig. 4b) and band ratio analysis (Fig. 5b), a general agreement can be found, although SAM seems more specific but somewhat less sensitive.

Two scans of the vault of the Saint Telmo's Church (Fig. 6) are presented in Fig. 7 and 8. In this case, LidArt was at about 11 m from the fresco. The treatment with a chemical compound was clearly identified in both cases.

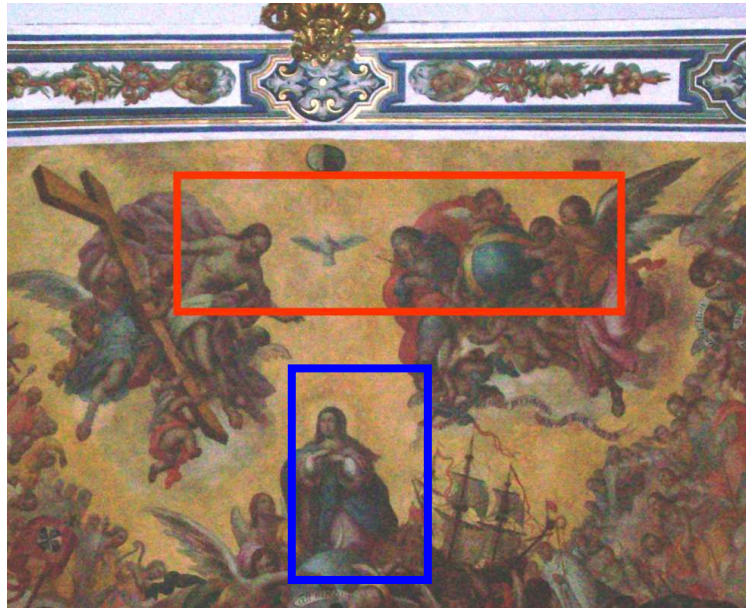


Figure 6: Fresco analyzed by LidArt in the vault of the Saint Telmo's Church, Seville, Spain (the red and blue rectangles indicate the scanned areas corresponding to Fig. 7 and 8, respectively)



Figure 7: a) RGB reconstruction. b) Two color image identifying heavily treated (blue), lightly treated (yellow) and uncertain (gray) areas

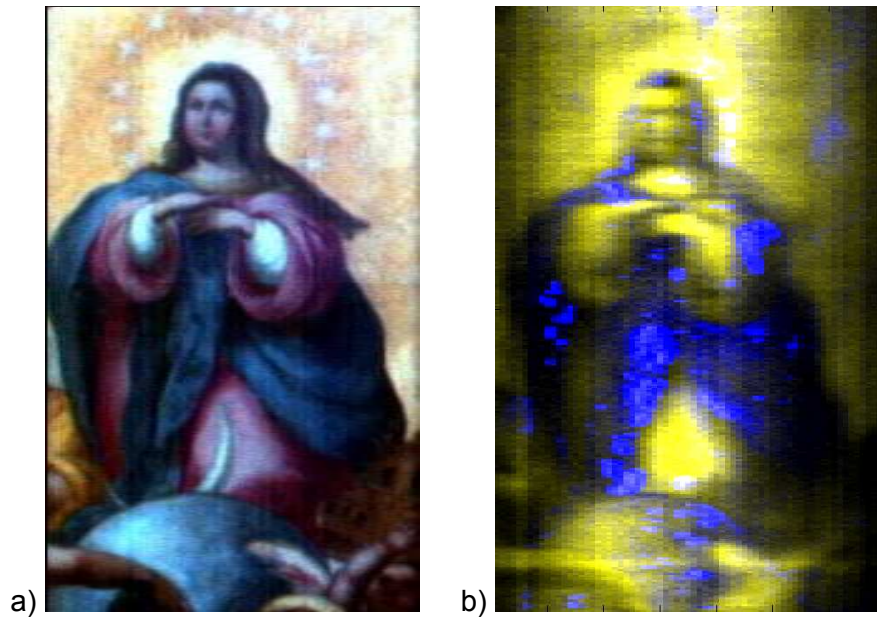


Figure 8: a) RGB reconstruction. b) Two color image identifying heavily treated (blue), lightly treated (yellow) and uncertain (gray) areas

Conclusions and perspectives

LidArt in the upgraded version participated to its first campaign. Sophisticated signal elaboration techniques as PCA and SAM proved to be useful in order to identify chemico-physical inhomogeneities in painted surfaces. Although only part of the data have been analyzed and the results are preliminary, the capability of LidArt in detecting artwork features invisible to the naked eye has been fully shown.

Future work includes, from one hand, the completion of the data analysis and, from the other hand, to establish a clear link between observed spectra and surface characteristics of the painted surface. For this purpose, a spectral database of chemical compounds relevant to cultural heritage under UV excitation should be built in the laboratory.

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