Scanning Lidar Fluorosensor for Remote Diagnostics of Artworks

The Laser Induced Fluorescence (LIF) technique has been applied in the field of cultural heritage as a diagnostic tool for the advantages it offers of minimal invasiveness, in situ applicability, remote measurement capability and high sensitivity. Scanning hyperspectral systems based on LIF have been designed and built at the Diagnostics and Metrology laboratory of ENEA-Frascati in order to obtain analytical information on CH surfaces by 2D images collection

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Introduction

The respect of the artwork, its conservation status and the preservation of the historical-environmental context are at the centre of the modern concept of restoration. Innovative non destructive diagnostic technologies, suitable to the characterization of historical surfaces, as painted surfaces, multilayer frescos or decorations on wood, are then currently under development to meet the conservators' requests, to gain information on past and not well documented restoration steps, as well as to investigate the possible cleaning procedures effects.

To this aim, laser-based techniques are successfully used as diagnostic tools in the field of cultural heritage [1]. The increasing application of these non destructive technologies, both for conservation and restoration actions, is mainly due to the advantages offered by the use of laser, that allows to perform measurements on remote targets at large distance with minimum invasiveness. In particular, the realization of accurate laser scanning systems originated the development of remote spectroscopic diagnostics, by which a complete optical and spectroscopic characterization of outer surface layers can be achieved and high resolution 2D images can be released.

Among the spectroscopic techniques appropriate to remote application, the Fluorescence Induced upon ultraviolet Laser excitation (LIF) is able to supply valuable information: it allows indeed for identification of fluorophores groups relevant to different substances either present onto the surface due to biodegradation and environmental pollution or forming the outermost layers, for instance pigment, binders and consolidants in the case of painted surfaces. In particular, restorers need a precise knowledge of surface materials once engaged in removing traces of former restorations.

The Laser Induced Fluorescence (LIF) technique has already been used in the monitoring of the protective treatment on stone surfaces [2], to identify some acrylic resins of interest for artworks [3], or to detect cultures of fungal and bacterial strains [4].

Remote sensing systems have recently found application in high resolution scanning devices for mapping the actual preservation status of cultural heritage surfaces [5, 6].

Scanning hyperspectral systems based on Laser-

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FIGURE 1 From left to right: Hrastovjie Church (Slovenia) (http://www.randburg.com); Sucevita Monastery (Romania) (ENEA source); S. Telmo Palace in Seville (Spain) (http://www.minube.it)

induced fluorescence (LIF) have been designed and built at the Diagnostic and Metrology laboratory of ENEA-Frascati in order to obtain analytical information on CH surfaces by 2D-image collection.

Thanks to sophisticated data processing techniques, such as false-colour imaging, principal component analysis (PCA) [7] on spectra and spectral angle mapping (SAM) [8] on images, features invisible to the naked eye, as pigment compositions (e.g. titanium white vs. zinc white), pigment diffusions (lime and casein) [9], deteriorations, depigmentations, retouches and varnishes can be detected.

Real-time diagnoses of historical artworks have been performed during several in-field campaigns as, for example, in Slovenia, Romania and Spain (see Fig. 1).

In particular, the analyses performed on frescos inside the S. Telmo Palace in Seville, under a scientific cooperation between ENEA UTAPRAD and *UPO Natural Science Department of Seville*, and the Baptistery of Padua, under a collaboration signed with *Soprintendenza ai Beni storici Artistici e Etnoantropologici per le province di Venezia Belluno Padova e Treviso*, will be presented as successfully applications of the LIF line scanning system in the cultural heritage field.

Experimental Apparatus

The LIF technique is a molecular spectroscopy for surface analysis based on the interaction of the ultraviolet radiation emitted by a laser with the matter [10]. The emission of radiation by luminescent materials is observed whenever an absorption of energy sufficient to activate the allowed electronic transitions occurs. In a typical LIF instrument, an ultraviolet (UV) laser beam irradiates a sample and an optical system collects and measures the emitted fluorescence signal. The spectral content of the radiation coming from the examined surface supplies information on the composition of the outer layers, once interrogated at different excitation wavelengths. It is a fast, non invasive, remote, sensitive and selective technique.

A LIF scanning instrument able to collect hyperspectral fluorescence images on large areas has been realized at the ENEA in the Diagnostic and Metrology laboratory of Frascati. The system has been developed with the aim of increasing the performances in terms of space resolution, time resolved capabilities and data acquisition speed with respect to the previous versions [11]. The main improvement of the new recently built LIF system consists on the line-by-line scanning process, particularly suitable for investigation on large areas. A point-by-point LIF scanning system was, in fact, previously developed in ENEA [11] and applied in several campaigns of measurements due to its compact, reduced size and light weight. These allow for an easy transfer of the system and its operation from scaffoldings, in the case of surfaces out of the current maximum range for remote operation (10 m).

The new system and the related scheme are reported in Fig. 2.

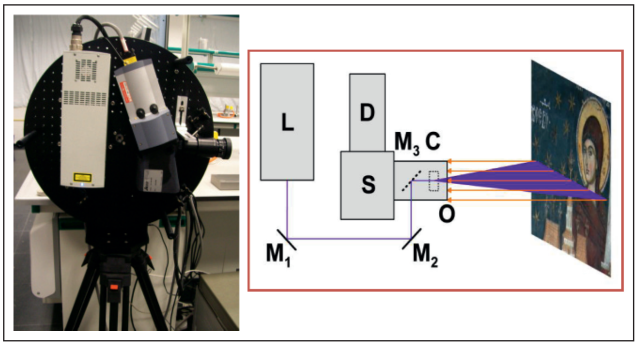

FIGURE 2 ENEA compact LIF line scanning system with the related scheme: L-laser, D-detector, S-spectrometer, M-mirrors, C-cylindrical lens, O-objective
Source: ENEA

The laser beam has a light blade shape. With the optical system based on the use of cylindrical lens, focusing the laser spot as a line, an image of 1.5× 5m^2 is currently scanned in less than 2 minutes at 25 m. A diode-pumped Nd:YAG laser source has been utilized to generate the UV radiation at 266 nm or 355 nm, depending on the applications, with repetition rate of 20 Hz, pulse duration of 10 ns and energy of 1.5 mJ. This arrangement is characterized by having the target spatial and spectral information on two mutually orthogonal directions imaged on the detector, with a sub-millimeter spatial resolution and a spectral resolution better than 2 nm. Moreover, time resolved measurements on the nanosecond scale can be performed by controlling the electronic detector gate in a boxcar-like configuration. The collected data are released as false colour reflectance and fluorescence images suitable to the identification of original and added materials.
Each scan is controlled by a portable computer where a specific program developed in LabView allows to set experimental parameters, control data acquisition, and perform a preliminary data analysis. In the main control panel, data are shown both as 2D monochromatic images (1024x1024) and LIF spectra for each pixel. Additionally, the LIF scanning system can be utilized, with the laser switched off, to collect reflectance images upon the availability of an intense standard light source. When using a continuous light source like a lamp, the synchronism for data acquisition is given by the detector itself. Both fluorescence and reflectance images can be reconstructed in false color by using the three most intense features detected, associated respectively to Red, Green and Blue channels (RGB).

Results

The results obtained from the LIF system application on two different artworks are reported here below as successful case studies.
LIF analyses inside the monumental complex called S.Telmo Palace have been carried out on the fresco *"La Glorificacion de la Virgen"* from Domingo Martinez in the *Virgen del Buen Aire Chapel*, in order to reveal traces of former restorations to which the presence of consolidants and retouches on the pigments could be ascribed.
The most significant spectral features of LIF spectra have been identified by the Principal Component Analysis (PCA) [7]. By analyzing the LIF spectra from a portion of the vault (Fig. 3a), the identification of areas which have been heavily treated during the restoration can be documented by using the band fluorescing at 360nm.
In Fig. 3b, the fluorescence black and white image obtained with the band at 360nm is shown.
The black corresponds to pixels with high fluorescence emission intensity, whereas the white area to pixels with low fluorescence. A conventional photo of the same scanned fresco surface is reported in the figure, for comparison.
The presence of the same band peaked at 360 nm has also been revealed on the other LIF images acquired in the same chapel, with maximum intensity at precise locations, presumably related to the restoration treatment. Although a precise identification and/or discrimination is not immediately possible, it is worth noticing that we obtain an extremely good localization of the use of such a chemical. Moreover, the grey level scale gives a qualitative evaluation of the amount of film used, since a direct proportionality between the film thickness and the LIF signal intensity should hold. Colour rendering has been chosen (Fig. 3c) in order to better distinguish low (in yellow) and high (in blue) intensity from the material fluorescing at 360 nm.

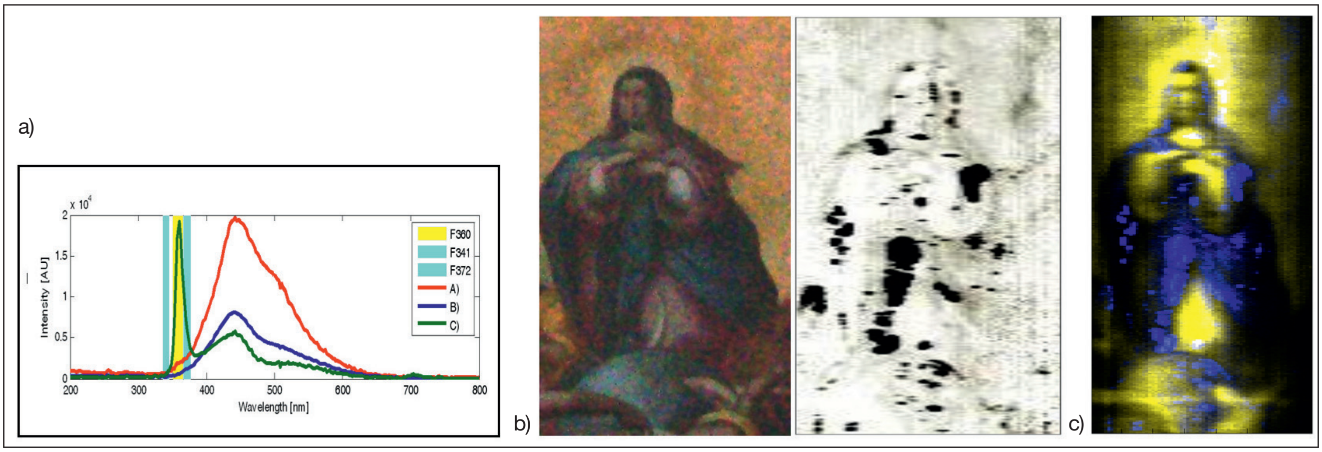

FIGURE 3 a) LIF spectra from different areas. Specific band at 360nm in evidence; b) Black and white fluorescence image at 360 nm, compared to a conventional photo; c) Colour rendering from fluorescence image at 360 nm
Source: ENEA

The vault was analyzed not only for the purpose of retouch identification, but for pigment analysis also. In this case, the Spectral Angle Mapper (SAM) algorithm for LIF image analysis has been used. SAM is a classification method that permits rapid mapping from a comparison between a reference spectrum and the measured spectra [8]. According to SAM, the spectrally resolved intensities can be treated as vectors' components, and it is then possible to compute the angle between a given pixel spectrum and a reference spectrum: the smaller the angle, the higher the similarity between pixel and reference spectra will be. To improve the diagnostic readability of images and to emphasize the selected areas, a threshold for the spectral angle has been introduced, thus obtaining a black and white version of the original scanned image. Whenever the reference spectra pertain to a specific pigment, this processing highlights only these areas significant for that pigment diagnostics.
In Fig. 4, SAM similarity maps obtained using blue and red pigment reference spectra, respectively, are shown.
During the in-field measurements in the Padua Baptistery, LIF spectra and images have been collected and processed in order to retrieve information on constituent materials. The field campaign was carried on in June 2010, prior to planning the following

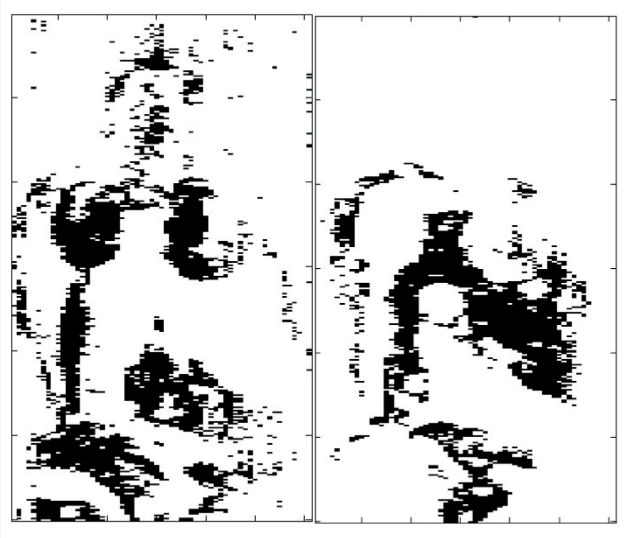

FIGURE 4 SAM analysis by the reference spectra of blue (on the left) and red pigment (on the right), respectively
Source: ENEA

restorations. To this aim, the investigation was focused on the recognition of consolidants and binders, with the support of an available data base and the development of statistical tools for main spectral-band identification.
The construction of the Padua Baptistery, located on the

right side of the cathedral, started in the XII century and was accomplished in 1281. Its frescos are considered Giusto de' Menabuoi's masterpiece. Two selected areas of the Paradise fresco on the central dome and of the Genesis on the tambour have been investigated by means of the ENEA LIF scanning system.

In the Baptistery, different fresco portions have been scanned within the dome and on the tambour. Data were acquired at a 15 m distance from the dome at a slightly smaller distance from the tambour. The images collected are shaped as rectangular stripes about 1.5 m wide and typically from 8 m to 12 m long.

Data were acquired operating the set-up both in reflectance and fluorescence acquisition mode, the latter upon excitation at 266 nm, and also in this case processed by means of the automatic statistical analysis (PCA). Once the major fluorescence bands have been identified, their assignment has been checked against the available consolidant data base by means of SAM projections, and the relevant distribution on the image has been obtained. Conversely, the contribution of pigments, which cannot be effectively disentangled from the emission of plaster and binders, was investigated mostly in the reflectance images analyzed by means of SAM maps based on an internal standard for each color, so that spatially non-homogenous changes in the spectral content could be recognized, and possibly ascribed to the pigment deterioration or retouches.

The band analysis, upon which the monochromatic images reconstruction reported in Fig. 5 is based, derives directly from the PCA results. In particular, the narrow UV bands at 293 and 370 nm have been considered.

In A and B insets the absolute intensity measured at 293 nm is shown, which appear to generate a quite uniform distribution on the entire images. Upon the assumption of a linear dependence coupling the quantitative distribution of fluorophores to the respective peak intensity, we infer a corresponding uniform distribution of the compound. A similar situation has been observed for all scanned areas in the dome, thus supporting a diffuse and homogeneous use of the compound characterized by the emission at 293nm, in general compatible with acrylic resins (e.g., primal AC33). On the right side of Fig. 5 (C and D insets), the absolute intensity measured at 370nm is shown, which is peaked on well localized areas. Concerning the identification of the compound to which this emission could be ascribed, although several compounds present this signature, most probable candidates among consolidants are vinyl compounds

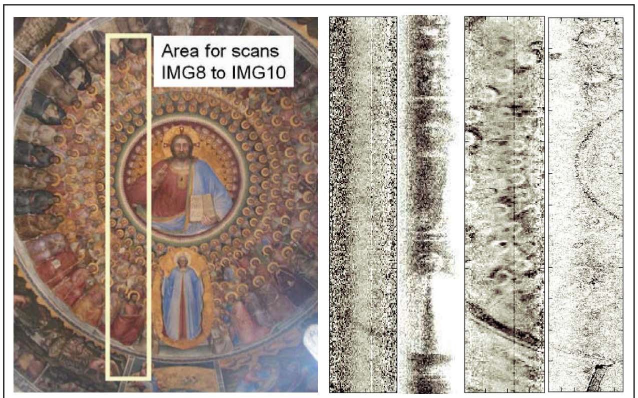

FIGURE 5 Sections of the dome vault (picture on the left) scanned by LIF. Grey levels correspond to different emission intensity (black represent the highest intensity); A) and B) band at 293nm; C) and D) band at 370nm
Source: ENEA

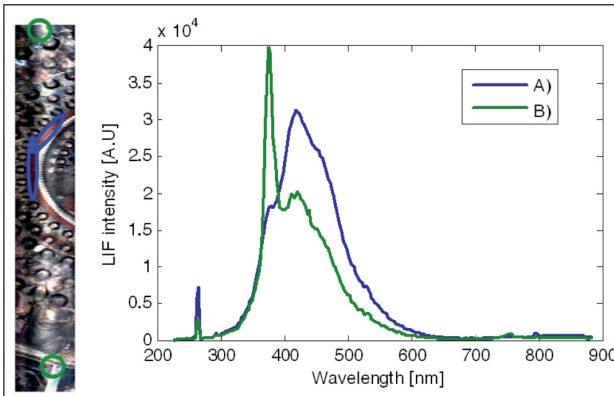

FIGURE 6 a) False color RGB reconstruction of a section of the dome vault based on bands at 293nm, 370nm and 550nm; b) average spectral content in selected spectral regions, which are marked on the left image
Source: ENEA

(e.g., mowilith), which emit at longer wavelength with respect to acrylic resins.

Further qualitative results of LIF scanning can be obtained by combining three significant bands in a single false color image. An example of this elaboration is presented in Fig. 6 (for the monochromatic image shown in Fig. 5D). The inset (a) shows the RGB reconstruction based on bands peaked at 550nm, 370nm and 293 nm, while the inset (b) shows the average spectrum in the respective circled area on the left, where significant emissions at 375nm and at 293 nm (confirming PCA results) are observed, their possible assignment to different consolidants being discussed above.

Conclusions

LIF scanning has shown, in conclusion, its versatility in obtaining valuable information on the presence and distribution of different species on large areas. In particular, traces of former consolidants have been remotely revealed and mapped on frescos in the Virgen del Buen Aire Chapel in Seville and on Padua Baptistery vault.

The results here reported demonstrate that laser-based imaging on surfaces of interest for Cultural Heritage permits to obtain valuable information from fluorescence data remotely and non invasively. The capability of remote material identification by means of the available data processing methods on raw hyperspectral images has been demonstrated, whereas quantitative data acquisition still requires additional reference measurements.

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