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Laser spectroscopy and imaging applications for the study of cultural heritage murals

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HIGHLIGHTS

- LIF system scans artwork surface remotely.
- LIF system obtains hyperspectral fluorescence and reflectance images.
- Digital image analysis, PCA and SAM evaluate distribution of chemicals and damage.
- LIF prototype allows to scan several m^2 of a wall at 16 m of distance.

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ABSTRACT

Laser induced fluorescence (LIF) associated with imaging scanning techniques has already proved to be a powerful diagnostic tool for artworks. The aim is to assess on-site and remote sensing systems and imaging measurements on murals in order to detect vulnerability and weathering forms due to the effects of environmental conditions. It also seeks to identify treatments in order to optimize interventions by restorers. Four murals (16–18th centuries) were studied using a LIF prototype remotely operating in reflectance and fluorescence mode. Relevant spectral features are identified using principal component analysis and a spectral angle mapper to assess surfaces using imaging applications. The combination of these methods makes possible to identify bio-crust, fissures and the presence of different treatments.

1. Introduction

Active remote sensing systems, generally known as LIDAR (laser radar), have been included in high resolution scanning devices in order to map the current preservation status of cultural heritage surfaces [1–7]. Conservators are interested to map chemical components and neo-formation due to weathering as well as in the identification of physical damages (surface cracks) occasionally or eventually covered by former restorations [8,9]. Valuable information, especially on rendering with false colors, can be found from the precise location of the image on the surface, regardless of the specific issue.

Laser scanning prototypes, initially developed in remote vision and in metrology devices based on the amplitude modulation technique, have been specifically designed for multispectral applications suitable for the analysis of large surfaces relevant to monumental cultural heritage. Colao et al. [10] demonstrated the application of fluorescence technique to detect retouched crack, unseen by bare eye, on mural *a fresco* painted in Hrastovlje Church (Slovenia). An Italian-Swedish cooperation, investigating Coliseum façade by means of lidar fluorescence technique showed the possibility to locate metal clamps, used as reinforcement structures, and to establish their conservation status by detecting the protective coating added during former restorations [11]. An innovative hyperspectral LIF (laser induced fluorescence) line scanning system was designed and patented at the ENEA laboratory in Frascati [12,13]. The prototype is capable of rapid 2D image acquisition in the visible/UV range, and was developed to investigate the presence of pigments and consolidants, as well as the occurrence of both bio-deterioration and depigmentation on wall paintings.

On-site field campaigns using LIF remote scanning systems were carried out in Andalusia (Spain) in 2010, 2011 and 2012 on 16th to 18th century murals executed using the *secco* technique on gypsum and calcite. The monuments studied were the chapel of Virgen del Buen Aire (Seville, Spain), the church of San Agustín

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(Marchena, Seville, Spain), the monastery of San Jerónimo (Granada, Spain) and the church of the Santo Cristo de la Salud (Malaga, Spain).

The Chapel of the Virgen del Buen Aire is part of the San Telmo Palace in Seville, which is now the seat of the Andalusian regional government. Construction on the building began in 1682 outside the walls of the city, and the chapel vault was painted by Domingo Martínez in the late 17th and early 18th centuries. The scans were carried out during the second phase of the restoration executed by the Andalusian Institute of Cultural Heritage. The second study, also in Seville, was of the murals in the chapel of San Agustín in the town of Marchena. The old church and convent were built between the 17th and 18th centuries for Augustinian monks. The church ornamentation includes polychrome religious plaster figures, geometric elements, exotic animals and vegetables. The decoration was probably the work of local painters with Latin-American influences. The church of the monastery of San Jerónimo in Granada is another Andalusian mural masterpiece. The stone interior was completely covered with various frescos using *secco* techniques painted by Juan de Medina in the 18th century. The last example, the church vault of the Santo Cristo de la Salud in Malaga was painted by Alonso Cortés, also on gypsum over the brick and wood structure and using tempera techniques in the 18th century. We know it was restored in 1989 and we scanned different zones of the vault prior to the current restoration carried out by the Andalusian Institute of Cultural Heritage.

Murals are elements of the architecture that cannot be understood if it is isolated of the construction [14], the characterization of murals and the weathering forms are usually studied with traditional techniques [15] though new nondestructive techniques (as IR thermography) enable to assess of damage from distance in real time are been used to see water filtration on roofs that could reduce structural integrity [16]. Structural problems like water filtration or capillarity problems are associated to efflorescences, depigmentations or bio-attack, two former could be detected by LIF, other damages like fractures or fissures could be filled with treatments that could also be detected with LIF. For this reason, these four cases were chosen as sites to demonstrated the potentiality of the LIF system. Thus laser spectroscopy and imaging techniques were used on murals to check deterioration, to assess weathering factors and to discriminate the both the initial painted surface composition and its actual state after successive restorations, through reflectance and fluorescence images.

2. Methods and equipment

The LIF scanner used was designed to collect the entire fluorescence spectrum following UV laser excitation. A quick scanning system was employed in order to remotely obtain both reflectance and fluorescence images.

The fluorescence scans were carried out operating the laser at 266 nm; alternatively reflectance scans were acquired performing a scan with the laser switched off and exposing the sample to the light emitted by a calibrated halogen lamp. The result is a spatially resolved reflectance spectrum, subsequently used to compute the CIE/lab coordinates after calibration against a reference surface. Both systems were used on site and several images were acquired with a millimetric spatial resolution.

For the current measurements it was necessary to ensure that laboratory painted samples did not suffer photo-damage induced by the laser. The maximum laser energy was 1.5 mJ at the output before defocusing through the cylindrical lens, corresponding, at a 5 m distant probed point, to a maximum laser fluence of 0.01–0.02 mJ/cm^2 which is well below the threshold of 0.1 mJ/cm^2 established as conservative estimate of for fulfillment for non-destructivity on the considered painted surfaces [5,10].

2.1. LidArt: The line scanner

Our first LIF-scanning system [12] was capable of collecting hyperspectral fluorescence images scanning a surface point by point with 1 mm resolution at about 3 m distance. This equipment was upgraded for applications to large cultural heritage surfaces (e.g. frescos, decorated façades, etc). A compact set-up was built to increase performances in terms of space resolution, time resolved capabilities and data acquisition speed. The new scanning system uses a diode-pumped Nd:YAG laser source in combination with IV harmonic crystals to generate UV radiation. The system has line focalization which uses a quartz cylindrical lens, an imaging spectrograph (Jobin–Yvone CP240), and a square ICCD sensor allowing for the multichannel spectral resolution [7] (ANDOR iStar DH734, pixel size 13 μm), mounted behind a slit parallel to the laser line footprint during scanning [13].

Rejection of elastic laser backscattering and subsequent high order signals was accomplished by means of a low pass filter at the detector entrance. After acquisition, the fluorescence spectra were corrected for the instrumental spectral response, with the reference radiance emitted by Ocean Optics Mod. DH2000 calibrated source.

The system, installed on a tripod, has a cylindrical shape of about 38 cm dia and 15 cm high with a weight below 25 kg. The current system performances are summarized in Table 1. During the campaigns in Andalusia, typical scan size was 128 pixels wide and 200–600 pixels high, with 250 spectral channels from 200 nm to 800 nm at a nominal spectral resolution of 2.5 nm. With this optical system using a cylindrical lens, a 1.5 × 5 m^2 image at 15 m distance was currently scanned in less than 5 min, with a space resolution of about 11 mm. A picture of the LIS scanning prototype in operation during a campaign in Andalusia is reported in Fig. 1.

During all measurement campaigns, the defocusing effects due to chromatic aberrations were limited by operating the system in two different spectral regions: firstly the collection optics was focused on the UV region from 250 to 450 nm, then on the visible spectral region from 450 to 700 nm.

With the laser switched off, the LIF-scanning system was also used, to collect reflectance images based on the availability of a standard light source assuring the operation with an average illuminance of not lower than 10 cd/m^2. Since these

Table 1
Characteristics of the LIF-scanning system assembled for use during the campaigns in Andalusia.

General features	
Laser operation	1.5 mJ pulsed, 20 ns @ 20 Hz
Laser sources wavelength	266 nm, 355 nm
Working range	3–30 m
Maximum resolution	1.0 mm @ 3 m
Scanning mirror movements	
Step precision	0.0017°
Max pixel per row	640 pixel
Overall time per row[a]	0.2–2 s
Data acquisition	
ICCD pixel size	25 μm
Spectral resolution	2.5 nm

[a] Motor actuation and acquisition.

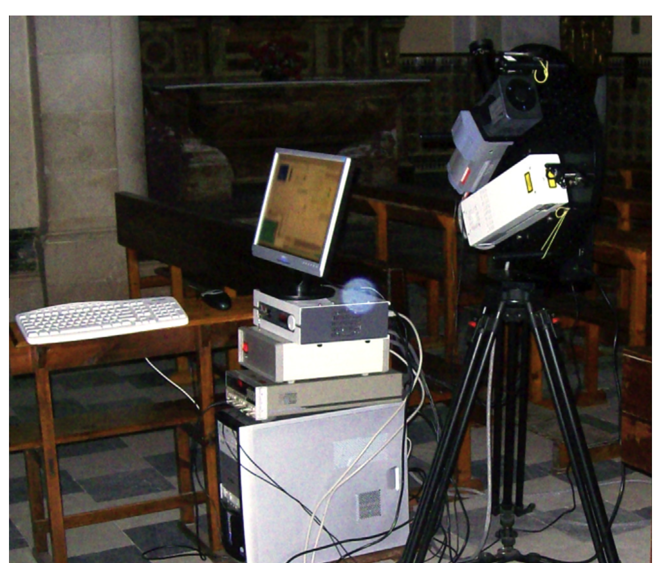

Fig. 1. ENEA LIF scanning system operating in the chapel of San Agustín in Marchena. Computer control on the left, the rotating wheel for vertical scanning, on which the laser and the detector are mounted, on the right, above the tripod.