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Laser scanning technologies for 2D and 3D imaging and characterization of decorated monumental surfaces

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Abstract

Laser scanning prototypes, formerly developed in active remote sensing systems and in remote vision and metrology devices based on the amplitude modulation technique, have been specialized for high resolution multispectral applications suitable to be used in the characterization of large surfaces relevant to monumental Cultural Heritage.

A three colour imaging topologic radar (RGB-ITR) has been developed for high resolution 3D imaging of frescos and successfully utilized in chapels of churches dating back to the Renaissance period. The high resolution 3D models reconstructed have allowed the hyper-realistic rendering of coloured features and the identification of surface irregularities, either in the layers or in the thickness of the underlying plaster, possibly related to otherwise undetectable damages.

A laser induced fluorescence scanning system, capable of 2D monochromatic images acquisition on up to 90 different spectral channels in the visible/UV range has been developed and utilized in field campaigns in order to investigate the presence and the aging of consolidants as well as the occurrence of bio degradation. Its utilization in combination with the RGB-ITR on the same field campaign is reported. A new prototype with a line scanner facility for high speed data acquisition has been recently realized and is currently under laboratory tests.

Different methods for image classification are presented, examining the possibilities offered for data fusion from different active and passive sensors, based on both optical and acoustical techniques. Two methods have been selected for LIF data processing software, one based on spectral angle mapper and the other one on principal component analysis. Both methods have been implemented to extract the information relevant to conservation strategy and visualize damaged areas in suitable false colour combinations of the collected images.

Eventually, an augmented reality system with the possibility of projecting the image reconstruction on the real target has been realized as a tool for accurate surface study and for better fruition.

Results on data collected in preliminary laboratory investigations on reference materials and during a recent field campaign on frescos and are reported and discussed.

1. - Introduction

Non invasive optical diagnostics are of special interest for application to Cultural Heritage. Laser based devices, coupling the possibility of remote application up to several hundred meters with image capabilities, coming either from precise scanning systems or multichannel detectors, have recently increased this interest.

Laser radar, based of elastic backscattering from the target, can be utilized to remotely get accurate information about the target shape and reflectance. Remote vision and metrology devices based on the amplitude modulation technique (imaging topologic radar) belong to this category.

After development for industrial applications, these instruments have been specialized for high resolution multispectral applications suitable to be used in the characterization of large surfaces relevant to monumental Cultural Heritage.

A three colour imaging topologic radar has been developed for high resolution 3D imaging of frescos and successfully utilized in chapels of churches dating back to the Renaissance period. The high resolution (sub millimetric) 3D models reconstructed allowed for hyper-realistic rendering of coloured features and for identification of surface irregularities, either in the colour layers or in the thickness of the underlying plaster, possibly related to otherwise undetectable damages (scratches, detachments, etc).

Laser scanning prototypes have been already developed in active remote sensing systems for environmental applications, such as the fluorosensor lidar for oil spill detection at the marine surface [1]. These instruments, detecting wavelength resolved the radiation anelastically scattered from the target, are able to identify surface species by means of their characteristic spectral signatures (namely fluorescence) after a selective UV laser excitation. A LIF (laser induced fluorescence) scanning system, capable of 2D monochromatic images acquisition on up to 90 different spectral channels in the visible/UV range has been developed and utilized on field campaigns in order to investigate the presence and the aging of consolidants as well as the occurrence of bio degradation [2]. A new prototype with a line scanner facility for high speed data acquisition has been realized and is currently under laboratory tests.

Several methods for image classification are known, the most common are presented here while examining the possibilities offered for data fusion from different active and passive sensors based on both optical and acoustical techniques. In particular two methods have been selected for LIF data processing software, one based on SAM (spectral angle mapper) and the other on PCA (principal component analysis). SAM algorithm has been implemented to extract the information relevant to the presence of a specific component (whose spectrum is contained in our data base) at the imaged surface, while the PCA is a statistical tool allowing for a blind identification of most important spectral component in an image, thus increasing the chances to best visualize damaged areas in suitable false colour combinations. Joint operation of the LIF scanner and the RGB-ITR in field campaigns already resulted to the advantageous to the restorers [3]; a further example is given here after treating LIF images with the PCA algorithm.

An augmented reality system with the possibility of projecting the image reconstruction on the real target has been realized as a tool for accurate surface study and for better fruition.

Results on data collected during Hrastovlje campaign on frescos and in preliminary laboratory investigations on reference materials are reported and discussed. Some conclusions are presented at the end, highlighting further work needed to increase the applicability of these systems to Cultural Heritage monumental surfaces characterization and preservation.

2 Experimental apparatus, laboratory results and data processing

2.1 Image Topologic Radars

Imaging Topological Radars (ITRs) are a class of 3D laser scanners that exploits the amplitude modulation range finding technique for the determination of distance. This technique enables the simultaneous recording of both range and reflectivity data, a feature that makes ITRs especially suited to Cultural Heritage applications, particularly for the realization of accurate and realistic 3D models of delicate artworks of both small (~1 m) and intermediate or large scale (up to ~30 m).

2.1.1 Monochromatic ITR

ITR systems [G. Fornetti, L. Bartolini, M. Ferri de Collibus "Multispeckle topologic radar system equipped with a coherent light beam transport and unimodal propagation elements, relevant to metrology and vision applications" Italian patent RM 2003 A000588 deposited on 22.12.2003] belong to the category of amplitude-modulated (AM) laser rangefinders. Range information is obtained by determining the round trip time delay of an AM sounding beam via the measurement of the phase delay $\Delta\phi$ of the signal photocurrent with respect to a reference signal. For each sampled point, the distance d between the scanning mirror and the target is given by the formula:

$$d = \frac{c}{n} \frac{\Delta\phi}{4\pi\nu_m} \quad (1)$$

where ν_m is the modulation frequency, c the velocity of light in vacuum and n the refraction index of the transmitting medium. For laser optical powers such that the signal shot-noise dominates over all other noise sources in the detection process, the accuracy of measurements can be showed to increase with the modulation frequency ν_m .

Due to the cyclic nature of the modulation process, the AM range finding method is generally affected by the so-called “folding” ambiguity. Univocal distance measurements are only possible within a well-determined range window, equal to half the value of the corresponding modulation wavelength λ_m . In order to overcome this limitation which would confine high resolution to short distances, two modulation frequencies are simultaneously used. Provided the low-frequency range window is chosen large enough to encompass the whole scene of interest, unambiguous yet less accurate low-frequency measurements can be used to remove the ambiguity that affects the corresponding high-frequency, more accurate, measurements. This technique enables to measure distances at the level of accuracy permitted by the high-frequency mode but well beyond its intrinsic range and can profitably be used to obtain accurate digitisations of large scenes, such as building facades or interiors, vaults etc.

ITR systems are designed to have a passive optical head - mainly constituted by mirrors and lenses - separated by the active opto-electronic system, which includes the laser source and the detector with dedicated electronics. Unlike laser scanners based on optical triangulation, in ITR systems the launching optics is coaxial with the receiving optics in a strictly monostatic configuration. This feature enables to avoid self-occlusions during the scanning process and eliminate off-axis optical aberrations, resulting in an improvement in lateral resolution.

The active and passive subsystems are optically coupled through optimized optical fibre connections. This modular setup enables to place the passive module in the position that is more convenient for the measurement, without compromising the overall functioning of the system even in extreme or hostile conditions, such as at high or low temperature or in presence of intense ionizing radiation background. Monochromatic ITRs, using a single laser source in the NIR region of the electromagnetic spectrum, have been utilised in several field campaigns both in Italy (palaeochristian church of S. Maria Antiqua in Rome, Etruscan tomb of the Blue Demons in Tarquinia) and abroad (Sucevița Monastery in Romania) [3].

2.1.2 RGB-ITR – the form and the colour

Profiting of the experience matured over a decade with monochromatic ITRs, at ENEA CR Frascati the RGB-ITR has been recently realized and patented [G. Fornetti, L. Bartolini, M. Ferri de Collibus “Threedimensional Radar optical method and device based on three modulated RGB diode lasers for metrological and art work applications” Italian patent RM2006A000651 deposited on 6.12.2006]. RGB-ITR is a colour 3D laser scanner, which enables the simultaneous recording of both range and colour, in the form of RGB triplets. This is the first AM 3D scanner ever realised that can natively acquire colour information.

The system uses three laser sources at optical wavelengths of 450 nm (blue), 532 nm (green) and 650 nm (red) respectively, combined into a single ray by means of a dichroic optical component. A motorized mirror is used to focus and sweep the beam onto the target, and the collected backscattered signal is then split again into the three original red, green and blue components by means of an optical demultiplexer.

Each colour return signal is separately detected by a low-noise avalanche photodiode detector, and analyzed by means of a lock-in amplifier unit, also used to modulate the correspondent beam component. Typical modulation frequencies are 190 MHz for red, 1-10 MHz for blue and 25 kHz for green. The three colour channels are converted in standard RGB form by using the Grassmann law - which states the linearity of chromatic response in human colour perception - with coefficients corresponding to the optical frequencies of the laser sources used. The RGB triplets are then subject to a calibration procedure that enables to fix the white point in colour space by means of data preliminarily acquired on a white certified diffusive target. Specifically developed, copyrighted software applications are finally used to process range and calibrated RGB data and generate faithful, highly realistic 3D digital models. The resulting models can be further post-processed and exported into the most common 3D file formats.

The portable system is shown in **Fig. 1**, as settled during the field campaign at Hrastovlje church (see sect. 3.1); its characteristics are summarized in **Table I**.

2.2 LIF scanners

It is well known that fluorescence signatures of materials are of interest in Cultural Heritage surface characterization. Provided that a sufficiently low intensity beam is focussed onto the examined surface to avoid the occurrence of photobleaching, laser induced fluorescence (LIF) can be considered a non destructive surface investigation technique, with interesting possibilities for remote application. By coupling the use of a laser source with suitable scanning devices fluorescence images can be collected as well. Apart from the optical scanner quality, which determines the geometrical parameters, performances relevant to specific applications are based on the spectral signature characteristic for each chemical compound laying on the examined surface. The detection of the emitted fluorescence radiation allows the identification of the different materials utilized, which is needed in view of a planned restoration. In fact it reveals with high space resolution the occurrence of retouches, traces of former restorations and consolidants not otherwise reported in the documentation relevant to the artwork, and to identify extraneous materials onto the surface such as degraded substances from pigment or consolidants, air pollutants, waxes, microalgae and fungi responsible for biological attack. The construction of relevant data bases containing the fluorescence signatures at different laser excitation wavelengths (266 nm and 355 nm) is currently in progress in our laboratory.

2.2.1 The point scanner

The hyperspectral scanning LIF system here used to collect data during the field campaign (sect. 3.2) is based on a previous instrument's version with a point scanner [4] successively patented [F. Colao, R. Fantoni, L. Fiorani, A. Palucci "Fluorescence scanning electro-optical device for outdoor applications to Cultural Heritage" Italian patent RM2007A000279 deposited on 21/5/2007]. All the mechanical and optical elements are installed in an aluminium box of 58×43×36 cm³, for less than 15kg. Its small size and light weight allow an easy transport of the system and its operation from scaffoldings, in the case of surfaces out of the current maximum range for remote operation (10 m). A diode pulsed Nd:YAG laser (Thomson DIVA) is used as light source to generate radiation at 266 or 355 nm, producing laser pulses of 10ns duration at fluence of 1 to 50mJ/cm². A linear array (Ocean&Optics) is used as spectrometer; its entrance is protected from the intense backscattered radiation by means of an appropriate dichroic filter. Since no optical elements are used to collimate the laser beam the overall spatial resolution is a function of the operation distance and in the present case on the field we had a resolution of approximately 1 to 2mm from the spot size on the target at about 5 m distance. The digitized spectrum collected at each scanned point is transferred to a portable computer where a LabView program allows the user to set experimental parameters, control data acquisition, and perform a preliminary data analysis. As a result up to 90 different monochromatic images (collected from 280 to 800 nm in adjacent steps with 10 nm resolution) are collected from the scanned area. Unfortunately, hyperspectral image collection by a point scanner is a time consuming operation: typically 1 m² of surface could be scanned in 8 hours at 1mm lateral resolution.

2.2.2 The line scanner

Our former LIF scanning system, capable to collect hyperspectral fluorescence images scanning a surface point by point with 1 mm resolution, has been upgraded for applications to large Cultural Heritage surfaces (e.g. frescos, decorated facades etc). A new compact set up has been built aimed to increase performances in terms of space resolution, time resolved capabilities and data acquisition speed. Major achievements have been reached completely changing the optical approach and consequently the detector utilized:

- in the scanning the step to step point focalization has been changed into line focalization by using a quartz cylindrical lens and an imaging spectrograph (Jobin-Yvone CP240);
- the linear array detector, responsible for the multichannel spectral resolution, has been replaced with a square ICCD sensor (ANDOR iStar DH734, pixel size 13µm), mounted behind a slit parallel to the laser line footprint during scanning.

This arrangement is characterized by having the spatial and spectral information on two mutually orthogonal directions imaged on the detector, with submillimetric spatial resolution and 5 nm spectral resolution. Additionally, it is possible to implement time resolution measurements on the

nanosecond scale by controlling the electronic gate of such a detector, collecting time resolved images delayed with respect to the excitation laser pulse.

The overall current system performances are summarized in **Table II**. With the new optical system based on the use of cylindrical lens an image of $1.5 \times 5\text{m}^2$ is currently scanned in less than 2 minute at 25 m. The compact arrangement is shown in **Fig. 2**, the same diode pumped Nd:YAG laser source has been utilized in combination with III and IV harmonics crystals to generate the UV radiation.

Preliminary laboratory experiments have been already performed in laboratory collecting passive images and LIF signals from different standards (white and black paper, dye loaded plastics), and have shown the capability of remote material identification by means of the available data processing software (see sect. 2.2.4) on raw hyperspectral images. Prior to field utilization additional work is in progress to correct image intensities taking into account the optical collection efficiency at different angles.

2.2.3 Image processing

As classification we mean the operation to assign an object to a pre determinate group, generally fixed [5]. To this aim the object must be characterised by a measurable set defining a multidimensional *features vector*. An automatic classification system is composed by a first part where the characteristics are translated and extracted; in a second part the classification algorithm assigns the membership degree of a class [6].

Most used methods are based on the time analysis, (i.e. integral and differential estimator), on the mapping in frequency domain based on a metric, (i.e. Spectral Angle Mapper Classification (SAM), Spectral Correlation Mapper (SCM)), on multivariate statistic analysis (i.e. Principal Component Analysis (PCA), Support Vector Machine (SVM)) and on omomorphic transformations that preserve the defined operations (CEPSTRUM which is the anagram of the word spectrum).

In the following we are focussing our attention only for the first family of methods and SVM. As example in **Fig. 3** we have a set of archaeological samples separated by the Centre of Gravity (CG) method. In this case for the assignment we need a reference database.

In **Fig 4** (left) we select two areas of a sonar picture of an amphora and were looking for similar pixels. In this case the analysis did not need the use of a reference database. In **Fig. 4** (right) we show the result of the internal/external volume identification on the same target performed by SVM.

2.2.4 Features characterization algorithms developed on reference samples.

Two methods have been selected for LIF data processing software: SAM and PCA.

We used the Spectral Angle Mapper (SAM) algorithm for LIF image analysis [7]. According to SAM given a reference spectrum and a pixel in the scanned areas, we have to consider the spectral channel intensities as the coordinate components of two vectors in a multidimensional space. Since any two vectors generate a hyper plane and two directions over it, the SAM algorithm computes a spectral angle between the pixel spectrum and a reference spectrum: the smaller is the angle more similar will be pixel and reference spectra. The method takes the arccosine of the dot product between the test spectrum u and the reference spectrum w with the following equation:

$$\alpha = \cos^{-1}(\hat{u} \cdot \hat{w}) = \frac{\sum_{i=1}^N u_i w_i}{\sqrt{\sum_{i=1}^N u_i^2 \sum_{i=1}^N w_i^2}} \quad (2)$$

Our laboratory data base of consolidants has been utilized to test SAM capabilities of their identification on fresco surfaces, painted with different pigments, at two different UV wavelengths [7].

Principal Component Analysis (PCA) is a technique which reduces the dimensionality of data, transforming the original variables into new uncorrelated ones (principal components or factors, PC), which are linear combinations of the original data and confine the greatest proportion of the total variance, according to the following algorithm:

$$x_{ik} = \bar{x}_k + \sum_{\ell=1}^N p_{\ell k} t_{i\ell} + e_{ik} \quad (3)$$

This statistic tool has been implemented in order to have the possibility of automatic handling of multispectral images. We used the entire spectra as input data, organized in a matrix containing the intensities at the different wavelengths in columns and the spectra in lines. The method has been tested on consolidants [8]: in this case our dataset had 3600 lines and 120 columns and succeeded in their identification by the first 3 components upon excitation at 266nm. Once PCA is run, the most important components (usually the first three) can be utilized for false colour image reconstruction, stressing the information content peculiar to the image, for instance the dominance of a specific colour or a kind of consolidant coating not uniformly present. Note that PCs are not necessarily (and in most cases not even eventually) associable to a specific spectral feature for a single constituent, so they do not permit to identify the anomaly at the surface, but only to reveal its presence.

2.3 Augmented Reality in the Cultural Heritage context

Augmented Reality (AR) [9] is a recent technology under development in the most advanced laboratories. It deals with computer based systems that display synthetic information to a user in such a way that the data appear merged to the objects in the real world surrounding him. In Cultural Heritage context, AR can be a promotion tool for didactic or tourist fruition, but it is expected as a powerful aid especially for a restoration operator, allowing the exploitation of all kind of geometrical mapped data, such as material characterization, damage diagnosis, restoration history, planned restoration actions.

A “see through” configuration for AR systems includes optical see-through Head Mounted Display (HMD), i.e. a portable display placed in front of the eyes of the user with a degree of transparency that allow to see the real world around him with no significant distortions or colour modifications. In this way the image from the real world is received by the retina directly using the light incoming from behind the HMD screens. In between the user and the real world, the device places the augmented information by optical semitransparent mirror that superimpose to the real world the light coming from little monitors embedded in the HMD.

Another key component used in many AR realisation systems is the “tracking device” that helps the system to identify the scene of the real world watched by the user, in order to properly place the relevant synthetic information. Knowing the user position and orientation, it is possible to dynamically update accordingly the augmented data over the scene. The whole process is generally known as registration task. To accomplish the tracking function, different kind of hardware sensing devices exist, each suitable for specific application context, according to requirements in accuracy and speed and also to environment characteristics such as physical accessibility, wideness etc. Of course, the algorithmic solution, necessary for elaborate the sensing data to realize the pose estimation, varies too.

2.3.1 A tool for AR fruition of LIF data

We realized a prototypal operator assistant for work of art restoration. It's an AR development suitable for room-wise wide working environment. Apart from the algorithm developments, the hardware system consists of a Main Host (MH), a video camera, a monitor and an optical see-through HMD. The system intelligence performs three main tasks: the tracking of user head in the work environment, the interactive manipulation of the augmented contents, and the correct presentation of the virtual information. This must be blended with the real scene, in order to avoid hiding any useful information. This is realised by the HMD where we present all the information needed for the assisted operations, while the service monitor shows other kind of information.

The video camera placed on the user head constitutes the tracking device. Each acquired frame is processed by computer vision techniques to estimate the relative pose between the video camera and a particular fiducial sign pre-disposed on the objects where we want to see the augmented data on. That fiducial signs are well known pictorial markers whose geometry and pattern are fixed in set up stage. To carry out correctly the pose estimation, we have to know the prospective projection and optical aberration under which the world is seen by the objective of the video camera, this requirement is fulfilled in a calibration step previous to the working time.

The major weakness of computer vision relied solutions is due to the occlusion problem, which arise when the markers go out of camera field or it is covered by something (i.e. the user arm). To partially overcome this problem, it is necessary to use more markers on the same scene. **Fig. 5**

shows what the user see through the HMD: a 3D elaboration of LIF data acquired on the square portion is blended on the real Byzantine icon.

3 Results of a field campaign: Hrastovlje church

The ENEA RGB-ITR and LIF scanning systems were applied to frescos analysis in the Romanesque church of the Holy Trinity in Hrastovlje, a small village of Slovenia. The interior walls are completely covered with the frescoes of 1490, but the church suffered many restorations in the past; the frescos remained hidden for a long time and have been rediscovered on 1949 under a thick layer of lime. Frescos show scenes from the Old and New Testament.

3.1 RGB-ITR models

The RGB-ITR has been utilised in a 3D digitisation campaign, carried out in Hrastovlje (Slovenia, 2007) upon invitation of the Institute for the Protection of Cultural Heritage of Slovenia. An accurate, colour 3D model of the interiors of the Romanic Holy Trinity church was realised, to be used for monitoring, restoration and cataloguing purposes. The 3D model of the apse, representing the Throne of Grace, and of the entire church vault is shown in **Fig. 6**. The model of the famous wall where the “Macabre Dance” is represented has also been acquired.

About 60% of the church's surface was 3D digitized in 5 days by means of the RGB-ITR, for a total of 11 scans and almost 90 data recording hours. During the campaign, the RGB-ITR instrument fully demonstrated its capability for metrology and structure profiling. In Fig. 7 we can see a virtual meter overlapped on the 3D model: with this instrument, it is possible to investigate all real distances (in meters), between the blue and red points marked. In Fig. 8 we can see the profile obtained by the intersection of a virtual plane and the 3D model. The virtual plane can be moved freely in the virtual environment so to obtain virtually endless contours of the investigated object. This instrument is very powerful for the remote diagnosis of the model structure: in fact, by the analysis of the profile, we can highlight possible fissures or deformations which can corrupt the stability of the monument.

Furthermore, the software tool developed for handling 3D models allows building a sort of hyper-texture to overlap the 3D model: each layer of this hyper-texture contains spatially-referenced information, obtained by the different instruments, for a multi-diagnosis of the investigated monument. An example of data collected during Hrastovlje campaign is shown in **Fig. 9**, where the false colour reconstructed LIF image is overlapped on the 3D model independently collected.

3.2 LIF images

The LIF system provides information on the present conservation status, identifies areas with biological attacks and gives details on the restoration methods of the frescoes under study.

In every scanned image the light emitted by each pixel is decomposed in its components, providing the maximum extent of spectral information today conceivable in the UV to VIS wavelength range (200 – 800nm). 2D monochromatic images are reconstructed at each detected wavelength. In **Fig. 10a** the fluorescence image at 470 nm of the detail of a fresco, obtained with the laser excitation wavelength at 355 nm, is shown, with the fluorescence spectra by different pixel corresponding to different area on the fresco. A line along a crack in the wall appears in the RGB image reconstructed by the CG method in **Fig. 10b**, which gives evidence of deterioration, depigmentation and paint retouches. SAM analysis has been applied to these images (**Fig. 11**). After identifying the reference spectrum on the retouched scratch, it has been possible to find out traces of other retouches made with the same material.

A clear evidence of the crack area is also obtained by PCA once reconstructing the image by using the first three principal components, as shown in **Fig. 12**. The comparison of Fig. 12 with Fig. 11, on one hand, stresses the power of the statistical analysis (PCA) which is able to recognize blindly the presence of an anomaly, on the other hand demonstrates the superiority of SAM, once a reference spectrum is available, since it allows the identification of the origin of the anomaly from its spectral signature (repainted plaster).

4 Conclusions

Two prototypes of laser scanning systems for painted surface diagnostics have been realized and successfully demonstrated in a field campaign on the frescos of a renaissance church in Slovenia.

Accurate 3D models have been built containing both the metrology data and three colour images of the scanned surfaces. Results of hyperspectral LIF scanning, after image processing, have given additional information on surface degradation and retouches not evident from the surface reflectance at the investigated visible wavelength.

Work is in progress to utilize the augmented reality tool on data collected during the Hrastovlje campaign, in order to supply the restorer a powerful method to exactly locate damages visualized with either of the laser based remote imaging diagnostics.

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Table captions

Table I – Characteristics of the RGB-ITR system as assembled during Hrastovlje campaign (* due to a compromise with the time available for scanning, a resolution 4 times bigger than the actual ITR resolution was settled).

Table II – LIF line scanner performances (* corresponding to a line of 1.5 m length at a 25 m distance).

Figure Captions

Fig. 1 – The RGB-ITR prototype during field operation. Front: optical head and fibre glass connections; Rear: laser and detector, control electronics.

Fig. 2 – Compact LIF line scanning, the vertical wheel is mounted on a tripod, vertical scanning is performed by means of an accurate stepping motor on the back side of the wheel. Transmitting and receiving optics are in the front, the ICCD and the laser on the rear.

Fig. 3 – CG identification of the materials in an underwater image of archaeological goods by visible spectra. Colours after classification correspond to different surface biolayers.

Fig.4 (left) - Selection of the signal to classify an amphora. We selected two kinds of spectra (black squares) and looked for similarity.

Fig. 4 (right) - Result of classification by SVM and identification of external/internal volume.

Fig. 5 - LIF data projection on the image of a real icon, as seen by the operator through his HMD.

Fig. 6 – 3D model of the apse and vault of the Holy Trinity Church Hrastovlje

Fig. 7 – Virtual metrology on a section of the 3D model of the Macabre Dance fresco.

Fig. 8 - Accurate profilometry on the 3D model of the painted apse

Fig. 9 – 3D model of the entire wall with the Macabre Dance fresco. In the middle the model is overlapped with a 2D LIF image (PCA reconstruction in false colours), showing effects of discolouration and retouches.

Fig. 10 - Images by LIF scanning of the detail of a fresco in the church of the Holy Trinity in Hrastovlje a) Fluorescence image by LIF system at 470 nm, b) the corresponding false colour image.

Fig. 11 - SAM image analysis of the detail of a fresco in the church of the Holy Trinity in Hrastovlje. By considering as reference spectrum, in red, the fluorescence spectrum emitted from the crack area in a), SAM provides a map of pixel with high spectral similarity as in b).

Fig. 12 - PCA RGB reconstruction from 90 LIF monochromatic images as the one reported in Fig. 10.

Scanning system type	Polar
Wavelength laser sources (red, green, blue)	700 nm, 530 nm, 460 nm
Modulation frequency (high, low precision)	190 MHz, 10 MHz
Spot size at 3.5-5m	0.8-1.2 mm
Lateral resolution at 3.5-5m (x, y)	1mm, 1mm*
Error distance measurement at 3.5-5m (z)	0.2-0.3 mm
Acquisition time per point	10 ms
Acquisition time for a 1800x1800 image	9 hours

TABLE I

Horizontal resolution	640 pixel
Angular resolution	0.1 mrad
minimum acquisition time per line	200ms
FOV aperture	3°

TABLE II



FIGURE 1

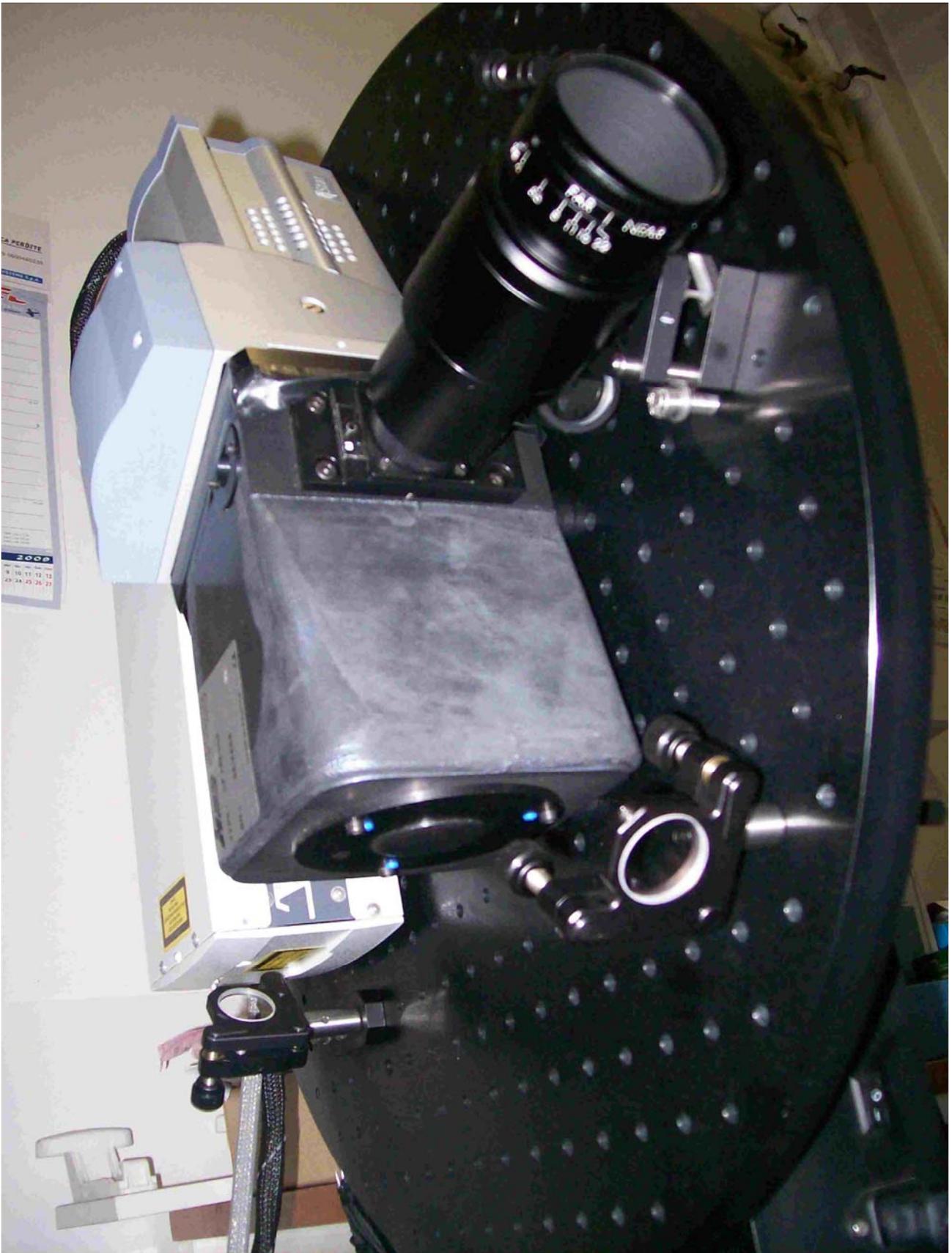


FIGURE 2

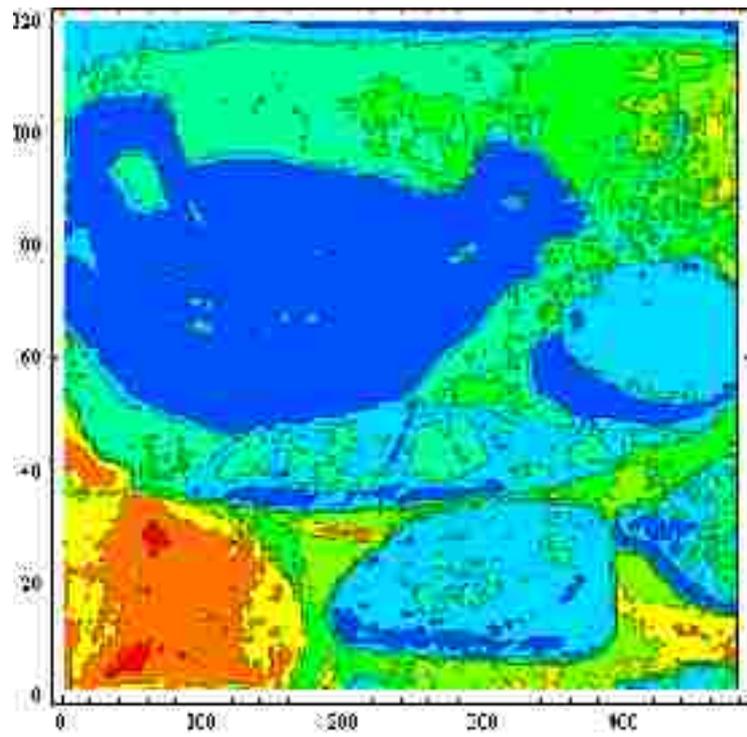


FIGURE 3

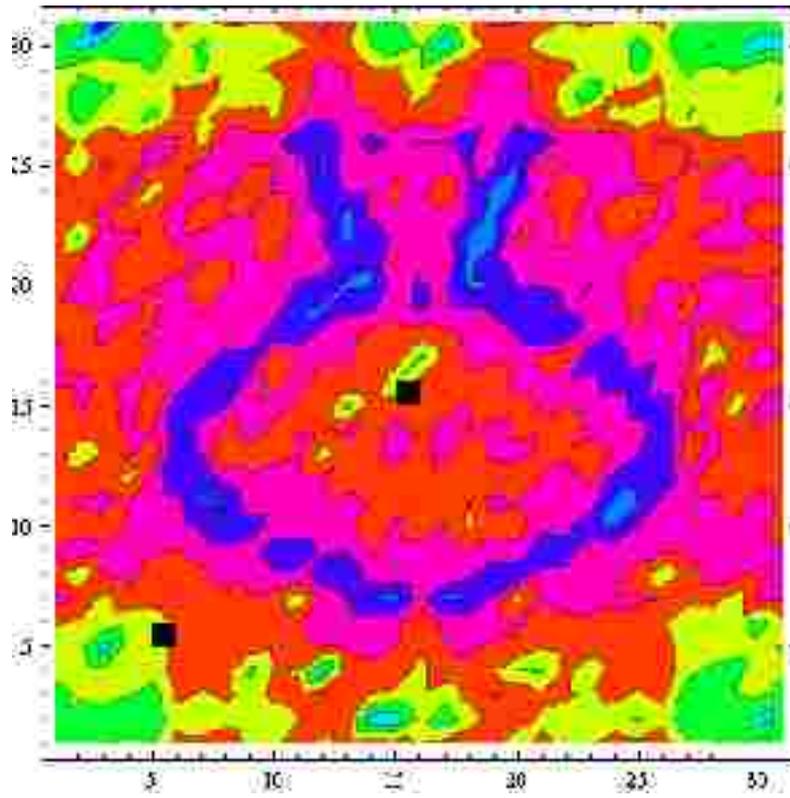


FIGURE 4 (left)

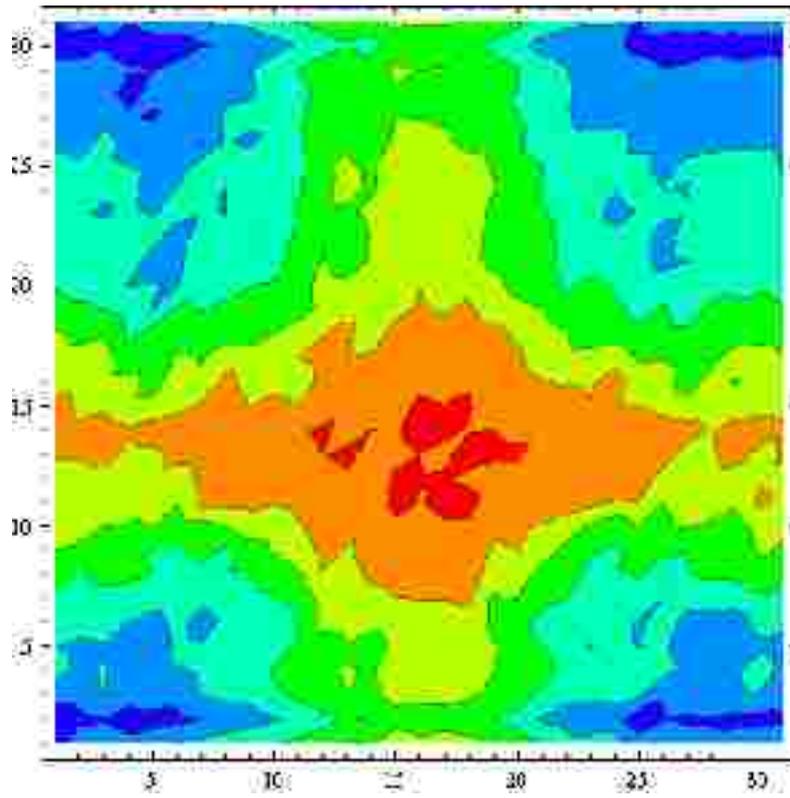


FIGURE 4 (right)



FIGURE 5



FIGURE 6

```
Point 1 = (-0.7080, 0.4188, -3.168)
Point 2 = (-0.5685, 0.4100, -3.194)
dx = 0.1395
dy = -0.0007921
dz = -0.006001
```

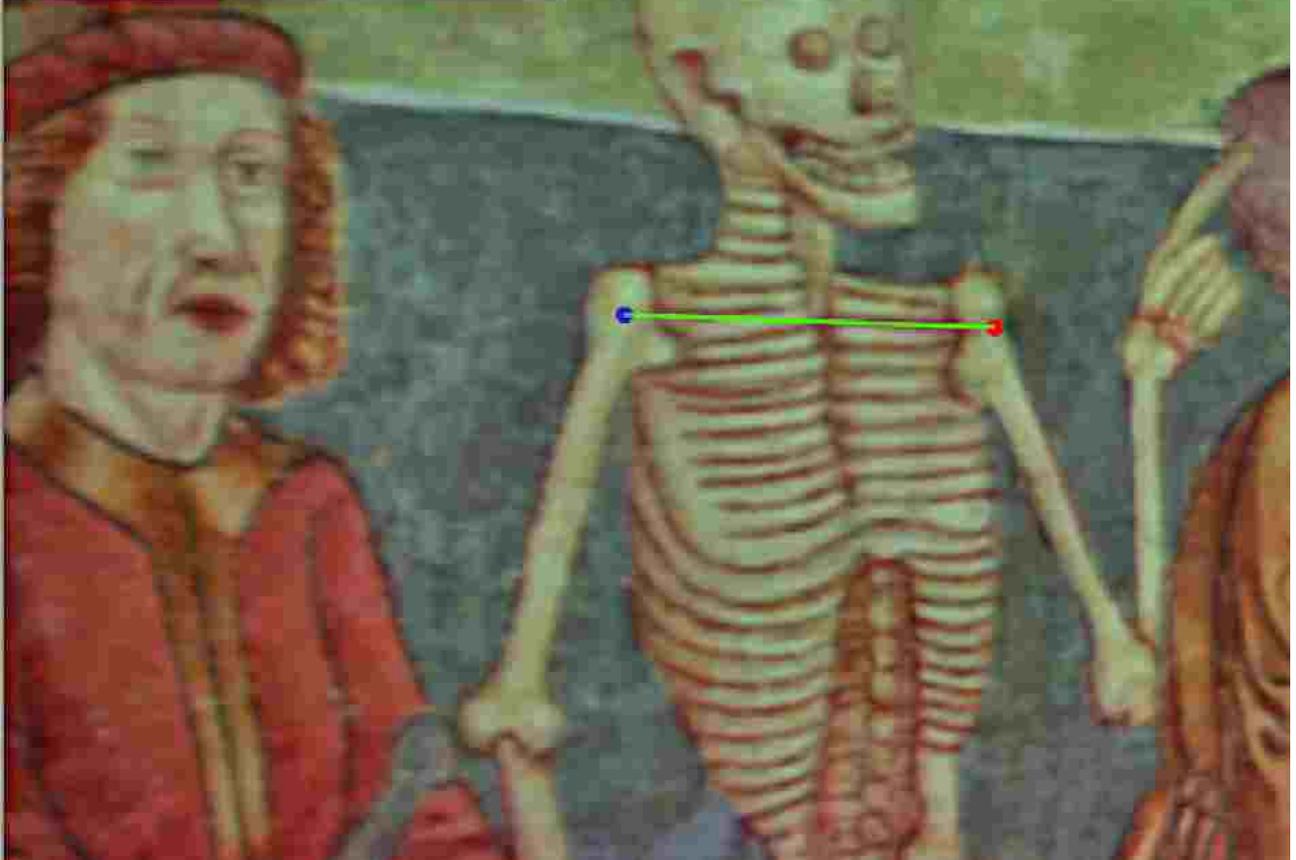
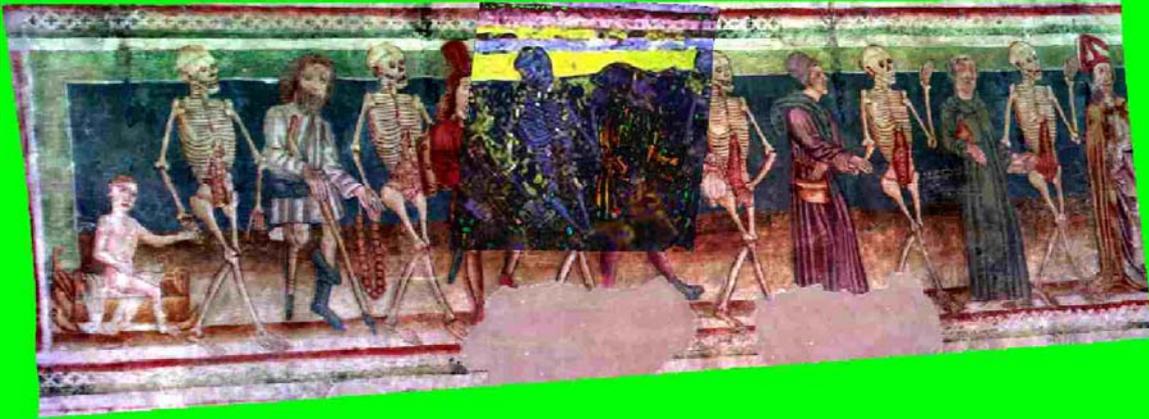


FIGURE 7



FIGURE 8



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P.V. Viewer 1.0.0
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FIGURE 9

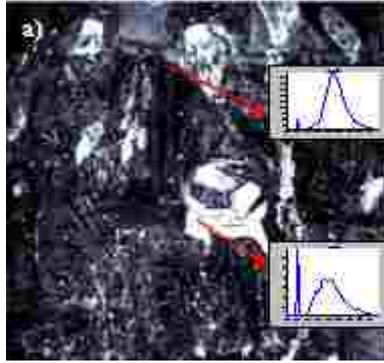


FIGURE 10a



Figure 10b

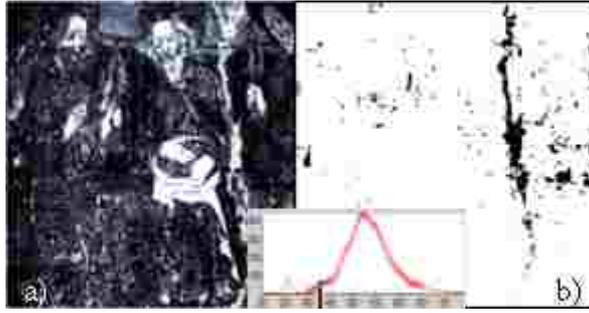


FIGURE 11



FIGURE 12