The Importance of Artworks 3D Digitalization at the Time of COVID Epidemy: Case Studies by the Use of a Multi-wavelengths Technique

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***Abstract*—At the moment when this article is written, a pandemic disease is attacking our lives, our style of living and our economy. The present work uses this occasion for focusing the attention on the importance to make available a digital copy of our knowledge, history and habits. The slower passing of time inside own residence let the individual to rediscover natural indoor activities, like reading a book or watching a documentary, and try to mentally escape by a virtual visit in a museum or a city. The first evidence coming out from these sites is mainly the limits of this technology for appreciating the artworks, even inside 3D environments, and, probably the most important, the lack of standardization in terms of accessibility and quality of the products. The present work focuses the attention only on one of the aspects of the processes for studying and documenting an artwork: the data acquisition and pre-processing data fusion. For approaching these steps, an out-of-the-market 3D technology based on the combination of several laser sources will be described: the description of this kind of systems is the pretext for analyzing the main differences with the available devices and techniques today largely used in Cultural Heritage environment, but especially for highlighting how the research can try to unify the gamification with diagnostic and restoration support in this sector.**

Keywords-laser; 3D scan; Cultural Heritage; colorimetry; monitoring; gamification

I. Introduction

At the moment when this article is written, a pandemic disease is attacking our lives, style of living and economy. Far from being an historical sight of what is happening, the present work uses this occasion for focusing the attention on the importance to make available a digital copy of our knowledge, history and habits. Also if our lives are surrounded by the technology, a first evidence coming out from these days of forced quarantine is that still a huge part of the reality, probably the most of that, has remained outside the domestic walls. The slower passing of time inside own residence let the individual to rediscover natural indoor activities, like reading a book or watching a documentary, and try to mentally escape by a virtual visit in a museum or a city. However, also if online there are interesting examples of virtual tours acces-ible by the users, the first evidence coming out from these sites is mainly the limits of this technology for appreciating the artworks, even inside 3D environments, and, probably the most important, the lack of standardization in terms of accessibility and quality of the products. Also in a situation like the interdiction of the mobility and access to the main cultural sites, what the technology has to offer is not just a replacement of the real observation, but a new way to know, study, monitor and divulge the Cultural Heritage. The present work focuses the attention only on one of the aspects of the processes for studying and documenting an artwork, the data acquisition and pre-processing data fusion: these two steps can be considered the starting point for an advanced analysis and state of the health monitoring of the monuments, as well as a way to create new contents for narrating the beauty and the hidden sides of the artworks. The 3D digitalization has grown fast in the last decades and it has found application in several sectors, from building to oil and gas infrastructures monitoring, from contents creation for the movies and games industries. Since several years these techniques were adopted also in the Cultural Heritage sector, introducing a modern and more complete approach at the study and dissemination of the artworks, but also bringing with it a new class of problems not present in other sectors, like for example the industrial ones: these differences can be observed mainly in the variety of free-form shapes, polychromatic and poly-material surfaces, which usually need of different approaches and techniques. In this article 3D and infrared-imaging sensors, at a prototype stage, will be presented: also if they are not still adopted largely in the market, they can be considered mature technologies and they have been applied in several case studies. The description of this kind of systems is the pretext for analyzing the main differences with the available devices and techniques today largely used in Cultural Heritage environment, but especially for highlighting how the research can try to unify the gamification with diagnostic and restoration support in this sector.

II. Material and Methods

A. The Multi-wavelengths Laser Scanners

This work will focus the attention on a mature technology, but still not diffused at the level of big distribution: the multi-wavelengths laser scanner. This technology was developed several years ago with the intent to monitoring critical parts of components placed in or composing nuclear infrastructures [1]: for reaching this goal, the passive (optical components) and the active (electronic components) parts were physically uncoupled, but connected together by the use of fiber optics, responsible of the transmission of optical signals derived from the interaction of several laser sources with the matter. This kind of laser scanner uses several laser sources, actually the most advanced version is equipped by three of them, for the simultaneous and punctual acquisition of both structural and color information. Every laser source mounted in the scanner is amplitude-modulated by distinct sinusoidal waves with different frequency: actually an high- ($190\,MHz$ for the Red channel) and two low-frequencies ($3\,MHz$ and $10\,MHz$ respectively for the Green and Blue channels) are employed. The estimation of the color and distance information is the result of the application of the `lock-in` technique, which can detect, if the carrier wave is known, a low electronic signal inside a noisy environment: because of this feature, this kind of laser scanner is not affected by external light sources, even for the digitalization of the colors information. A deeper explanation of the consequences of this technique, which can detect the painted portions of a surface without the use of digital cameras, will be described in the `Results` section. The digitalization of the investigated surfaces is made by moving a single spot, resulting from the superimposition of the laser beams [2], following a uniform TV-raster path.

Figure 1. The three wavelengths laser scanner: the optical head is placed on a tripod, while the electronic modules are arranged inside the yellow boxes.

In the last months the optical head has been equipped by a third motor, which ensures the digitalization of the surfaces in all the surrounding directions.

Fig. 1 shows the three wavelengths laser scanner, equipped by a `Red` (660 nm), `Green` (517 nm) and `Blue` (441 nm) laser. The system is actually composed by two main modules, the optical and electronic ones.

Using the same technology and just replacing the three original wavelengths and the associated detectors, it is possible to investigate the surface also outside the visible spectrum range: actually, an `Infrared` version, equipped by a 1550 nm laser, can digitalize medium/large surfaces and reveals hidden drawings and variations of the author. Differently from other `infrared` imaging system, this device is able to capture very wide angles of view (80° x 310°, corresponding at $265\,m^2$ at $10\,m$) with a high resolution (distance point-to-point of $500\,\mu m$ at $10\,m$).

B. The Post-processing Pipeline

One of the strongest points of the multi-wavelengths laser scanner devices are the extremely fast and easy post-processing phases: in fact, the current adopted processes in a standard 3D content creation pipeline, in case of the described technology, are replaced by several in-hardware solutions and customized algorithms. Also if the market devices, photogrammetry or laser scanners, are more robust in terms of both hardware and software solutions, in most cases they present limits and need of an integration with other techniques or an hard job during the post-processing phase: for example, the scanner, moving the laser beams on the surface following a regular path, like shown in Fig. 2, and acquiring by a constant sampling the back-reflected optical signals, collects an ordered grid of points, from where it is easy to obtain automatically regular triangulated meshes, with `ordered textures` (differently from photogrammetry [3]) and `UV coordinates`. The regularity and cleaning of the datasets generated by this kind of scanners simplify the process for resizing the texture and reducing the number of polygons in the mesh: especially this last feature is under development for the automatic generation of `BIM` [1] models [4].

Also if the possible file formats for exporting the 3D textured models are the most common, like `PLY` or `OBJ` for the meshes and `PNG` or `JPG` for the textures, the `RAW` data are stored in a customized data structure, which nowadays can result also obsolete, but it easily allows to make some operations, like to parallelize the data structures creation or restore possible corrupted single data channel. Assuming that a scan is composed by RxC points, where R is the number of rows and C the number of columns of the laser beam's path on the surface, as shown in Fig. 2, the post-processing pipeline can be described with the following equations:

[1] BIM is the acronym of Building Information Modeling; in Cultural Heritage field, is better to talk of HBIM, Historical BIM

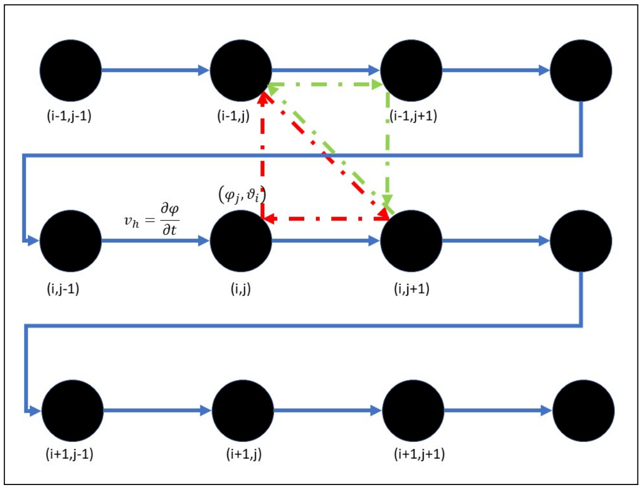


Figure 2. The TV-raster path made by the scanner: every single point represents the position where the laser signals are sampled and color and distance information are estimated.

- Range estimation:

$$\begin{aligned} \overline{\lambda}_{\nu} &= \frac{c}{2 \cdot \nu} \\ M_{i,j}(\overline{\lambda}_{\nu}) &= \overline{\lambda} \cdot \frac{\alpha_{i,j}}{2\pi} \\ N_{i,j} &= \left\lceil \frac{M_{i,j}(\overline{\lambda}_{lf}) - M_{i,j}(\overline{\lambda}_{hf})}{\overline{\lambda}_{hf}} \right\rfloor \\ D_{i,j} &= N_{i,j} \cdot \overline{\lambda}_{hf} + M_{i,j}(\overline{\lambda}_{hf}) \end{aligned} \tag{1}$$

where *c* is the speed light, ν is the modulation frequency, $\overline{\lambda}_{\nu}$ the associated wavelength, $\alpha_{i,j}$ is the shift angle in radians estimated by the lock-in of the i-th row and j-th column of the regular path shown in Fig. 2, *hf* and *lf* stay respectively for high- and low-frequency modulation[2].

- Versors calculus:

$$\begin{cases} x_{i,j} = \sin(\theta_i) \\ y_{i,j} = \sin(\phi_j) \cdot \cos(\theta_i) \\ z_{i,j} = \cos(\phi_j) \cdot \cos(\theta_i) \end{cases} \tag{2}$$

where ϕ_j and θ_i are respectively the azimut and zenit angles at the i-th row and j-th column of the regular path shown in Fig. 2.

- Point cloud assembly:

$$\hat{X}_{i,j} = D_{i,j} \cdot \hat{x}_{i,j} \tag{3}$$

where $\hat{X}_{i,j}$ are the three dimensional coordinates of the i-th,j-th point, $D_{i,j}$ the distance as expressed by the Eq. 1, $\hat{x}_{i,j}$ is the versor of Eq. 2.

- Creation of the list of faces (triangles):

$$\begin{aligned} F_{i,j}^{up} &= j + [((i-1) \cdot C),\ (1 + (i-1) \cdot C),\ (1 + i \cdot C)] \\ F_{i,j}^{lw} &= j + [((i-1) \cdot C), (1 + i \cdot C), (i \cdot C)] \end{aligned} \tag{4}$$

[2]In the case of the three stimulus scanner, the low frequency is at 10 MHz and high at 190 MHz

where $F_{i,j}^{up}$, $F_{i,j}^{lw}$ are respectively, as shown in Fig. 2, the upper (green triangle) and lower (red triangle) faces connected by the i-th anf j-th vertex.

- Color equalization and texture creation: for a complete explanation of this procedure refer to [2]

If the environment to digitalize requests to place the scanner at different locations (`stations`), a registration procedure is needed. This procedure is based on the use of the color information for extracting common features on pairs of point-clouds and than an `Iterative Closest Point` algorithm estimates the scaling-roto-translation matrix [5].

III. Results and Conclusions

A. Three Wavelengths Laser Scanner Results

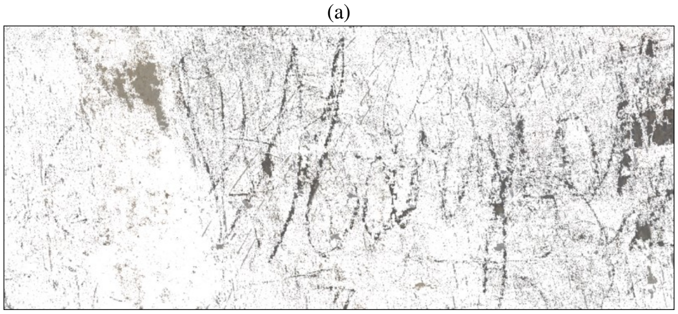
In this section several results obtained by the two main technologies described in this work are presented. The first example reported is the acquisition, made recently by the three color laser scanner, in the building `Casa dei Cavalieri di Rodi` [6]. During the acquisition phase, several light conditions occurred: as reported in Fig. 3 and shown in detail in Fig. 3, the color acquired by the three wavelengths laser scanner `(b)` is not affected by the presence of ambient light, differently from what happens with a standard digital camera `(a)`.

(a) (b)

Figure 3. On the left, a photo acquired by a standard digital camera: it is clearly visible the shadowed and sunny sides; on the right, the color acquired by the three wavelengths laser scanner: the information is uniform on the entire surface

The third example is the use of laser for studying charcoal writings drawn on the walls of one of the towers of the `Aurelian Walls` surrounding the city center of Rome. These writings were presumably written by soldiers at the end of the XIX sec.: at that time, an additional floor divided the room, where the scanner operated, in two separated rooms and than it was removed after 30 years. Nowadays, the writings are visible at a distance between 5 and 7 m and not all of them are easily readable, mainly because written on a dark brown background, with a different calligraphy and characters size. Fig. 4 shows an example of one of the writings found on the walls of the tower: (a) is the original image acquired by the laser scanner; (b) shows the same image post-processed by Principal Component Analysis (PCA) algorithms [7] [8], for a preliminary background subtraction, and morphological operators [9], for the contours enhancement that, in this case, revealed the name `Marya`.

(a)



(b)

Figure 4. (a) the image acquired by the three stimulus laser scanner (distance about 7 m); (b) the same post-processed image reveals a writing not easily visible with the eyes

The 3D model of the room with the color images acquired by the three stimulus scanner is under study of the researchers for decoding all the writings [10]. A partial 3D model is shown in Fig. 5

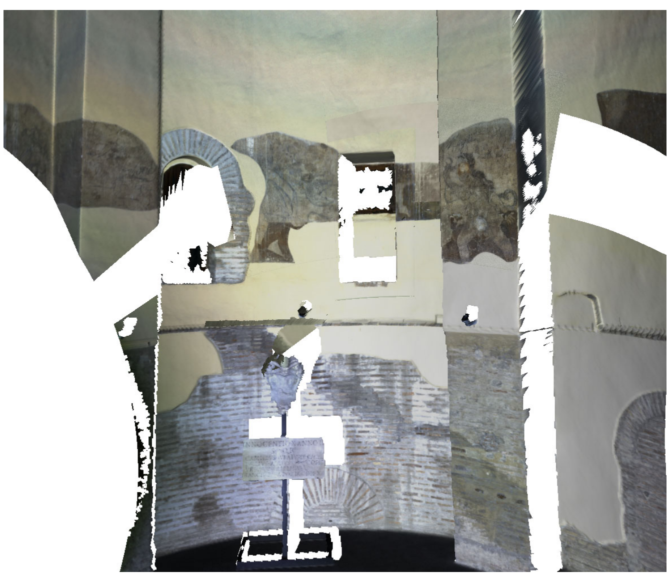


Figure 5. A partial 3D model of the tower at the Aurelian Walls

B. Infrared Laser Scanner Results

In this case the example describes one of the major results obtained substituting the three chromatic wavelengths by the infrared laser source. This particular digitalization was made inside `Palazzo Chigi` in Ariccia [11], near Rome. Fig. 6 shows a small detail of the oil-on-canvas called `La Primavera` painted by the artist `Mario Dei Fiori`: in the image it is possible to observe several variations of the right hand's fingers made by the painter. The rest of the painting and the digitalization of other twos, collected by a single acquisition made at an average distance of $5\ m$ from the targets, are under study and will be integrated with the 3D color model acquired by the three stimulus laser scanner: the resulting 3D model with colorimetric and infrared information has the double function to support the professionals of the Cultural Heritage sector and to enrich and support the creation of contents used for dissemination. Due to the wide angle of view of the scanner, another interesting result obtained by this technology during a data acquisition campaign, where several spectral techniques were used, like `Raman`, `fluorescence` and `XRF`, was that the resulting infrared image was used as reference map for planning the acquisitions with specific instruments on targeted portions of the painting.

(a) (b)

Figure 6. On the left, a digital photo detail of the oil-on-canvas painting, called *La Primavera*; on the right, the IR map obtained by the laser scanner: several variations of the author can be observed around the fingers.

C. Final Considerations

The technologies above mentioned are still at a prototype stage and need to be integrated in a single device. The possibility to have several wavelengths combined together in a single or reduced number of beams managed by the same optical device, to share the same coordinates system and to operate remotely without the needs of scaffolds are some of the features for realizing a real `3D hypespectral system`, which can generate `3D hyperspsectral images` without a complicated data-fusion and registration [12] processes. In projects with the intent to preserve and monitor the Cultural Heritage [13], similar systems could provide an all-in-one solution for recording a more complete state of health of the artworks. Actually a new design for the multi-wavelength system is under development: the simplification of the data registration, fusion and color equalization processes is at the base of the development of the multi-wavelengths technology, also with the focus to reduce the costs of this kind of analysis and 3D multi-spectral contents realization. As mentioned at the beginning of this work, the scope of this research and the development of these instruments base the idea that the technology has to support the knowledge of an artwork, and not substituting the pleasure and the importance to observe it and the place where it is located.

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