Terrestrial and Subsea 3D Laser Scanners for Cultural Heritage Applications

Methodologies in cultural heritage applications are slowly but steadily evolving with the introduction of bespoke innovative technological tools. Beyond complementing the work of the experts, these cutting-edge innovations may also provide new and stimulating paths for artworks fruition. In this framework, terrestrial and subsea 3D laser scanners developed at ENEA mark a one-of-a-kind achievement, as witnessed by the results of the several measurement campaigns conducted. The devices are designed to provide 3D accurate models of targets of interest both in terrestrial and in subsea environment. In particular the terrestrial version, the RGB-ITR, is equipped for unique color rendering of the investigated scene

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Introduction

An increasing interest appears to be emerging within the cultural heritage (CH) community over the use of cutting-edge technologies. Remarkable results of field trials have been instrumental for raising the awareness that improved technological capabilities could enable innovative practices in the fruition, preservation and restoration of art works. Among the several technological tools deployed, one has particularly seized the attention of the general public and is steadily gaining ground among CH professionals, namely the 3D laser scanning. It is a relatively new technology that has been in development over the last 15 years. Several different setups are available – like laser beam modulation with coherent or incoherent detection techniques, time-of-flight scanners based on pulse beams, triangulation and structured light systems – but all of them are capable of recording geometric spaces in 3D with great accuracy [1]. If on the one side digitization of artistic monuments with 3D laser technologies has always a huge visual impact, on the other an increasing number of professionals and stakeholders acknowledge its potentialities as an improved diagnostic and monitoring tool. To date, the debate in the CH community over the usefulness of this technology is still ongoing, with innovators opposing to many still skeptical and reluctant to accept its introduction. Nevertheless, there is an application where the point of view is unanimous: this is when it comes to subsea applications, particularly those for visualization and diagnosing in marine archeology. The subsea environment is hardly accessible but is

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home to cultural heritage of inestimable value, which witnesses the evolution of mankind, its struggle to make sea a less hostile environment, and the evolutionary path of navigation. Here, the line of separation of 3D laser imaging as a tool providing a striking but needless visual impact from a "game-changing" factor in subsea CH practices is less sharp and the CH community more keen to admit the value of this innovative technology. Nevertheless, subsea 3D laser imaging comes with specific issues to face, the solution of which requires the development of bespoke methodologies and techniques. The presence of water and the demand to operate at depth add considerable scientific and technological challenges to face and this explains why subsea 3D laser vision lags largely behind its counterpart on dry environment.

At ArtVisLab (Artificial Vision Laboratory) of ENEA Frascati considerable efforts are underway for consolidating the achievements in developing innovative terrestrial 3D laser scanners tailored for CH applications. A proven track record of trials conducted on masterpieces of global importance witnesses the high profile of the scientific and technological findings. In particular, the Red Green Blue Imaging Topological Radar (RGB-ITR) scanner is the last prototype developed in ArtVisLab and it allows simultaneous measurement of distance and color of each pixel recorded over the scene. Far from being a pure scenic effect, color registration enables a new methodology in remote colorimetry, where data are not affected by the influence of external light sources and are reusable over time for further analysis comparison.

At the same time ArtVisLab has the in-house scientific and technological skills which have been instrumental for developing the prototype of a subsea 3D laser scanner for application in marine archeology. ArtVisLab is a unique laboratory in this sector with a dual commitment (terrestrial and subsea applications), where the learning process in one field suggests new and innovative developmental paths for the other.

In this contribution this specificity is outlined with:

- Up-to-date results from an experimental campaign where the digitization of the "Amore e Psyche" lodge, with frescos painted by Raffaello Sanzio and his school, was performed by means of the RGB-ITR laser scanner.
- a breakthrough coming from the laboratory where, for the first time, colored 3D images of samples immersed in water have been recorded with a modified version of a prototypal subsea 3D laser scanner.

The RGB-ITR Colour Laser Scanner

RGB-ITR is a patented 3D colour laser scanner completely designed and realized at ENEA laboratories. The competitiveness of this instrument with respect to the commercial ones can be mainly summarized in three points: it was developed trying to focus the attention on specific needs of CH professionals (e.g., non-invasiveness and versatility), introducing quantitative remote analyses useful for restorers and cataloguers (like remote colorimetry combined with structure monitoring) and getting advantage by the instrument prototypal status for expanding the scanner features, involving a large community of professionals and stakeholders.

The technique adopted for the simultaneous collection of distance and colour information is based on amplitude modulation [2,3] of three monochromatic laser sources (650 nm, 532 nm, 450 nm), which operate as carrier waves. The distance and colour information are extracted from modulating waves by phase-shift and reflectivity responses of the target at the three wavelengths.

The precision of distance measurements is ensured by the use of two modulating sinusoids, one at few MHz (i.e., 5 MHz) and one at several hundred MHz (i.e., 200 MHz): the first wave gives a rough measurement of the distance between the centre of the instrument and the target (up to 30 m), meanwhile the second wave gives a very high-precision distance measurement, without ambiguity, in a shorter range (i.e., a 190 MHz modulation frequency can work, avoiding the ambiguity, in a range of about 0.78 m). The result of the combination of these two data is a very high-precise distance measurement (about 0.2 mm at 10 m).

The non-destructive character of the technology has been tested on different painted surfaces prior to application. For instance, on Renaissance frescos the absence of photobleaching has been verified on historical pigments specimens irradiated with 3mW for 1 sec on a 0.5 mm dia. spot at 5 m (for an exposure time exceeding of a factor 10 that needed during the measurements). Two proprietary software applications complete the system with ScanSystem used for system control and ItrAnalyzer for data processing and visualization.

From Remote Diagnosis to Virtual Fruition: Digitization of the "Amore e Psyche" Lodge

An accurate digitization of the "Amore e Psyche" lodge was performed in June 2011 by means of the RGB-ITR laser scanner. In four days and four nights the scanner collected the entire vault, storing both colour and distance information for each sampled point. The mean distance between the centre of the scanning mirror and each part of the lodge was about 8 m and the spot size was about 0.2 mm. The scanner was mounted in the configuration shown in Fig. 1, which permitted a very fast movement of the entire system in the room and let the possibility to allow daily visits of the lodge, interdicting only a very small area (about 1 squared meter).

FIGURE 1 RGB-ITR scan system in tower configuration. Lasers and electronic units are allocated in the yellow boxes, while the optical head is above
Source: ENEA

The initial idea of the vault digitization was to document the stability of the structure and the state of conservation of the frescos painted by Raffaello Sanzio and his school. The digitization was divided into four scans and the system calibrated after each scan by executing a measurement of a standard white target (SPECTRALON STR-99-020) placed at various distances (the range was between 5-12 m with a step of 0.50 m), obtaining three colour curves for the three lasers utilized in the digitization. The importance of this calibration is essentially due to the possibility to normalize the back-reflected light, collected by the three photodiodes used by the RGB-ITR, for future data comparison acquired also by means of other instruments. This feature is extremely important in the CH environment because it permits to observe the status of pigment conservation of the work of art over time and to monitor changes after a restoration. Due to the generalization of the data structure acquired by the ITR systems, the result of digitization can be used not only for restoration and cataloguing, but also for fruition and educational purposes. The high quality of data allows high level zooming of images, permitting to observe details that a visitor cannot see in standard conditions. Differently by commercial instruments, the post-processing time needed for building a usable 3D model for fruition purposes is reduced by the intrinsic feature of the collected data: in fact, the possibility to acquire both colour and structure information at the same time permits to obtain a self-registered mesh with texture, which can be directly utilized in 3D theatres or educational games, without the use of any invasive backreflected targets or algorithms for the stitching of 2D over 3D images. A view of the 3D complete mesh with texture of the lodge is shown in Fig. 2.
The complete and accurate 3D model of the lodge was shown in important exhibitions in Rome ("The Renaissance in Rome" at Palazzo Sciarra, and "Amore and Psyche" at Castel Sant'Angelo). In both exhibitions the idea was to give continuity to the narration of the exhibition, showing also monuments which cannot

be physically present, although are important for a complete explanation of an artistic period or subject. In Fig. 3 an example of data analysis with ItrAnalyzer is shown. It is possible to select a row of the matrix representing the three superimposed back-reflected laser layers and the software will show the reflectivity of every single pixel. With this instrument is possible to perform the so-called differential colorimetry: at the moment the results of the lodge digitization, made by the RGB-ITR scanner, cannot be directly compared with colorimeter measures, but they can be used for monitoring the state of the art of the pigments over time, and for comparisons in future different measures collected by the scanner during scheduled periods.

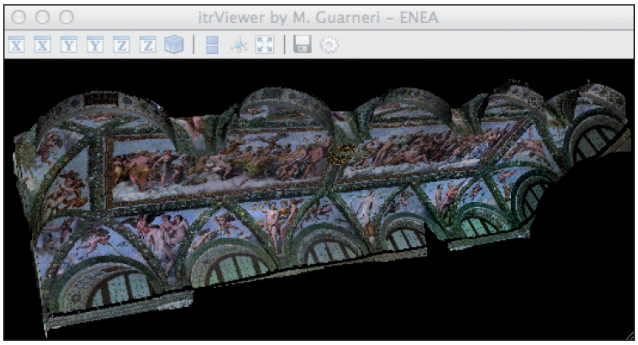

FIGURE 2 3D view of "Amore and Psyche" Lodge
Source: ENEA

Subsea 3D Laser Scanner

Recording faithful and accurate 3D images of subsea targets by means of laser-based devices is a challenging task, mainly when water turbidity increases. This because seawater is a medium which absorbs and diffuses light at the same time and in a more severe way as the concentration of dispersed particles increases [4]. In particular the backscattering process, where a fraction of the laser light is reflected backwards, gives rise to an unwanted disturbance signal which limits the performance of a 3D laser imaging system. This makes the development of a subsea 3D laser scanning system not a mere transposition for operation at depth of its terrestrial counterpart. So, new scientific and technological challenges arise and, after several years of experimental [5] and theoretical researches [6], carried out in the framework of the BLU-ARCHEOSYS[1] project, ArtVisLab has completed the realization of a prototype (Fig. 4) for subsea 3D laser imaging, named RE-VUE (REmote Viewing in Underwater Environment). In its basic configuration the device is based on a continuous-wave (CW), amplitude-modulated (AM) laser source (405nm, 20mW) whose wavelength matches a minimum in the absorption curve of clean seawater. The RE-VUE device can investigate scenes with a horizontal angle of view of 40° and a vertical one of several tenths of degrees. It is fully remotely operated by a laptop, where a proprietary software is installed, capable of working at a maximum depth of 400m.

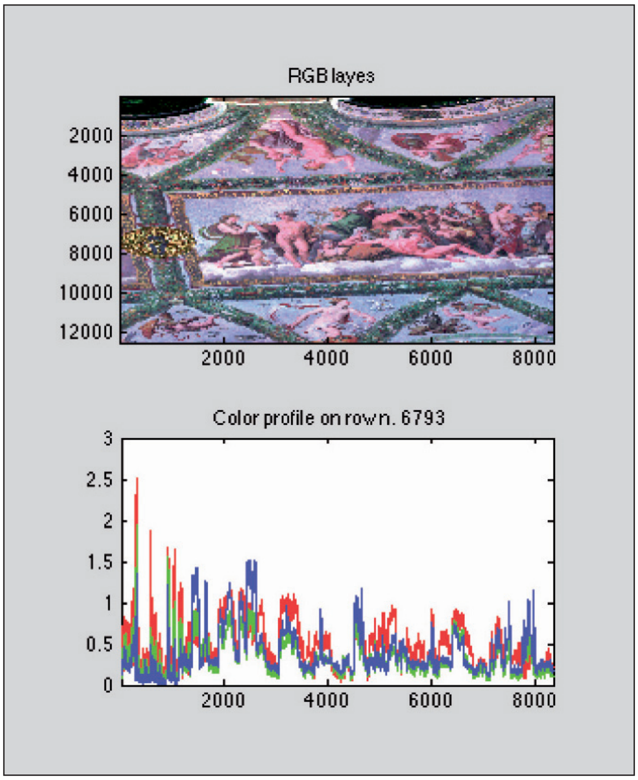

FIGURE 3 Colour profilometry of row 6793
Source: ENEA

During 2011 the RE-VUE system has been immersed in a test pool filled with relatively clean water, and submillimetric range resolution of targets at 7m of distance from the sensor has been recorded. Being

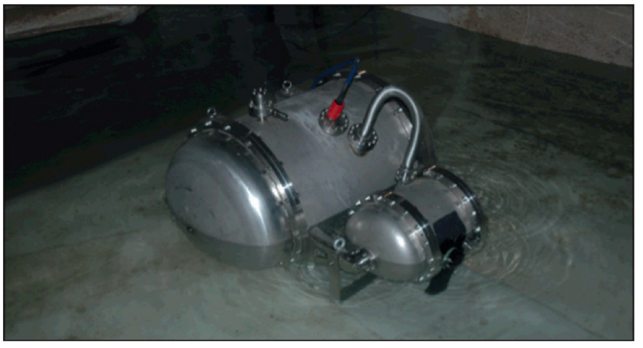

FIGURE 4 Photo of the RE-VUE system used for underwater 3D imaging. The small cylinder contains the laser source, the scanning system and the receiving stage (lens and fast photomultiplier). The big cylinder, instead, hosts the electronic modules (e.g., lock-in amplifier)
Source: ENEA

based on a single laser source, the RE-VUE maps the reflectivity of the investigated scenes in gray scale. The device is ready for installation onboard a ROV (Remotely Operated Vehicle) and deployment for inspection of subsea archaeological sites.

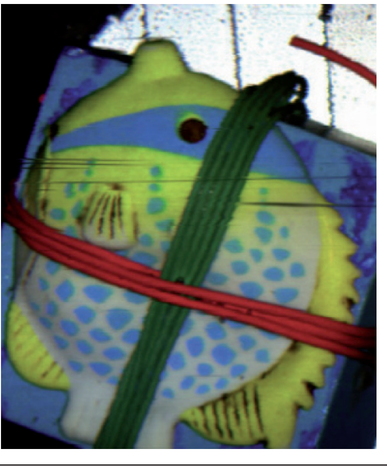

FIGURE 5 Result obtained by an upgrade of the RE-VUE system equipped with three CW AM laser sources at 450nm (blue, fm=100MHz), 532nm (green, fm=30kHz) and 650nm (red, fm=190MHz): high-resolution and high-contrast 3D color image of a plastic fish immersed in a 2m-high clean water column acquired at high rate (1000 sample points per second)
Source: ENEA

Moving from the experience acquired in developing RGB-ITR, a first attempt devoted to acquire 3D color images of underwater targets has been recently performed by using an upgrade of the RE-VUE where three low-power (mW), continuous wave, amplitude-modulated laser beams at 450nm (blue), 532nm (green) and 650nm (red), respectively, are used for scanning the target under investigation. The three laser beams are combined into a single white ray by means of a dichroic optical component. A first result obtained by means of this upgrade of the RE-VUE is shown in Fig. 5. In detail, the figure provides the 3D color model of a plastic fish immersed in a 2m-high clean water column. The fish model is characterized by high resolution and shows high contrast. This last result has been obtained with an acquisition rate of 1000 sampled points per second and with high angular resolution (some thousandth of degrees as steps of scan motors). Furthermore, such a result demonstrates the possibility to perform high-quality 3D color imaging even in underwater environment. This finding has prompted a new perspective for subsea 3D laser colour imaging, and ArtVisLAb is actually working on the development of a marinized prototype under the IT@CHA project[2].

Conclusions

In this contribution we have outlined the commitment of ArtVisLab at ENEA Frascati to develop 3D laser scanners for application in Cultural Heritage both in terrestrial and subsea environment. This activity demands multidisciplinary skills covering optoelectronics, photonics, theory of laser beams propagation in turbid media, software development, instruments' programming, mechanical design, subsea engineering, data processing, digital and analog electronics, colour theory, image processing. The recent campaign, where RGB-ITR has been used to digitize the whole Sistine Chapel inside the Vatican City and with a laser beam for the first time ever projected onto the "Universal Judgment" of grandmaster Michelangelo, tells a fascinating story. Processing of the massive quantity of data is still underway, but what emerges is that a cutting-

edge technology is unveiling, in the experts' opinion, details never recorded before.
With the RE-VUE and its improved version to acquire 3D colour images in the subsea environment, ArtVisLab is ready to give its contribution for introducing best and innovative practices in marine archaeology. In this case the way ahead is full of scientific and technological challenges to face, but the consensus coming from the CH community over the project is encouraging and instrumental for a positive completion.

Notes

1. BLU-ARCHEOSYS (Innovative Technologies and Advanced SYStems as Support in Underwater ARCHaeology) FAR – D.M. 593 8 august 2000 – art. 5 – Ministry of Education, University and Research.
2. IT@CHA – Italian Technologies for Advanced application in Cultural Heritage Assets. PON 2007-2013 – Beni Culturali

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