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3D photogrammetric reconstruction by "Structure from Motion" as a monitoring technique for safety, conservation and improvement of the fruition of cultural heritage

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***Abstract* –In the last years, with the large growth of new state-of-the-art technologies used in the field of cultural heritage, it's increasingly necessary to promote non-invasive and non-destructive techniques which are "sensitive" to the nature of the site in which they are applied, respecting the Italian historical-artistic heritage. Within the COBRA project [1], ENEA developed a new low-cost and non-destructive survey technique by 3D Photogrammetric reconstruction, using the Structure from Motion (SfM) method, for innovative applications in the field of cultural heritage [2]. This paper shows an application of this methodology on the archaeological complex of Priscilla's Catacombs in Rome.**

Three case studies have been identified, with several design purposes, showing the different applications of this technique: a sarcophagus called "Sarcofago delle Muse" , a chapel named "Cappella Greca" and a masonry element, which are all situated in the "Criptoportico" area.

I. INTRODUCTION

ENEA research centers have an active role in the development and dissemination of methods, IT services, digital technologies and advanced tools for the preservation of cultural heritage.

From 2015 ENEA is involved in a project, named CO.B.R.A. (sviluppo e diffusione di metodi, tecnologie e strumenti avanzati per la **CO**nservazione dei **B**eni culturali, basati sull'applicazione di **R**adiazioni e di tecnologie **A**bilitanti), which focuses on disseminating and transferring advanced technologies and methods to small and medium size industries aimed to protect and conserve the cultural heritage.

The paper shows the use of the 3D photogrammetric reconstruction as a low-cost, contactless and non-destructive survey technique which executes the scanning of archaeological finds and/or structures in a "contactless" way, producing 3D models by SfM method, using Agisoft PhotoScan Pro code [3].

From the acquisition of two-dimensional digital images, it is possible to obtain the 3D model of the object under the form of a "points cloud" and its geometrical data in terms of shape, size and space position. The SfM technique has many advantages: it guarantees an easy access, it is contactless, fast, non-invasive and non-destructive. Furthermore, from the point of view of the "technological transfer", it can be easily used in museums or archaeological sites to produce multimedia videos of the structures, for the valorisation by means of "virtual reality" and the digital archiving of artworks or archaeological elements **Errore. L'origine riferimento non è stata trovata.**.

This technique is based on the principles of optics, photography and descriptive geometry, and in particular on the inverse perspective theory. It can be used in every field of cultural heritage because it provides an easy to use and a fast way to obtain the metrical information of the detected object, which are fundamental for the study of monumental complexes as well as of small size objects.

The need of heavy hardware and software resources for images processing, data analysis and storage is met by network access to the computational capabilities of ENEA HPC CRESCO (Computational Research Centre for Complex Systems) ICT infrastructure [4].

The "computer graphics" software and tools, are available through an intuitive interface named FARO2

(Fast Access to Remote Objects). Moreover, images and results of the photogrammetric reconstructions are archived in the AFS and GPFS ENEA storage areas for future post-processing.

II. CASE STUDIES

The following three case studies were identified for three different purposes in the Priscilla's Catacombs, in agreement with the Pontifical Commission for Sacred Archaeology.

The first case study is a sarcophagus named "Sarcofago delle Muse", situated in a critical area not accessible to visitors because of safety reasons. In this case the SfM technique was used to improve and increase the remote fruition of this good in virtual mode. Moreover the photogrammetric 3D reconstruction of the sarcophagus was used to create 3D virtual videos of it, that the tourists can observe in the museum during their visit at the catacombs.

The second case study is the "Greek Chapel" which represents one of the most important archaeological sites of the Priscilla's Catacomb. It is divided in two sections by an arch and it's richly decorated with fresco paintings, dating back to the third century B.C., stucco and fake marble. The paintings of the chapel show some scenes of new and old testament, but some surfaces are affected by biological attacks. In this case the SfM reconstruction was used to monitor and check the evolution over time of biological attacks in shapes and sizes.

The last case study concerns the 3D reconstruction of a damaged masonry element and the detection of its cracks pattern. The damaged masonry element whose surface is characterized by lots of important cracks, already monitored with traditional instruments, is very close to the Criptoportico area. In this case, thanks to the use of the SfM technique, it was possible to reconstruct the whole element and to map the cracks detecting their taxonomy, their extension and the class of damage associated to each one, with the aim of monitoring the cracks patterns over time.

A NIKON D60 digital camera was used to produce 2D images with a 3872x2592 px resolution and 5MB each for the three case studies above mentioned.

A. 3D Photogrammetric reconstruction by SfM

This technique, based on photogrammetric principles, was used to create three-dimensional models of the three above mentioned case studies, under the form of "points cloud" and/or "polygonal mesh", in order to obtain their correct geometrical data in terms of shape, size and spatial position.

A large number of 2D images were post-processed and managed by Agisoft PhotoScan Pro code, according to a semi-automatic procedure based on "Computer Vision" algorithms, in order to define high-quality polygonal 3D models characterized by a multi-view reconstruction and to gain the correct measures of a detected object in terms of shape, size and 3D space position.

The semi-automatic computation procedure is divided into the following steps (**Errore. L'origine riferimento non è stata trovata.**):

1. the alignment of the loaded images;
2. the multi-stereo matching process, to detect the position and the orientation of the camera shots and the "sparse cloud";
3. the "dense image matching" algorithm, to extract the "dense cloud" model;
4. the computation of the polygonal model, made of faces and vertices;
5. the computation of the "texturized model" of the specimens.

The code also provides a fast and automatic way to scale the models, starting from the acquisition and the assignment of a single reference measure of the real structures.

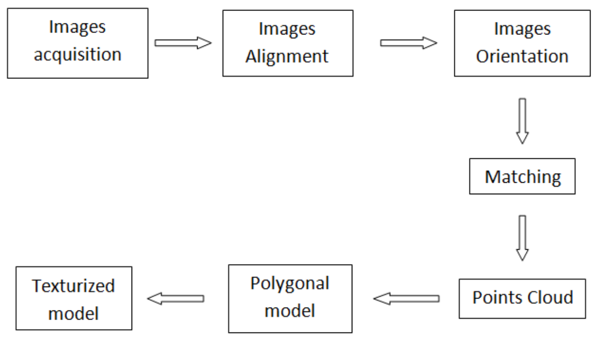

Fig. 1. Photoscan Pro Workflow

Thanks to the remotely accessible Graphic Processing Units (GPU) by the user-friendly FARO2 interface it was possible to have graphic and structural codes to process heavy jobs for 3D photogrammetric reconstruction and FE analysis, using the computational resources offered by CRESCO HPC multi-core clusters (**Errore. L'origine riferimento non è stata trovata.**).

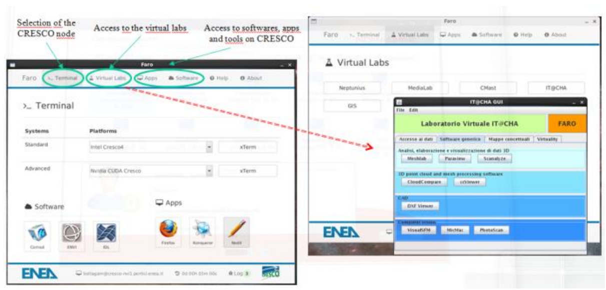

Fig. 2: Remote access to FE software

The 2D images were taken by the "close range photogrammetry method" that is suggested when the acquisition distance is less than 300 meters.

All the images, videos, reports, documents and 3D photogrammetric post-processing reconstructions were archived in the AFS and GPFS ENEA storage area for future comparisons, elaborations and disseminations.

III. THE "SARCOFAGO DELLE MUSE"

The "Sarcofago delle Muse" is a very fragmented sarcophagus, with symbols taken from pagan world.

A. Bevignani assembled all available fragments with great patience (**Errore. L'origine riferimento non è stata trovata.**Fig. 3), in an area very near to the "Cappella Greca", which is part of the "Criptoportico" but it is not currently visible because it is not included in the path of the museum visit.

Thanks to this reconstruction it was possible to recognize that the sarcophagus belongs to the group of "Asian sarcophagi" of the Sidamara. It is 2.30 meters long and 1.10 meters high, made of six tortuous columns on the front side bound by five arcades, each forming a niche containing the figure of a muse. For security reasons, the sarcophagus was placed in a not accessible area and therefore, it is not clearly visible.

Fig. 3: 2D picture of the A. Bevignani reconstruction

To make this archeological structure virtually accessible outside and exploiting its greatness and beauty to researcher, specialists and tourists, a 3D photogrammetric reconstruction was proposed and performed. Due to the poor lighting of the area, because of the unfavorable position of the site, in order to capture clear photographic images, two LED lights were used to uniformly brighten the surfaces and to reduce optical distortions during the 3D reconstruction.

From 80 digital images captured, of 5MB each, 67 images were post-processed and high resolution 3D photogrammetric reconstruction was carried out, see the dense cloud (

Fig. 4), the mesh by triangle elements (

Fig. 5) and the 3D textured model with high resolution (Fig. 6).

Fig. 4: Dense cloud

Fig. 5: Polygonal mesh

Fig. 6:Textured model

Moreover figure 6, if compared with figure 3, shows the high quality of 3D processing results by SfM methodology.

IV. THE "GREEK CHAPEL"

Unlike other diagnostic and monitoring techniques with moisture-sensitive electronic components such as laser scanners, the photogrammetry is not influenced by environmental conditions of low temperatures and high humidity. For this reasons it must be emphasized that it was the only one able to produce the full acquisition of the Greek Chapel and to return a 3D real scaled model. More than 400 digital images were acquired and 364 of them were post processed:

Fig. 7 and Fig. 8 respectively show the textures of the longitudinal right and left sections.

Fig. 7: Longitudinal sections- right side

Fig. 8: longitudinal sections- left side

In this case study the SfM reconstruction was also used to show the application of the photogrammetry for monitoring and checking the evolution over time of the biological attack in Fig. 9 and Fig. 10.
The reconstruction of the biological attack resulted geometrically scaled thanks to the real scaling of the 3D photogrammetric reconstruction of the entire Greek Chapel based on fixing the real distance physically measured between two points (markers) by Photoscan Pro code.

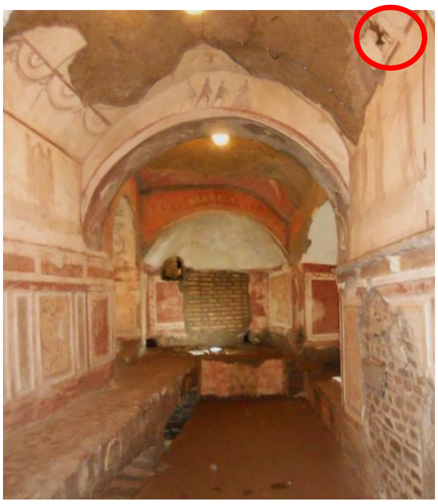

Fig. 9: 3D texture of the Greek Chapel and biological attack in the red circle

Fig. 10: Photogrammetric reconstruction of the biological attack

Consequently, sizes and area of the biological attack were also calculated in an automatic way by software tools.
Two photogrammetric reconstructions were performed: the first set of images was acquired in June 2016, the second one in November 2016.
The biological attack showed different shape (Fig. 11 and Fig. 12); the model was geometrically scaled. The size of the maximum length (**l_{max}**), the maximum height (**h**$_{max}$) and the area were measured (table 1) by Photoscan.

Table 1. sizes and area of geometrical attack.

June 2016 (Fig. 11)	l_{max} [m] markers 7-8	h_{max}[m] markers 5-6	Area[m^2]
	0.185	0.159	0.0138
November 2016 (**Errore. L'origine riferimento non è stata trovata.**)	l_{max} [m] markers 6-7	h_{max}[m] markers 8-9	Area[m^2]
	0.165	0.142	0.0105

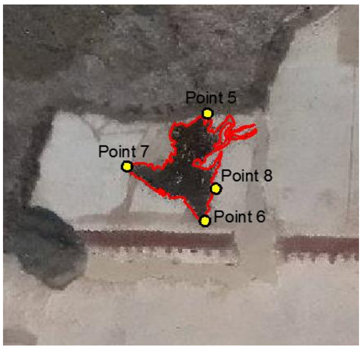

Fig. 11: Biological attack: June 2016

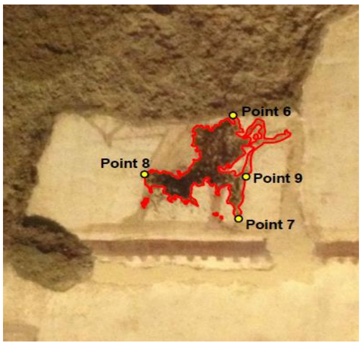

Fig. 12: Biological attack: November 2016

The goal of this study was to show the effectiveness of this technique, to produce a 3D metric-corrected model in order to monitor the state of conservation of the biological attacks in a very fast, low-cost way, and also with a not very specialized staff, simply using the hardware and software capabilities of ENEA ICT infrastructure.

V. FIGURES AND TABLES CRACK PATTERNS DEFINITION OF A MASONRY WALLS

Photogrammetric scanning was also used in this last case as a monitoring techniques in order to assess the cracks pattern and the structural health of a damaged masonry wall very close to the "criptoportico" area, already monitored by a traditional glass sensors.

The SfM technique was used to detect the survey of the crack pattern, the mapping of the cracks and to define their taxonomy [6][7].

A photogrammetric scanning of more than 300 images produced a high-density cloud of 19˙438˙228 points and a polygonal mesh of 3˙547˙077 triangle elements; the 3D digital reconstruction of the masonry walls gave a very detailed textured model (Fig. 13).

Fig. 13: polygonal mesh (left), texture (right)

Starting from this 3D model, a map of the cracks was completely described (Fig. 14) according to the macro-seismic European EMS98, also used by the 2nd GNDT level cards, considering five levels of damage (low, moderate, high, very high and collapse).

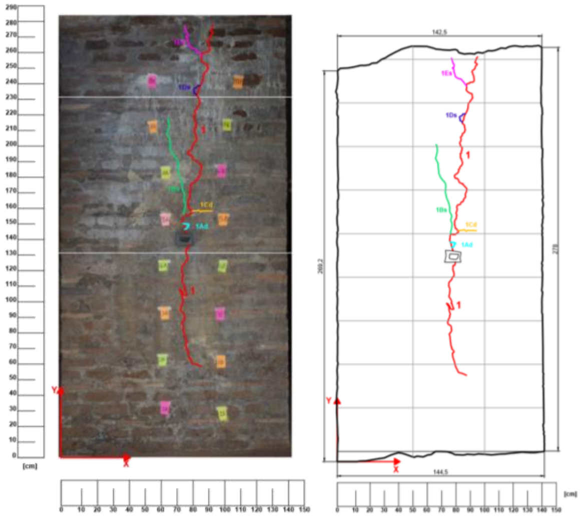

Fig. 14: crack pattern (left) - taxonomy (right)

The methodology and the applied approach are fast, easy to use and periodically repeatable over time allowing to check and verify the evolution of the damage extension during the time.

VI. CONCLUSIONS

The paper aims to propose the use of photogrammetry as a monitoring technique for different purposes producing 3D metric-corrected models for safety, conservation and improvement of the fruition of cultural heritage. Its strength lies in the fact that it is possible to obtain metrical information, where areas to be inspected are not easily accessible, by a low-cost and fast methodology, only depending on hardware and software capabilities. Resolution of 3D model and rendering of colors are also depending on the quality of the original digital images especially with regard to the number of pixels. It should be also underlined that photogrammetry is very useful where it is not easy to introduce other sensitive instruments, but it cannot replace the capabilities of other technologies that are complementary and return the best results if used together.

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