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RESTAURO, CONSERVAZIONE E TUTELA DEL PATRIMONIO CULTURALE

Applications of 3D technology in cultural heritage

107

Digital survey and 3D digitalization

Digital reconstruction, 3D - printing and Augmented Reality

Accessing and Information System

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Sommario

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Attualità

6 **VIII Congresso Internazionale “Colore e Conservazione”**

9 **La conservazione si evolve in 3D, ma riprodurre così bene che senso ha?**
Luca Di Berardino

12 **Tecnologia laser: la XII edizione della conferenza internazionale di LACONA**
Alessandro Zanini

Dossier
Applications of 3D technology in cultural heritage

14 **Preface / Prefazione**
Laura Pecchioli

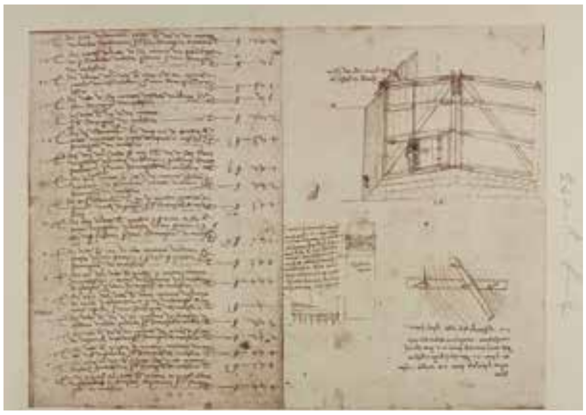
16 **Introduction / Introduzione**
Paolo Salonia

DIGITAL SURVEY AND 3D DIGITALIZATION

21 **3D survey and GPR for cultural heritage. The case study of SS. Pietro and Paolo Church in Casalvecchio Siculo**
Sebastiano D'Amico, Mauro Saccone, Raffaele Persico, Valentina Venuti, Grazia Vera Spagnolo, Vincenza Crupi, Domenico Majolino

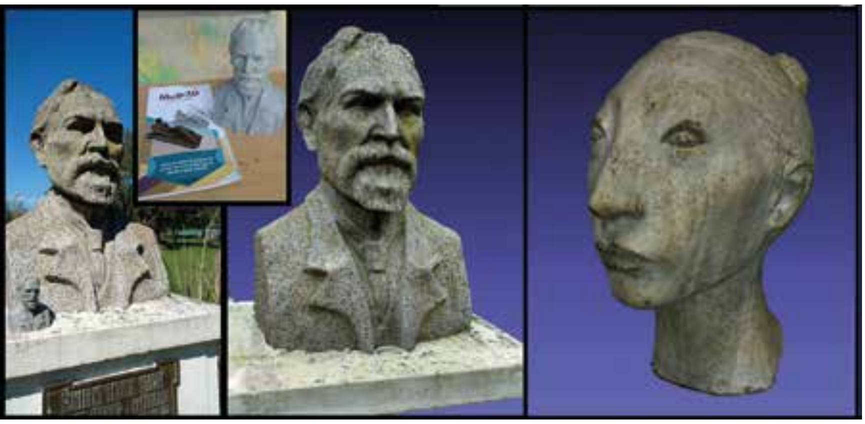
26 **3D archaeological field recording in Ostia**
Axel Gering, Laura Pecchioli, Marco Dehner, Bendegúz Takáts

33 **3D Documentation of an ancient wooden lock of the Navigli canals in Milan, based on da Vinci's studies**
Laura L. Micoli, Gabriele Guidi, Claudio Giorgione, Claudio Calì, Anna Galli, Marco Martini

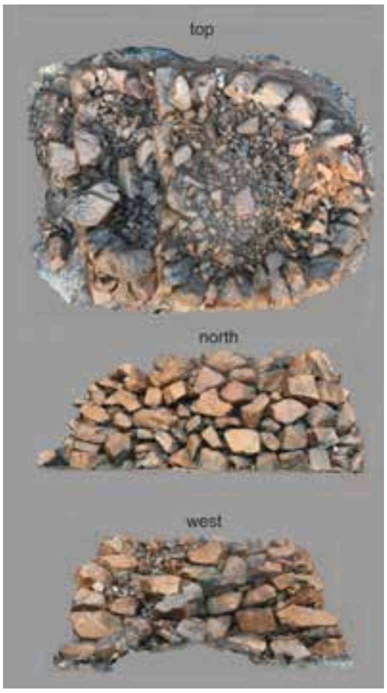


40 **3D application in Estonian cultural heritage. Benefits and considerations based on the Chr. Ackermann Investigation Project**
Andres Uueni, Hilkka Hiiop, Fabrizio Ivan Apollonio

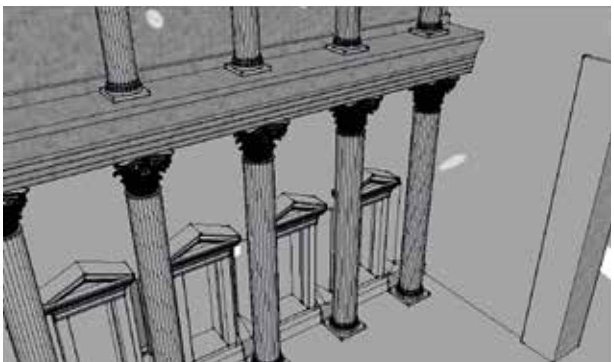
45 **3D imaging system for the digitization of the Argentine museums' collections**
Mercedes Morita, Gabriel M. Bilmes



50 **Photogrammetric recording of an Early Iron Age hut tomb in central Oman**
Paul A. Yule, Michela Gaudiello



55 **Analysis of skylight illumination using 3D. An experimental case of the Roma and Augustus temple in Ostia**
Daniel Damgaard



DIGITAL RECONSTRUCTION, 3D-PRINTING AND AUGMENTED REALITY

61 **The re-erection of Old Kingdom offering chambers in the Neues Museum Berlin**
Thomas Lucker

67 **Virtual reconstruction of a historical design exhibition**
Donatella Biagi Maino, Michela Gazziero, Giuseppe Maino

73 **Rilievo ed elaborazioni 3D per il restauro. Esperienze dell'Opificio delle Pietre Dure di Firenze**
Laura Speranza, Mattia Mercante

82 **An Augmented Reality system for assisting art conservation and restoration**
Marcello Carrozzino, Raffaello Brondi

ACCESSING AND INFORMATION SYSTEM

87 **Digital models for publishing of research project data. The case of Villa Corsi Salviati Guicciardini in Sesto Fiorentino**
Marco Callieri, Emma Cantisani, Alberto Casciani, Oana Adriana Cuzman, Rachele Manganelli Del Fà, Cristiano Riminesi, Paola Rosa, Piero Tiano, Silvia Vettori

92 **A 3D-based Information System to manage conservation and "lifecycle" of the Neptune Fountain in Bologna**
Fabrizio Ivan Apollonio, Vilma Basilissi, Marco Callieri, Dora Catalano, Matteo Dellepiane, Marco Gaiani, Federico Ponchio, Francesca Rizzo, Roberto Scopigno, Giorgio Sobrà

99 **3Robotic and Virtual Reality for cultural heritage digitization and fruition**
Daniele Calisi, Fabio Cottefoglie, Lorenzo D'Agostini, Francesca Giannone, Fabrizio Nenci, Paolo Salonia, Marco Zaratti, Vittorio Amos Ziparo

105 **MuPriS: modern technologies making museum of sarcophagi content more accessible**
Laura Pecchioli, Barbara Mazzei

111 **Structure-from-Motion (SfM) technique in the Catacombs of Priscilla in Rome. Improvements in the conservation,the safety and the fruition**
Marialuisa Mongelli, Irene Bellagamba, Giovanni Bracco, Beatrice Calosso, Silvio Migliori, Antonio Perozziello, Samuele Pierattini, Andrea Quintiliani, Barbara Mazzei

Notizie e informazioni

117 **Conservazione di arte urbana**
Ester Giner Cordero

119 **Taccuino IGIIC**
Lorenzo Appolonia

ACCESSING AND INFORMATION SYSTEM

Digital models for publishing of research project data

The case of Villa Corsi Salviati Guicciardini in Sesto Fiorentino

Marco Callieri, Emma Cantisani, Alberto Casciani, Oana Adriana Cuzman, Rachele Manganelli Del Fà, Cristiano Riminesi, Paola Rosa, Piero Tiano, Silvia Vettori

The project was created with the aim of setting up a research program and to define operational protocols for the conservation of cultural heritage in stone material (e.g. statues, fountains, etc.) preserved in historical gardens.

The Garden of Villa Corsi Salviati Guicciardini (fig. 1)[1] in Sesto Fiorentino, Florence, was chosen as an exemplary case study for the purposes of the project. It represents an important example in the evolution of historical gardens[2] and the statues in the central yard in front of the Villa show the characteristic conservation problems of garden stone furniture.

The two statues, chosen as the project's case study (fig. 2), are not "wholesome" works and are re-assembled with parts from different statues. The different types of marble that form the statues have different granulometry – a characteristic also perceptible to visual examination – and therefore affected by various degradation phenomena; this feature allows us to have several representative cases of conservative problems. First of all, to assess the state of conservation of the marble, it was necessary to study the environmental conditions to which the case studies are subject; for this aim, sensors to evaluate the climatic parameters (exposure, temperature, relative humidity, contact temperature, etc.) were arranged on the statue. Micro samples were taken from the statues for petrographic and diffractometric analyses in order to obtain a complete characterization of the constituent material

Fig. 1. Villa Corsi Salviati Guicciardini, the facade on the garden.

1

Fig. 2. The two statues, case study of the project.

2

and to assess their state of conservation [Amoroso, 2002]. After this first fact-finding survey, the two statues were subjected to cleaning tests, carried out in different times and ways. The statues were treated with products for the consolidation and protection, and control of the biological patina. Such interventions were monitored by colourimetric and absorption tests [Manganelli Del Fà, 2016].

The Institute for the Conservation and Valorization of Cultural Heritage (ICVBC) pays close attention to dissemination and valorization of the results obtained from projects and scientific research, by the use of communication tools of information technology, and by creating thematic websites[3]. The aim is to reach a wider audience, and not only the scientific community, when presenting the activities of the Institute, and to spread knowledge in a simple and effective way. To this end, we created a website for this project that provides all the basic information regarding the activities. The site also allows visitors to visualize the 3D models of the statues. On these models, the user can access localized information on the methodologies used to characterize the materials, and on the state of conservation, using a number of clickable hotspots, in a simple and immediate way.

Equipment and methods

Three-dimensional digital models used in the project, have been created using Agisoft PhotoScan[4], software that performs photogrammetric processing of digital images and generates 3D spatial data. The created models usually need some refinements and editing to correct imperfections or errors in the surface. These operations were performed by MeshLab[5] [Cignoni, 2008] an open source system for processing and editing 3D triangular meshes, that provides a set of tools for editing, cleaning and texturing meshes.

Models of the statues were integrated into a web page for publishing the data collected during the project using a platform for 3D web publishing called “3DHOP” (3D Heritage Online Presenter)[6] [Potenziani, 2015], an open-source software package developed by the Visual Computing Lab (ISTI-CNR, Pisa).

3D model reconstruction

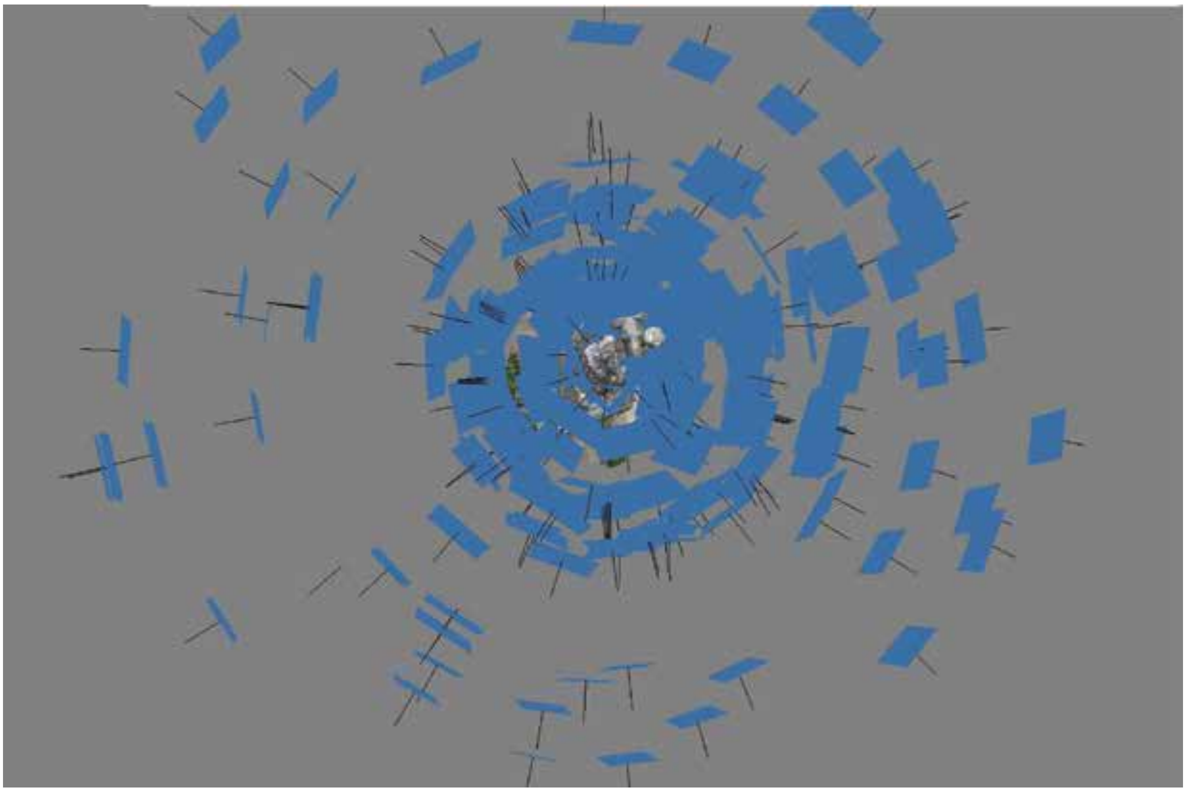
Today a wide range of sensors and the development of informatics[7] have increased the performance of photogrammetry and automated many processes with good results. The modern techniques of Structure-from-Motion (SfM) open new perspectives in the field of architectural documentation and Computer Vision algorithms are ready to be used by non-technical users [Westoby, 2012].

SfM is a range imaging technique that allows us to reconstruct three-dimensional models starting from points extrapolated from two-dimensional images. Starting from a set of photographic images it is possible to rebuild a 3D model. Building the models consists of recovering 3D camera positions related to pictures and 3D positions of the content of the images; this is done by identifying similar content between N views, and solving 3D geometry problems.

Since the model is derived directly from photos, an accurate acquisition of the images is necessary, remembering that a point must be rebuilt in space if visible in at least three images. During this phase, the object is fixed, and the user moves around it in order to photograph the object from a different point of view. Clearly, all the photos must be correctly focused.

For each model, about 200 photos around the statue were taken for reconstruction (fig. 3). Generally, the images are taken from below, also using extendable pole photography to reach the higher parts. In this case, it was possible to capture detailed images (e.g. of the head) by the scaffolding used for cleaning; all the photos were taken by using a digital reflex camera Canon EOS 7D equipped with a 28 mm lens.

The first step is "images alignment": Image Matching algorithm searches the features between pictures and matches them. Structure-from-Motion estimates the relative camera position from the matched anchor points computed in this step, and at the same time it builds the sparse point cloud (fig. 4), that is an initial 3D representation of the scene. This step has needed one hour approximately, and it has produced a sparse point cloud of 15366 points. Multiple View Stereovision computes a dense representation of the scene by generating point clouds on the esti-



3

Fig. 3. The camera position around the statue.

Fig. 4. The phases of reconstruction of the model.
From the left to the right: sparse point cloud; dense point cloud; the mesh and the textured model.

4

mated position of the camera. This step has increased the point cloud up to 8000000 points, because the cloud directly derives from photographic images, it will be coloured.

Based on this last step, the software computes the "reconstruction of the 3D polygonal mesh". After the geometry (mesh) is generated, it can be textured using the initial photos. Texture mapping is a way to add surface details, for example colour information, projecting one or more images onto the surface of the 3D model. As a result of the process a model of 18500000 faces and a 2048 x 2048 pixel texture have been created.

The following step is "mesh decimation", removing detached components, close mesh holes, and other filtering operations and MeshLab, an open source system for processing and editing 3D triangular meshes, provides many useful tools for processing digitized 3D data. After the basic processing, the number of triangles has been reduced (2000000 faces) and can be easily usable on the web platform. It is not necessary for an online presentation to have an extremely high-resolution model, since its reading (colour, materials, etc.) is guaranteed by the presence of the texture that adds surface details.

3DHOP (3D Heritage Online Presenter)

Thanks to the recent advances in the web technology, it is much easier to offer the integration of 3D content in a web platform. The ease of displaying three-dimensional models without the installation of specific applications/plug-in has increased the use of the web platform for dissemination, teaching, and presentation of research results, also in the field of cultural heritage.

We chose to use the 3DHOP platform for Villa Corsi Salviati Guicciardini statues models, one software developed by the Visual Computing Lab of ISTI-CNR (Pisa). 3DHOP is a software platform able to cover the project requirements for the publishing of 3D data: a simple creation of the web pages, the ability to interactively show complex 3D models, and the possibility to link other data on the 3D scene, to present to the user the project information. For the use of complex three-dimensional models, the platform provides a multi-resolution approach which allows us to optimize network rendering and transmission speed. When the page is loaded, the 3D model is initially displayed at low resolution, and the quality increases the more the user stays on web page and moves closer to the surface.

Into 3DHOP, it is possible to insert clickable hotspots: as this is a widely available feature in web pages, it is usable also by naïve users, without specific instructions. On the statue's models, the clickable hotspots were used to allow the user to see the areas of the statues that have been used for test measurement for the various diagnostic techniques, focused at the assessment the state of conservation, and at the monitoring the protective treatments applied on the surface. For each technique, a pop-up describes in a simple way how the methodology works, and how it is used in the field of cultural heritage. The hotspots were divided into different classes, according to the techniques used:

- sampling (for the characterization of the materials that make up the statue);
- water absorption tests (for the evaluation of the efficacy of conservative treatments and their time durability);
- and colourimetric tests (to determine the interaction of the treatments with the material in terms of colour variation).

5

Fig. 5. The clickable hotspot on the model (right) and the information regarding the techniques used (left).

About the interface: clicking on the right menu, makes the hotspot visible, in a different colour, on the model; on the left of the window, is possible to read all the information regarding the selected technique (fig. 5). Clicking on the hammer icon of the right menu, the micro-sampling areas are shown on the model; the left panel explained why micro-samples are taken and the techniques used for the survey.

The other hotspots show the results obtain by the observation on polarized microscopes. For other techniques, only the methodology works are described because the data is still being processed. The information provided is general and are not related to technical details, purposely for professional and common users.

Conclusions

The documentation of cultural heritage is the basis of any policy of protection, restoration, and valorization. It has the aim of acquiring the information necessary for a good understanding of the asset, for both the scientific community and the general public. In this perspective, the scientific results of research projects should also be accessible but, due to the specificity of the results, it is sometimes problematic. For this reason, we chose to use an easily accessible web platform that could directly show the three-dimensional model of the asset, normally located and visible only on private property, enriched by information on the techniques used for material knowledge and conservation.

NOTES

1. Historical garden member of Adsi (Association of Italian Historical Residences).
2. The garden contains stratifications and transformations of successive stylistics since the 1500s.
3. http://www.icvbc.cnr.it/salviati/ (date of access: 11 March 2017).
4. http://www.agisoft.com/ (date of access: 11 March 2017).
5. http://www.meshlab.net/ (date of access: 17 June 2017).
6. http://vcg.isti.cnr.it/3dhop/ (date of access: 11 March 2017).
7. As new software and image matching algorithm.

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ABSTRACT

DIGITAL MODELS FOR PUBLISHING OF RESEARCH PROJECT DATA. THE CASE OF VILLA CORSI SALVIATI GUICCIARDINI IN SESTO FIORENTINO
Creating a digital model of an object allows us to get an accurate "copy" of it, both in shape and colour. The online interactive visualization of these models is a powerful dissemination tool that allows us to visualize the object in all its parts and to easily communicate the methodologies used and the results obtained in scientific projects and research.
For the project "La Conservazione programmata dei Beni Culturali lapidei in giardini storici. Progetto di ricerca e definizione di protocolli", the models of case studies, normally not visible because they are in private ownership, can be viewed on-line and include information about the project and the methodologies used for characterization Conservation status and monitoring of conservative treatments.

MODELLI DIGITALI PER LA PUBBLICAZIONE DEI DATI DEL PROGETTO DI RICERCA. IL CASO DELLA VILLA CORSI SALVIATI GUICCIARDINI A SESTO FIORENTINO
La creazione di un modello digitale di un oggetto permette di ottenere una "copia" fedele dello stesso, sia per forma che per colore. La visualizzazione interattiva online di tali modelli costituisce un potente strumento di divulgazione che permette di visualizzare l'oggetto in tutte le sue parti e di comunicare, in maniera semplice, le metodologie utilizzate e i risultati ottenuti nei progetti e ricerche scientifici. Per il progetto "La Conservazione programmata dei Beni Culturali lapidei in giardini storici. Progetto di ricerca e definizione di protocolli", i modelli dei casi studio scelti, normalmente non visibili perché posti in proprietà privata, possono essere visualizzati online, e su di essi sono riportate le informazioni relative al progetto e alle metodologie utilizzate per la caratterizzazione dello stato di conservazione e il monitoraggio dei trattamenti conservativi.

KEYWORDS
conservation, *digital model*, *communication*, *visualization*
conservazione, *modelli digitali*, *comunicazione*, *visualizzazione*

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ACCESSING AND INFORMATION SYSTEM

A 3D-based Information System to manage conservation and "lifecycle" of the Neptune Fountain in Bologna

Fabrizio Ivan Apollonio, Vilma Basilissi, Marco Callieri, Dora Catalano, Matteo Dellepiane, Marco Gaiani, Federico Ponchio, Francesca Rizzo, Roberto Scopigno, Giorgio Sobrà

The Neptune Fountain is the most symbolic monument of Bologna, jointly with the two towers. Commissioned by the bishop Pier Donato Cesi, the fountain is the latest episode in a strategy of urban renewal which redefined the appearance of both the central city area and the Piazza Maggiore. These architectural interventions were conceived to be an expression of the good government and munificence of the Pope Pio IV [Tuttle, 2015]. The design and construction of the Neptune Fountain was entrusted to the cooperation of two artists, the architect and painter Tommaso Laureti and

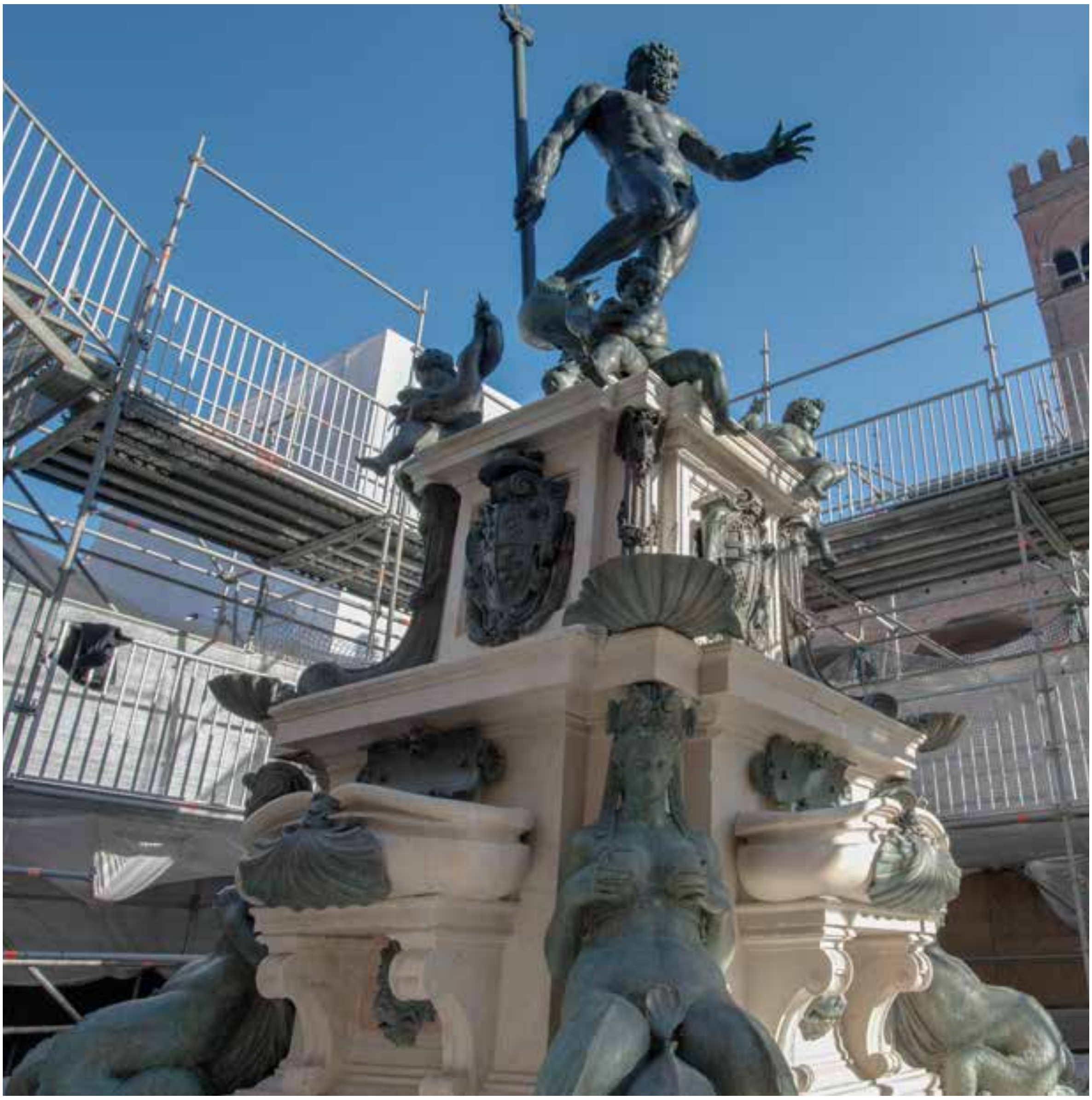

Fig. 1. The Neptune Fountain in Bologna during the restoration works. *Photo Angelo Rubino, ISCR.*

TORNA AL SOMMARIO

the Flemish sculptor Jean de Boulogne of Douai, known as Giambologna. In less than five years – from 1563 to 1567 – they built one of the most spectacular example of Renaissance fountains still existing (fig. 1).

It is an artifact extraordinary in size (a pyramid structure 10.50 x 10.50 x 8.50 meters), for quality of details, for engineering expertise in both the static and in the hydraulic system, capable of conveying to the jets over 2 l/sec without pressure machines.

Faced with the obvious state of deterioration besetting the Neptune Fountain, the Municipality of Bologna started a new conservation project in 2015 with the aim not only of restoring the surfaces, but also to analyse, maintain and adapt structures, hydraulic system and underground areas. The Municipality individualised the developement of an Information System (IS) to support the complexity that characterizes the monument and the conservative work operated by the multidisciplinary team set-up for the diagnostics and restoration (restorers, architects, arts historians, conservation scientists, hydraulic engineers, structural engineers, geomatics experts, computer and information scientists).

Therefore, University of Bologna, ISTI-CNR and ISCR-MiBACT (Institute for Conservation and Restoration) jointly designed a 3D-based IS providing innovative, efficient and user-friendly management of the entire process of collecting, preserving and retrieving the technical/scientific data related to the diagnosis and management of the restoration. The IS allows to share in 3D and in real time systematic georeferenced data able to completely support the process of study, restoration, communication and, later, maintenance operations of the intervention on the Fountain. Furthermore, the platform permits the integration of processes which are usually separated and supports the ongoing collaboration among the stakeholders in different typologies of restoration and maintenance interventions on cultural heritage.

Working assumptions

The restoration of the Neptune Fountain represents a good-practice example of how a documentation platform should be designed, involving its potential end users from the very beginning. We aimed at implementing user-friendly solutions [Matera *et al.*, 2006] related to two different documentation issues: enabling the archival of documentation concerning the complex and deep analytic process; conceiving restoration as a complicated process, based on the integration of a wide variety of skills and experiences. Therefore, a common data management platform was needed to support the collaboration of this interdisciplinary team. This involves an easy access to shared documentation, concerning both the data produced continuously during the activity as well as the available recording of past actions.

The digital platform concept integrates the two issues in a comprehensive solution developed starting from the analysis and representation of the entire real workflow planned for the restoration of the Neptune Fountain. The interface offers a holistic view of this workflow and supports it by supporting the operator in each phase of the workflow.

The final goal of the digital platform is to become the unified information reference not only for today conservation and restoration needs, but for a multifaceted process related to the entire artwork "lifecycle": from knowledge to use, from communication to management, from restoration planning to maintenance [Benedetti *et al.*, 2008]. Overall, the emerging model is that of a container of global knowledge, shared and made available at any time, in any place, to any user.

To fulfil this requirement the digital platform has been designed to be used both on the field and from remote locations, with low-end laptops and limited network bandwidth to allow everywhere and every-time access, mainly to follow the day-by-day work of restorers and by means of their usual devices. An easy and real-time access to the documentation (i.e. as soon as a member of the team adds some insight, it should immediately become visible to the rest of the group) should allow a fully understanding of the progress status and an easy monitoring of the evolution of the restoration.

A key issue concerns the 3D nature of large monumental complexes, such as the Neptune Fountain. This complexity in shape and extent makes very hard to obtain a full description of the artifact, as well as the management of the related textual and graphical representations (basically drawings). The starting point of the work here described is the attempt to provide a solution to this limitation.

The proposed solution is the use of the 3D digital model as a tool to index, organize and retrieve the available data and documents, starting from the observation that a 3D

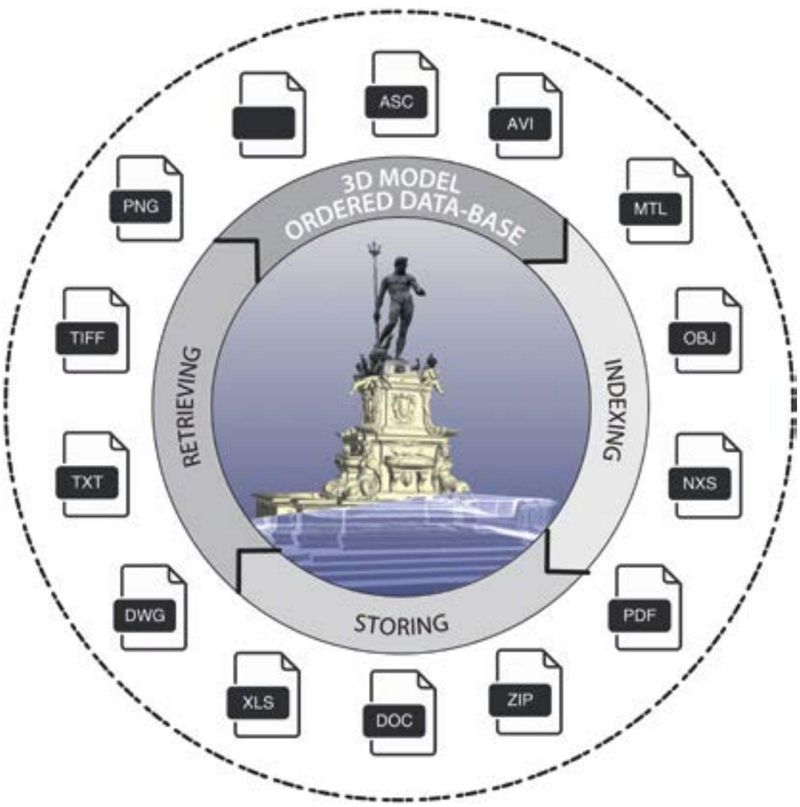

Fig. 2. The conceptual model of the 3D digital model.

2

model could be considered as a large, ordered database of spatial information, potentially also evolving over time (fig. 2).

3D models allow to visually represent numerical data, as well as abstract notions; they serve as a platform to test hypotheses (not only reconstruction, but also deconstructions and alternative interpretations); allow to integrate different types of data in a visual form. A 3D model is, by its own nature, a highly intuitive interface to an IS, describing the object represented by means of geometric and visual elements, which can be easily interconnected with all the other information/data assets. It allows to present information within an appropriate "context", allowing to link 3D objects with heterogeneous data of various kinds, and enabling users to perform searches based on the context and the content (semantic) [De Luca *et al.*, 2007].

Finally, a key notation is that a replica-style 3D model (i.e. the availability of a digital model that satisfies some given fidelity constraints concerning both shape and surface colour/texture) could became, in any moment, a physical prototype ensuring a continuous flow between the ideal and the real, thus providing constant interaction between "knowing" and "doing".

Design of the Information System

The solution proposed for the Neptune Fountain is a web-based IS. It uses the 3D media to support, in an innovative and user-friendly manner, all the phases of work (documentation acquisition/production, archival, search and consultation). The main goal is to be able to support the entire "lifecycle" of the restoration-related documentation process.

Our platform allows to archive and access geo-referenced data, using the 3D model as a spatial index to the data stored. Since we had a very complex test-bed to manage, it has been necessary to structure our representation in a hierarchical and decomposed manner (as presented in detail in the following paragraph). Therefore, the IS allows to store and consult the data either by looking to the entire monument, or by going down to smaller and smaller components.

According to the quality of modern digitization technologies, the resolution and accuracy of digital 3D representations might allow the experts to analyse the conservation conditions nearly with the same accuracy and precision available when they are on site, in front of the artwork (fig. 3).

To reach this goal we need 3D models providing a high-fidelity encoding of both the shape and surface colour/texture characteristics of the artwork. Obviously, we do not aim to replace the visual analysis performed by the expert over the real artwork. But a high-quality digital clone could be precious in all those cases the expert is not on the site (to check hypothesis and details in real time, avoiding to just rely on personal visual memory); or, when he is on-site, to allow to take geo-referenced notes during a real inspection session. Moreover, once we have a digital model, we can also go beyond visualization, providing features for taking measures, for data onsite comparison, for shape analysis, etc. [Scopigno *et al.*, 2011].

The base of the Neptune IS is a very accurate and high-resolution 3D model featuring 610 million triangles and a geometric accuracy of the surface of 0.2 mm. Hence, a multi-scale acquisition strategy was used [Callieri *et al.*, 2011]: each single component was acquired with an Eva Artech Scanner by University of Bologna and Studio MCM. The global model produced with a terrestrial laser scanner acquisition (produced at a lower density than the former ones) was used as a reference to strengthen the global alignment of all the components (sampled at much higher density). All the subsequent 3D data processing work on the sampled data was done using MeshLab, the open-source software for the visualization and editing of 3D models developed by ISTI-CNR [Cignoni *et al.*, 2008].

Consequently, our IS is based on the marriage of a classic relational database (used to categorize, structure, archive and access all the data) and a sophisticated 3D graphics interface, providing an interactive spatial index to the stored data, as well as supporting easy geo-tagging of each information token.

Concerning the system architecture, our work was simplified by the possibility of developing a custom system

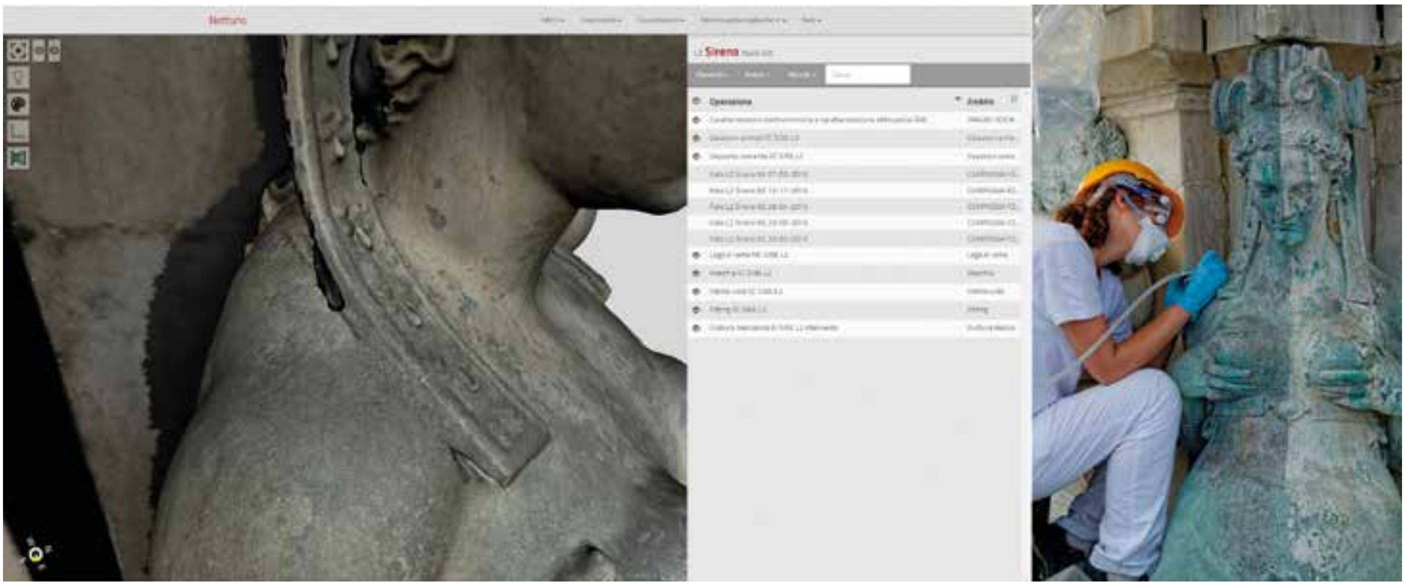

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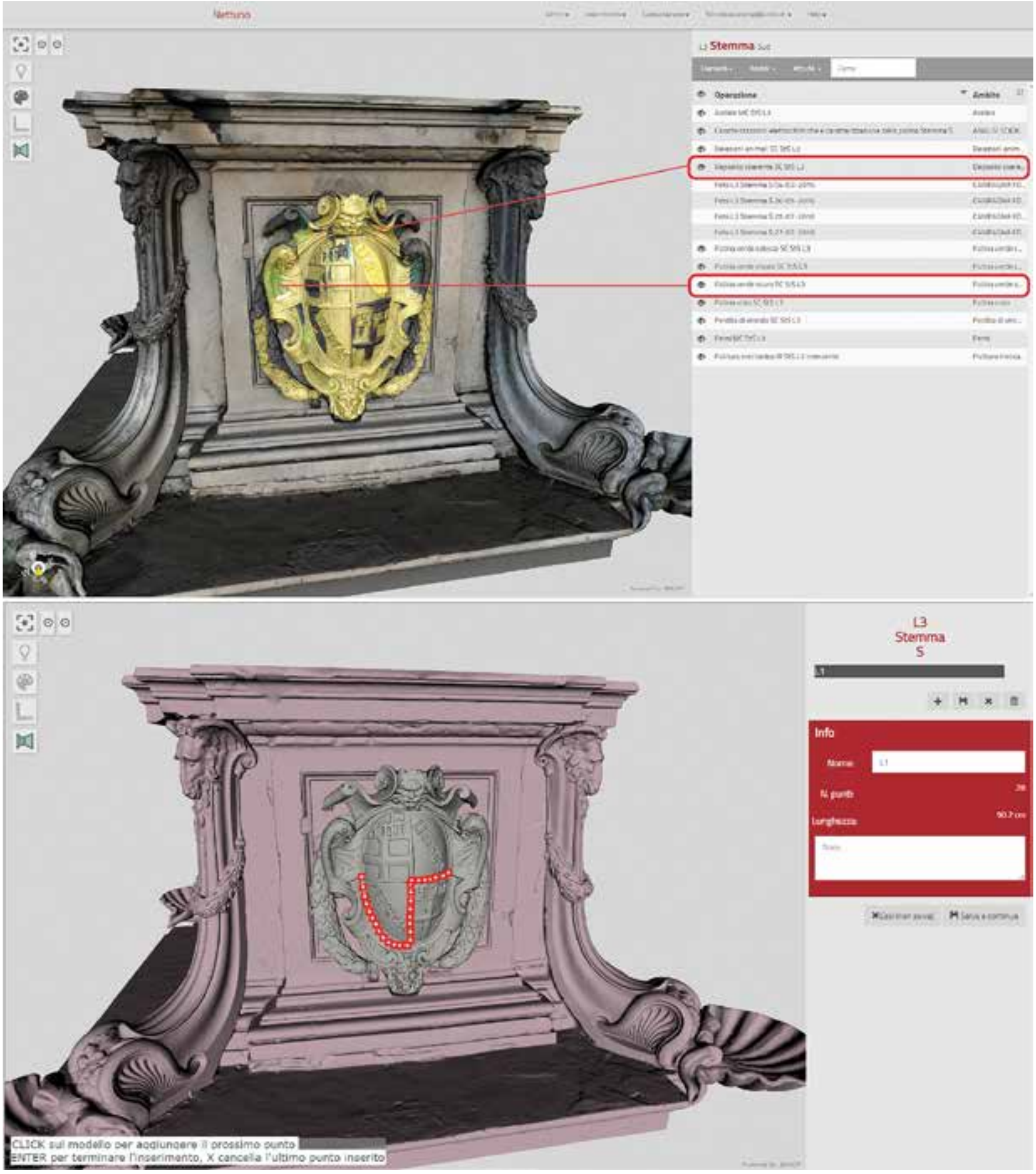
Fig. 3. Inspecting a detail on one of the Sirens (left) and cleaning the same area in the restoration (right).

TORNA AL SOMMARIO



4

Fig. 4. Tools for searching, visualizing and creating links, which interconnect the different information tokens (above); tools aimed at producing graphical characterizations over the surface of the artwork (below).

(which can be easily configured to the specific needs of the user community), rather than having to define the system on top of a generic platform, designed for different scopes (such as the common GIS platforms often used in restoration documentation). In our case, we have been free to select and implement only the needed set of functionalities on top of a 3D platform. The reduced set of functionalities has the advantage of requiring a much simpler and neat interface, thus allowing a much less steep learning curve.

The IS has been designed to support a set of basic functionalities as the following:

– browse the 3D representation, in real time and at full visual and geometric quality;
– provide easy tools to create the links, which interconnect the 3D model with the different information tokens (texts, pdf documents, scientific analysis reports, images, graphs, drawings) either related to the current restoration or to previous restoration actions;
– support the production of graphical characterizations over the surface of the artwork, i.e. draw points, lines and regions, with associated metadata introduced as annotations (fig. 4).

The IS has been designed as a web-based multi-user system (with user credentials and identity management). The system has been implemented on top of HTML5, PHP and WebGL, which provide resources for an efficient design of a web-based GUI (Graphical User Interface) and the efficient visualization of 3D models.

Moreover, since we need a dynamic system able to ingest multiple types of information tokens, we need an underneath infrastructure based on a standard relational database, that will store references to all 3D data, to all information tokens

TORNA AL SOMMARIO

ingested or annotated by the users and, finally, to all the links created among the 3D space and the information tokens.

An efficient visualization of the high-resolution 3D models is obtained by endorsing the 3DHOP platform [Potenziani *et al.*, 2015]. Rendering performances allow to manage models composed of hundred million triangles in real time on standard laptop computers.

Users' requirements have been the basis for the design of the Neptune IS. The platform should allow users to:

- access, directly from the physical context in which they operate, data and information on the artwork/monument under study; those data could pertain to previous or current interventions, to its history, following current preservation and conservation rules and norms;
- users should be free to move back and forth from data retrieval to data creation and uploading;
- the platform should be accessible from portable devices connected to internet.

Data organization and interface of the IS

The Neptune IS structure is based on a 3D model of the monument built and organized as a semantic cognitive system. A "knowledge system" of a monumental asset can be described as:

- a collection of objects, identified through an accurate and shared lexicon;
- subdivided in sub-elements considering the shape and structural analysis of the object, as well as the artwork construction characteristics (typological, morphological and constructive);
- organized in hierarchical levels of aggregation and classification.

The approach used within the IS arises from a broad number of experiences carried out over the last years [Apollonio, 2016], dealing with a wide set of objects ranging from simple bas-reliefs to entire buildings.

The hierarchical scheme obtained represents the semantic structure of the IS for the management of the data collected and is modelled with the aim to be flexible to allow subsequent modifications and to manage different types of documents. The process that led to the segmentation of the Neptune Fountain was divided in three steps:

- analysis of the fountain, to identify the characteristic features of its formal and constitutive structure;
- delimitation of the constituent elements, defining a hierarchical structure at several levels;
- labelling of the individual identified elements using a shared lexicon and solving cases of ambiguity in the presence of serial and repetitive elements in the monument decorative apparatus.

The user interface is a key point of the project because it is designed as a 3D virtual space in which to collect data, inverting the usual mode of visualizing information on a web browser (interactive navigation rather than a usual query interface). Therefore, after the selection of an element or an area on the 3D model, the user is presented all the data information tokens related to that specific selected item. Given the availability of a digital 3D replica, interactive navigation is the more intuitive and easy way to browse also over the stored data.

The GUI is composed of three parts: the 3D model visualization window (on the left-most part of the window), the navigation bar (on top) and the data and query frame (on the left). For each selected monument component, the system shows in the left-most frame all the documents

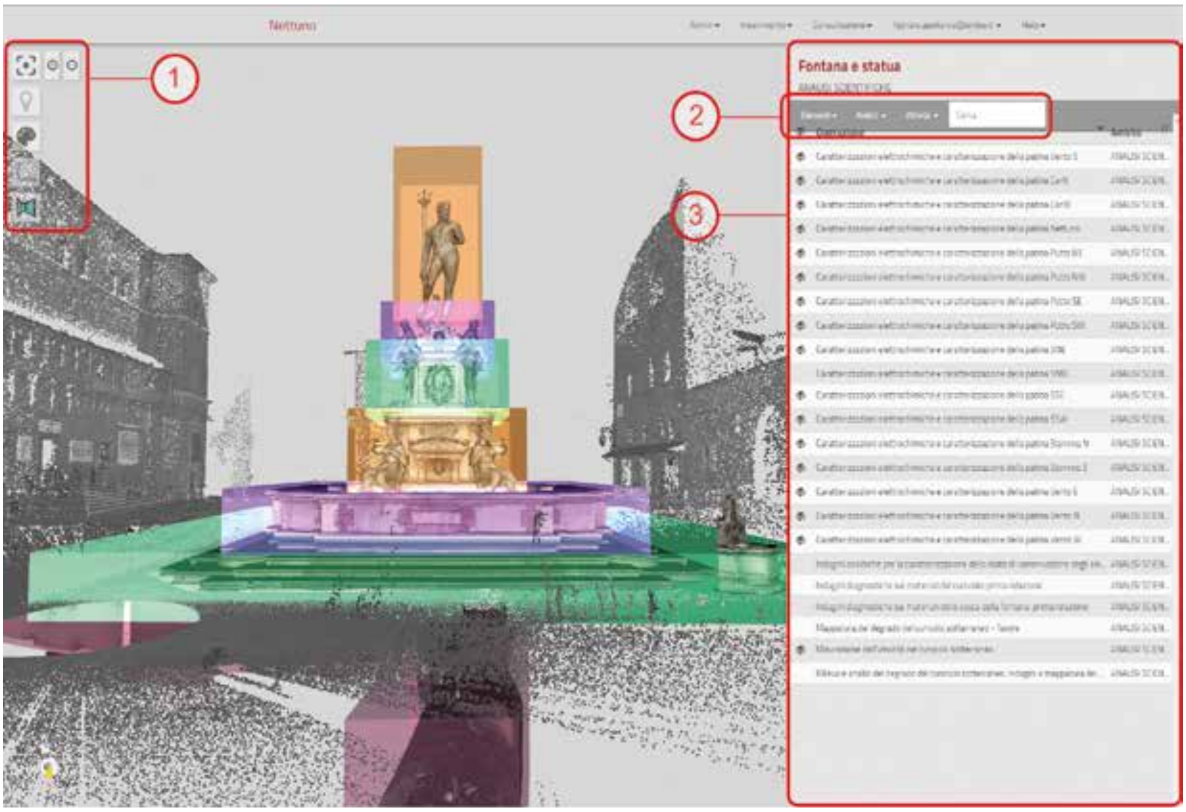


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Fig. 5. GUI key features: buttons to drive the interactive visualization (1); retrieving/searching menu (2); list of records stored in the IS and related to the selected element (3).

TORNA AL SOMMARIO

and data related to the current component; for each one of these users can toggle (on and off) the visualization on top of the 3D model (fig. 5).

Feedback gathered with the real test-bed

The model of interaction implemented on the Information System represents one of its most innovative features. In fact, the study of the users' needs and their contexts of work is at the basis of the development of the platform concept: supporting the needs and requirements of all specialists involved in the restoration process, to be used as an everyday instrument.

Therefore, the platform has been developed starting from the real process of restoration of the Neptune Fountain, taking care of its characteristics and of the real needs of the end users. The design of the IS functionalities and GUI was achieved adopting a User Centred Design (UCD) approach based on cycles of design, prototype evaluation and re-design. This UCD process has been carried on by involving users in testing the different interfaces with the aim to continuously improve the platform model of interaction until the achievement of the level of usability was considered proper.

The users have appreciated the possibility to analyse and inspect the digital 3D clone downloading very complex 3D models in a transparent manner, together with the scientific investigation data produced by the different members of the staff. Moreover, the possibility to perform this activity directly on site was evaluated as a crucial innovation for the restoration workflow. Those features facilitate the interaction with a flow of information produced by different devices, different experts and in different conditions, thus supporting a real collaborative effort. All this using standard level of connectivity granted by normal internet connection and speeds.

Concerning the interaction model, other elements that have be positively evaluated by the users are: the geo-referential mapping, extremely useful in the phase of diagnostic surveys, for the uploading of data or annotations on the conservation status; the possibility of cross-comparing easily the results of different diagnostic results, enabling new interpretation of data and facilitating the restoration activity; the management of the deconstruction of the monument in different elements that facilitates the mapping activity, allowing correct allocation of the objects in the surrounding context.

A second set of relevant features for the end users are those referred to the data integration and retrieval supported by the platform. In particular, users appreciated: the possibility to have functionalities for archival, retrieval and interactive access to different typologies of documents on the same interface (text, photos, graphics/drawings, pdf documents); the possibility to visualise graphic maps together with annotations and photos; the efficient and simple GUI for data acquisition and correlation; the immediacy of indexing and accessing data even on a very large-scale test-bed.

Finally, interviews with users showed that most of the users did not experience difficulties both in the consultation process (retrieving information), as well as in the data entry phase, thanks also to the high level of usability of the GUI (readability, clarity of the commands and the easiness of execution of the available functions).

Finally, we present some data on the use of the IS so far. Since the first version was delivered on June 2016 we have data concerning the first months of use[1]. In this period, more the 2000 high-level data entry operations have been performed on the system, creating more than 20000 digital objects. This latter datum includes both the single high-level assets (such as photographs, text or pdf documents) and the low-level elements stored in the database (e.g. all the regions produced by the restorers when they draw a relief are single small polygons defined in 3D space and stored individually in the underlying database).

Conclusions and future work

The Information System described in this paper has been designed and implemented to support a specific restoration project. On one side, this is a positive characteristic, since the design of the system has taken into account the needs of the typical users from the very beginning. The design has been driven by the users and, luckily, the results of the early evaluation have been very positive, demonstrating a high level of acceptance by the restorers and other operators. On the other side, the system has been designed for a specific restoration case (a very complex one indeed), originating the risk of a too much test-bed-specific design.

Our future work is to use this experience to derive a more generic system from the work done for the Neptune, which could become an open-source resource shared with the restoration community. We plan to define a service with a very easy customization interface, able to offer the functionalities described in this paper to a wider audience.

NOTES

1. The Neptune Fountain restoration was not terminated at the time we was writing this paper (July 2017).

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ABSTRACT

A 3D-BASED INFORMATION SYSTEM TO MANAGE CONSERVATION AND “LIFECYCLE” OF THE NEPTUNE FOUNTAIN IN BOLOGNA
We describe the Information System developed for the management of the “lifecycle” of the Neptune Fountain in Bologna. This system adopts the 3D digital model as main interface for collecting, recording, archiving and retrieving data related to the monument. The paper describes the system features and reports some early evaluations and feedbacks received from the operators who used it during the ongoing restoration.

UN SISTEMA INFORMATIVO BASATO SUL 3D PER LA GESTIONE DELLA CONSERVAZIONE E DEL “CICLO DI VITA” DELLA FONTANA DEL NETTUNO A BOLOGNA
Nel corso del restauro della Fontana del Nettuno a Bologna è stato sviluppato un Sistema Informativo per la gestione del “ciclo di vita” del monumento, che adotta il modello digitale 3D quale interfaccia privilegiata per la raccolta, l’annotazione, l’archiviazione e l’interrogazione dei dati. Il contributo presenta le caratteristiche del Sistema Informativo e fa un primo resoconto delle valutazioni emerse dagli operatori che ne hanno fatto uso.

KEYWORDS
restoration, conservation, Information System, 3D, communication, management, Neptune Fountain, web-based
restauro, conservazione, Sistema Informativo, 3D, comunicazione, gestione, Fontana del Nettuno, web-based, design centrato sull’utente

ACCESSING AND INFORMATION SYSTEM

Robotic and Virtual Reality for cultural heritage digitization and fruition

Daniele Calisi, Fabio Cottefoglie, Lorenzo D'Agostini, Francesca Giannone, Fabrizio Nenci, Paolo Salonia, Marco Zaratti, Vittorio Amos Ziparo

The conservation of cultural heritage sites is an important goal for both scientists and the general public and is a complex task that involves activities in the field of knowledge gathering, prevention and monitoring, and that requires the cooperation of several actors (i.e., surveyors and cultural heritage professionals) as well as inter- and multi-disciplinary approaches involving diagnosticians, restorers, art historians, chemists and architects.

Monitoring activities of the involved sites, in particular, play a key role as they allow to study and analyze the causes, the effects and the progression of the decay of a target heritage site. Data acquisition, processing, and maintenance are crucial issues in monitoring: in a typical scenario, surveyors access heritage sites with a number of different sensors, such as laser range finders or cameras, to collect all the required data. While this is acceptable for accessible sites, although it may require a very long time and many human resources, it limits the digitization of sites that are difficult to be accessed by humans.

The data gathered in this way is then processed in several different ways with the aim of extracting consistent and meaningful information: for example, accurate models of such sites, that are often a prerequisite for prevention, maintenance, restoration, and security tasks. In this phase, a lot of manual labor is currently needed to align scans, to create annotations, or to reconstruct textured meshed models, due to the intrinsic complexity of the algorithms involved and to the possible incompleteness of data.

The models obtained in this way are often used only for the purposes of a single monitoring task, although they have a broader exploitability, both in terms of intended uses and from a temporal point of view. This is due to the


1

Fig. 1. Multimodal interface in the Priscilla Catacombs.

difficulty of managing and sharing these models and of taking advantage of them without specific technical tools.

In the fields of Robotics, Artificial Intelligence, and Virtual Reality there has recently been an important progress in the development of robotic and automated technologies, as well as visualization techniques that can support and improve the efficiency of this task from different points of view. Leveraging on these improvements, we elaborated a paradigm which aims at improving efficiency and safety of monitoring activities and exploitability of the results through the development of novel technologies for exploration, digitization and visualization of cultural heritage sites. Our solution has been designed and developed during an FP7 European Project, called "ROVINA", that started in 2013 and is now successfully concluded. This project involved four academic partners (the University of Bonn, the Rheinische-Westflische Technische Hochschule of Aachen, the Katholieke Universiteit of Leuven, the Sapienza University of Rome), one company (Algorithmica s.r.l.) and the non-profit International Council of Monuments and Sites (ICOMOS).

Although our system has been thought for any indoor or underground archaeological site, that is difficult to be accessed by humans, or that is complex to be digitized using the common surveying strategies, we selected catacombs as case studies. Catacombs, indeed, are peculiar sites because i) they are rich in both geometrical and texture features, such as *loculi*, chapels, tunnels, frescos, and epigraphs; ii) they are challenging for navigability issues; iii) they often extend for several kilometers and at multiple depth levels. For example, the Roman Catacombs of Priscilla, that has been selected as our primary test site, extend for approximately 15 km over multiple floors.

State-of-the-art

Conservation of cultural heritage sites is a practice that encompasses several disciplines ranging from material theory to structural engineering. Although it is not feasible to provide a complete overview of the state-of-the-art, in order to place our system in context, we will provide a brief introduction to the major activities involved in the conservation of cultural heritage sites: measure, documentation, classification, and diagnostics.

Measuring is a key building block of any surveying activity. There are two types of measurements: "direct" and "indirect" ones. While direct measurements are performed directly (and manually) by the surveyor on the artifact, indirect measurements, on which our system is focused, entail the construction of a digital model of the involved artifact [Martinelli, 2006] in order to perform measures on it. Those models are usually obtained through the use of laser scanning and/or image analysis: both methods allow for morphometric surveys [Drap *et al.*, 2003].

Laser-based systems are common for architectural conservation [Barber *et al.*, 2006] and offer a wide variety of technologies (time-of-flight, phase modulation, optical triangulation, etc.) to adapt to the specific task (e.g., surveying large environments or digitizing small artifacts) and accuracy needed. These sensors can be rather expensive but offer a high precision and direct access to 3D information [Johansson, 2002]. Image-based systems have been shown to provide precisions similar to those of Lidar scanners, especially when a sufficient number of images close to the surfaces can be taken. They have the advantage that image/colour data are available, that are perfectly aligned with the 3D data. The captured data – as for lidars – produces point clouds that need further post-processing. Image-based systems usually employ high-resolution commercial cameras and commercial photogrammetry software or, more recently, self-calibrating Structure-from-Motion systems [Vergauwen *et al.*, 2006; Theo Moons *et al.*, 2008] or multi-view stereo approaches. These approaches are lower cost solutions compared to lasers, but can still provide high-quality reconstructions especially for what concerns appearance.

Documentation is the goal of many surveys and aims at producing digital archives of the site under observation. In the realm of cultural heritage, documentation activities are performed by public bodies that, for example, in Italy usually are Superintendences and Ministries. The digital archives can host contents in many different formats, including 3D models that can be either purely geometric or can also include textures from images. When the surveys have a purely descriptive documentary purpose, i.e., they are not intended for measurement or diagnosis, 3D models can have a lower resolution but they are, in general, more visually appealing. Their main goal is to disseminate cultural heritage to broad audiences, but also support archaeological interpretation [Beraldin *et al.*, 2005].

Classification activities are usually tied to documentation tasks and pertain to the categorization of elements of a site into taxonomies or ontologies with different degrees of complexity. For example, in an industrial context, it would be interesting to categorize rooms of a plant – and equipment therein – based on their functional properties. In a cultural heritage site, architectural components are classified on the basis of a number of different parameters such as the period of construction, used materials, state of conservation: this classification is usually performed by human users, who manually tag items and portions of the environment. When data is collected on a geographical scale, the models are generally archived into Geographical Information Systems (GIS). In such a scenario, data can be queried on both geographical and qualitative levels. For example, one may look for "all the sites built before 1000 BC in Italy" or "all the pots made of ceramic from Germany".

Diagnostics has the goal to collect and analyze the information about the state of conservation of the surveyed areas in order to prevent damage or perform the restoration. From a practical perspective, the diagnostic activities have the purpose of generating specific deliverables. Examples of such deliverables in the context of cultural heritage are the Table of Deterioration and the Table of Materials. The Table of Deterioration is a map showing possible deteriorations such as cracks and mold. In Italy, the table

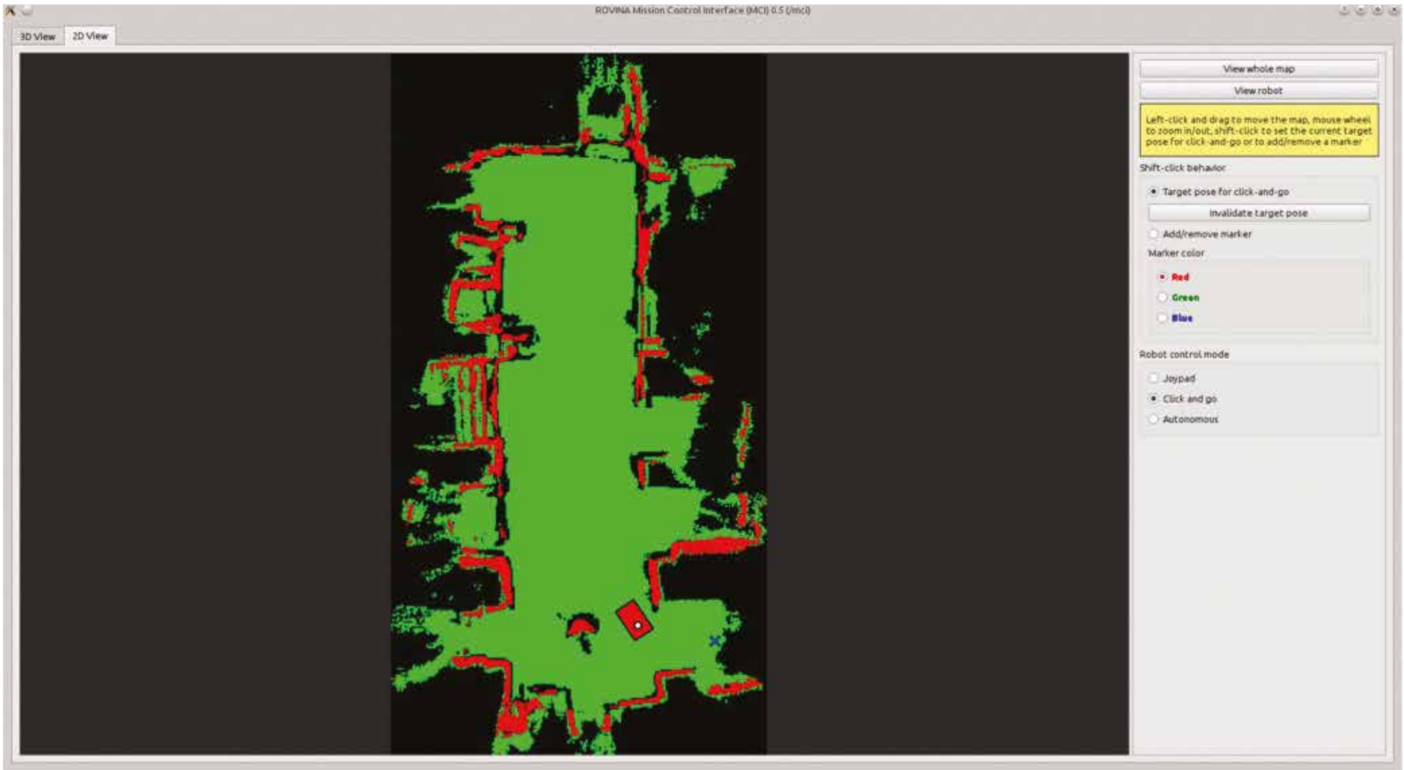

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Fig. 2. Supervisory interface.

follows the UNI-NorMal commission standards, that is composed by the "Ente Nazionale Italiano di Unificazione (UNI)" and the "Commissione NORmalizzazione MAteriali Lapidei (NorMaL)". At a European level, the standards are dictated by CEN (i.e., WS Construction, WS Measurement, WS Material). The Table of Materials instead maps the areas of the site under survey to the different materials of which they are composed.

The ROVINA paradigm

Our project aims at improving the state-of-the-art in measuring, documentation and classification (and thus indirectly supporting diagnosis activities) through a novel approach to surveying, data management, and fruition based on three main components:

- DigiRo, an automated robot for collecting data with high-precision sensors, including laser scanners and cameras;
- ARIS, the cloud-based Archaeological Information System, to manage, share and elaborate data in the form of photo-realistic and metrically precise 3D models of the explored sites;
- Web and VR Visualizers, that allow to virtually navigate the 3D models through a very intuitive interface which also allows for an immersive experience.

DigiRo: the digitization robot

While there have been many attempts in the past to use robots to explore hard-to-access sites [see, e.g., Thrun *et al.*, 2004], DigiRo is one of the first platforms specifically conceived for performing methodological surveys of unknown cultural heritage sites.

DigiRo development has been based on one hand on an iterative design process of the robotic platform and on the other hand on the integration and development of novel algorithms that extend the current state-of-the-art in autonomous mapping and localization, 3D reconstruction and on-line analysis. During the last year of the project the robotic platform went through its third and last iteration of a continuous process that has been guided by the requirements dictated by the analyses of the environments being explored: we thus equipped a commercial tracked mobile base with a sensor suite composed by an inexpensive 3D laser range finder, three low-budget RGB-D cameras, an array of 7 high-quality RGB cameras, an inertial measurement unit, battery status monitors and thermal/humidity sensors.

In addition, the robot is also equipped with a distributed computation system that includes: two laptops, one for running the algorithms in charge of the autonomous behaviours and another for logging the data coming from the array of cameras. Three inexpensive single-board computers are also on-board, their role is to pre-process sensor data and to interface with the other hardware components of the robot.

In order to allow DigiRo to survey archaeological sites in an autonomous or semi-autonomous way, several challenges had to be addressed, and dedicated computer vision and robotics solutions have been developed. At the core of the platform intelligence, there is the capability of simultaneously building a 3D map of the environment and localizing within this map (SLAM). DigiRo SLAM module extended different so-far state-of-the-art components such as g2o [Kuemmerle *et al.*, 2011], DCS [Agarwal *et al.*, 2014] and a variant of ICP [Serafin *et al.*, 2015], thus obtaining a novel 3D localization and mapping approach. Compared to most existing SLAM methods, DigiRo SLAM module builds 3D maps in real-time during the survey allowing the robot to act autonomously and enabling its own decision-making based on the environment explored so far. A considerable effort has been devoted in making the approach more robust and developing an extension of DCS, originally proposed by [Agarwal *et al.*, 2014], to assessing the degree of consistency of maps [Mazuran *et al.*, 2014] and to automatically calibrating the sensors [see also Basso *et al.*, 2014; Tedaldi *et al.*, 2014]. In order to safely navigate in the environment, the robot uses an abstract 2D representation of the environment called traversability map [Bogoslavskyi *et al.*, 2013] that, when coupled with exploration techniques that consider the expected gain of novel information [for an overview tutorial, see Stachniss *et al.*, 2012], allows for a safe and exhaustive survey of the environment.

Despite being still a research prototype, our robot has already obtained a number of achievements, showing that it has a good mobility and that it can run for a long time while processing huge amounts of data from a number of heterogeneous sensors. During the survey, while collecting data for off-line processing, the robot builds an on-the-fly mission-oriented reconstruction of the surrounding environment, that can be used either by the autonomous navigation system, but also by the surveyors to get a proper situation awareness remotely through the Mission Control Interface (MCI).

The MCI is the graphical interface used by surveyors during the missions at the cultural heritage sites[1]. The MCI is composed of a multimodal interface (fig. 1) and a supervisory interface (fig. 2). The first one allows to visualize all the relevant data provided by the robot in an integrated way: video streams, 3D local and global reconstructions based on coloured point clouds from the RGB-D sensors or from the 3D laser scanner, robot attitude, battery status, internal and external temperature and humidity, etc. The operator can change the point of view and inspect the explored environment or control the robot using a bird's-eye view. The operator can also select regions in the environment and annotate them for further analysis and classification. If the semantic segmentation module detects some interesting or known object, a marker is added to the map.

The supervisory interface, on the other hand, is used for mission control when there is little or no connectivity: a 2D representation of the environment is shown to the operator, where colours provide qualitative information about the terrain. The user can select target locations by clicking on the map, triggering the autonomous navigation behaviour. When the connection with the operator is about to be lost, he can instruct the robot to explore a given region for a specified duration and report back the data collected: when the connection is available again, the robot will send back the traversability map and the markers on interesting locations, so that the operator can choose to download pictures of these locations and possibly request further analyses. DigiRo has already accomplished a number of successful missions and its results have been presented at the Maker Faire European Edition 2014 where it won the Maker of Merit award.

ARIS: the cloud-based Archaeological Information System

The amount of data gathered by the robot and the complexity of the reconstruction process is such that it cannot be efficiently handled by a single computer. For this reason, the data collected by the robot are uploaded to the cloud where ARIS, our information management system, processes it in order to offer a number of different services. Although there are already many interesting examples of archaeological information systems (e.g., the Arches Project[2] by the Los Angeles Getty Institute), these projects focus on descriptive artifacts where qualitative data, such as textual descriptions, is manually provided by human operators. On the contrary, our Information System is focused on the management and automatic interpretation of large amounts of quantitative raw sensor data, such as laser scans, 3D images, and pictures.

To this end, ARIS is capable of automatically generating accurate 3D models and to automatically classify data into semantic classes through the use of beyond-state-of-the-art Artificial Intelligence technologies. Indeed, 3D scans and images can be interpreted more effectively within aggregate 3D models than on their own. In ARIS we compute 3D reconstructions of two different types: 3D point clouds and textured 3D meshes. For example, figure 3 shows a small portion of textured 3D meshed reconstruction of a catacomb that ARIS has computed from high-definition photos by using state-of-the-art photogrammetry approaches [Vergauwen *et al.*, 2006; Theo Moons *et al.*, 2008].

ARIS has been designed as a collaborative platform aiming at promoting cooperation among users with different types of expertise, during their conservation or analysis activities. To this end, it provides some useful facilities, such as the dashboard, chat sessions, and messaging systems in order to promote this social behaviour.

The data archive in ARIS is organized in sites, each of which contains a number of datasets, that can be uploaded by users and pre-processed in the cloud, in order to provide search and visualization capabilities. Search can be performed in two ways: the first is provided through a classic GIS-like interface that allows to search for datasets using location-specific information (e.g., latitude and longitude) and showing them in a layer over a geographic map.

The second way to search through the data is using semantic queries: users can specify a query as a conjunction of criteria across a number of user-defined semantic layers (e.g., "all the epigraphs which are in the region of Lazio, which are made of marble and which are from the second century"). These semantic queries are possible thanks to user-defined taxonomies and to an automated classification mechanism that are offered by ARIS. After defining the taxonomies, users can annotate a small number of images that are given as examples to ARIS machine learning technologies that will learn from those examples and then automatically annotate the rest of the datasets. Our approach to automatic classification com-

TORNA AL SOMMARIO

3

Fig. 3. Example of 3D reconstruction.

bines Random-Forest-based classification with Conditional Random Fields [Hermans *et al.*, 2014] and has won the IEEE ICRA14 Best Vision Paper Award.

3D Visualizers

The 3D model generated by ARIS is suitable for a multitude of applications. In addition to being functional to support documentation and monitoring activities, it has the great advantage of being visualizable on a plethora of devices (PC, smartphone, tablet, VR).

We developed a WebGL widget, the ROVINA Web Viewer. This is a tool to display and navigate the model in a web page. It can be used within ARIS or embedded in any other website. The user is then able to access the model via any web-capable device. As the model is both accurate and captivating, we identified two main end-user branches. The first branch of the public is that of the technical personnel. Viewing and handling the metrically reliable model can support the planning and verification of surveys and interventions. A typical example is that of producing a graphically realistic digital version of a statue before and after a restoration work. The digital version of the statue not only serves as a comparison, but it also allows for infinitely detailed (yet easily consultable) annotations and serves as a history diary of the statue itself.

The second branch of usage is that of the virtual touristic purposes. We leveraged on the recent spread of low-cost VR devices for smartphones (i.e. Google Cardboard, Samsung Gear VR and similar) by producing a mobile app that makes use of this technology, proposing an affordable, interactive and immersive experience. We then presented the developed applications at major public events (i.e. Digital Heritage EXPO 2015, Maker Faire Rome 2015). The apps met a notable interest from the community.

In particular, getting in touch with people helped to imagine a possible future usage. As high-end devices as "Oculus Rift", "PlayStation VR" and "HTC Vive" have recently made it to the market, bringing to the large public the opportunity of extremely detailed and smooth visualization experience of very large environments, it is envisionable the development of powerful VR applications that put the power of these tools to the service of technical personnel, who need high model detail, accuracy and longer time of use.

Conclusions

We discussed the main problems regarding digital reconstruction nowadays, which are mainly summarizable in:

- high cost, in terms of time and resources, of the various phases involved in the process;
- accessibility of the sites of interest;
- reusability and ease of distribution of the products of the digitization.

We then presented the solution proposed, designed and developed during the FP7 European Project "ROVINA", whose lifetime span has ranged from 2013 to 2016. The project introduced a strong automation component at several layers in the process, from the involvement of a robotic platform for acquiring the data to the automation of the processing and distribution of these data and the products of their exploitation.

We highlighted and described the technological components included and eventually made an overview of the public reaction to the project, which revealed an opportunity of putting the technology once more at the service of culture and restoration.

NOTES

1. See video http://youtu.be/l6MKMsnyHJw.
2. http://archesproject.org.

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ABSTRACT

ROBOTIC AND VIRTUAL REALITY FOR CULTURAL HERITAGE DIGITIZATION AND FRUITION

In this paper, we present our novel approach for acquiring and managing digital models of archaeological sites, and the visualization techniques used to showcase them. In particular, we will demonstrate two technologies: our Robotic System for Digitization of Archaeological Sites (DigiRo) result of over three years of efforts by a group of cultural heritage experts, computer scientists and roboticists, and our cloud-based Archaeological Information System (ARIS). Finally, we describe the viewers we developed to inspect and navigate the 3D models: a viewer for the web (ROVINA Web Viewer) and an immersive viewer for Virtual Reality (ROVINA VR Viewer).

ROBOTICA E REALTÀ VIRTUALE PER LA DIGITALIZZAZIONE DEL PATRIMINIO CULTURALE

In questo articolo presentiamo il nostro nuovo approccio per l'acquisizione e la gestione di modelli digitali di siti archeologici e le tecniche di visualizzazione utilizzate per illustrarli. In particolare, dimostreremo due tecnologie: il nostro Sistema Robotico per la Digitalizzazione dei Siti Archeologici (DigiRo) frutto di oltre tre anni di sforzi da parte di un gruppo di esperti del patrimonio culturale, informatici e robotisti, e il nostro Sistema Informativo Archeologico basato su cloud (ARIS). Infine, descriviamo i visualizzatori sviluppati per ispezionare e navigare i modelli 3D: un visualizzatore per il web (ROVINA Web Viewer) e un visualizzatore immersivo per la realtà virtuale (ROVINA VR Viewer).

KEYWORDS

digitization, robotics, Virtual Reality, Archaeological Data Management

digitalizzazione, robotica, realtà virtuale, gestione dei dati archeologici

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ACCESSING AND INFORMATION SYSTEM

MuPriS: modern technologies making museum of sarcophagi content more accessible

Laura Pecchioli, Barbara Mazzei

In cultural heritage, the usage of digital technology to detect, acquire and manage is a global trend in the 21st century. In recent years even disciplines like classical archaeology are involved in projects based on modern technologies. Especially in the case of 3D applied technologies, the perception, needs, and understanding and, above all, the record solutions have changed [Stylianidis *et al.*, 2016: 400].

Managing heterogeneous information related to cultural heritage sites and artifacts nonetheless remains a complex task. The application of 3D technologies puts requirements on the underlying technologies in terms of accuracy, performance, and usability, for a result of rich interdisciplinary research and development opportunities [Guidi *et al.*, 2009]. In recent years, there has been a significant trend towards the massive digitization of data, as this allows for more efficient and reliable storage and management processes.

Even the archaeology domain is characterized by an increasing volume of 3D digital content and the acquisition of 3D digital information with as main focus virtual reconstructions. Nowadays, people can visit and retrieve information in a museum in several ways as in the Medelhavsmuseet, the Musei Capitolini, Louvre Museum, Kunstmuseum Skagens and others. The first-mentioned site has made plans to digitize its collection in 3D with photos and X-ray scans, allowing museum visitors to explore the mummies in a way similar to what archaeologists do

Fig. 1. Early 1900: opening of the museum. *Source Photographic Archives of the Pontifical Commission for Sacred Archaeology.*

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TORNA AL SOMMARIO

Fig. 2. View of the exhibition: fragments on their basements. *Source Photographic Archives of the Pontifical Commission for Sacred Archaeology.*

2

when they are looking for novel discoveries from ancient remains. The common approach of all these institutions is to create a virtual tour on the website or on site[1] and in some cases one can download an application for a mobile device to receive information from the network and improve one's own experience. Project cases very similar to our application in the museum of sarcophagi in Rome.

Architectural and technological aim project

The aim is to preserve and give access to the archive in its entirety and to disseminate information. The MuPriS museum has been included in the visit to the Catacombs of Priscilla. The goal has been to enhance the environment and its graves by rebuilding the historical identity of the site through a permanent exhibition, maintaining the pieces in their original context of the Basilica and to improve the accessibility to the monument virtually by an online database and 2D/3D interface web application, developed to facilitate browsing and exploration of the collection by both experts and casual users. Through a facilitated accessibility to information, we provide the user own tools to understand and interact with the fragments and the museum environment.

Between history, archaeological investigations and restoration

The Basilica of St. Silvestro was rebuilt in the early 20th century on the foundations of a structure built in various phases during Late Antiquity. The present arrangement consists of two quadrangular rooms, both with an apse on the north-west side, aligned along the major axis and spatially connected. The north-west Basilica is still currently intended for liturgical use, as in antiquity it was destined for the cult of the martyrs buried in the catacombs below. The south-east Basilica was originally conceived as a space for burials (fig. 1). The presence of some venerated burials led to the realization of a second building thought to be a covered cemetery [Tolotti, 1970]. Today the burials and the fragments of sarcophagi have been moved into museum MuPriS.

The archaeological investigations have allowed the recovery of hundreds of sarcophagus fragments found buried in the Basilica and the surrounding area. In this latter area, there was a necropolis of the first century and numerous mausoleums built after the Basilica of St. Silvestro (4^{th}-5^{th} century). In the winter of 2009, the Pontifical Commission for Sacred Archaeology (PCAS) decided to proceed with the restoration of the stone artifacts and a large number of fragments (around 471 pieces) were reassembled. The high quality of materials and the variety of typologies, representing the sculptural production of over four centuries, led the PCAS to the decision to create a permanent exhibition (fig. 2). The sculptures were restored and archived following the standard of the ICOM-CIDOC (International Committee for Documentation of the International Council of Museum).

MuPriS: museum project

The Basilica is located above the Catacombs of Priscilla and is connected through two entrances to underground tunnels. The particular underground microclimate influences very strongly also the environments above, creating significant condensation and humidity problems. The project provided a new floor (100 m^2) over the burials in modules of different material (imperial travertine, glass, and metallic grid). The floor has been built to guar-

Fig. 3. MuPriS environment (2017). *Source Photographic Archives of the Pontifical Commission for Sacred Archaeology.*

3

antee a good air flow and microclimatic preservation of the burials, while giving access to the museum and access the tour of the catacombs [Mazzei *et al.*, 2013]. The project has been thought as a museum-construction site (fig. 3). The visitor can explore the objects, the Basilica, the burials, the stratigraphy of the walls, the new structure of the floor from different views. The technological solutions aim at integrating the visit, allowing for each fragment to retrieve further information directly in the museum using smartphones [Pecchioli *et al.*, 2017].

Visiting and QR-code

The museum exhibition is subdivided into six thematic sections and the physical space did not allow to exhibit detailed information, only a synthetic description correlated to an inventory number. The technological solutions aim to integrate the visit, allowing for the retrieval of further information about each fragment using mobile devices or through the website[2] by a QR-code. QR-codes (or the corresponding URLs) jump to specific areas of the museum, while the whole museum can be navigated with a touch friendly and engaging interface, even without using the QR-codes[3]. QR-codes (or with an URL) are connected to a local server through a Wi-Fi network in the Basilica, allowing information to be read on a virtual tour of the site as if on a real visit.

Digital survey

From the beginning digital technologies were foreseen as an instrument to support the whole project:

- both spaces of the Basilica have been digitally surveyed using a phase shift 3D laser scanner [a Cam/2 Faro Photon 120 unit]. This well-working solution produced a detailed digital 3D model of the ancient level of the tombs, giving to the designer all the measurements and the references necessary to define the new floor with accuracy[4] [Pecchioli *et al.*, 2017; Russo *et al.*, 2011] (fig. 4);
- a completely preserved marble sarcophagus carved with scenes from the everyday life and agriculture and sheep- farming activities was the chosen Structure-from-Motion process. It showed complex characteristics as sculpture and for the light subsurface dispersion of the marble. It has been used Agisoft PhotoScan as the standard first step based on automatic calibration and positioning of the photos in the 3D space, and the consequent generation of a point cloud with chromatic features of the object. The final result for the sarcophagus was a mesh made by 150000 polygons [Pecchioli *et al.*, 2017] (fig. 5).

Online museum

As described before besides the physical museum there is also an online part.

Database and 2D interactive interface

A small group of specialists inserted and checked the history, description, material, restoration information, and other aspects of each fragment. The study of the sarcophagi is a particular field of research in classical archaeology and not easily possible to acquire. Each fragment was described using a simple language, so that the user can read the descriptions through a friendly user interface. During the whole project, the information was inserted and updated using the Web application. The information was stored keeping track of past edits (versioning) and

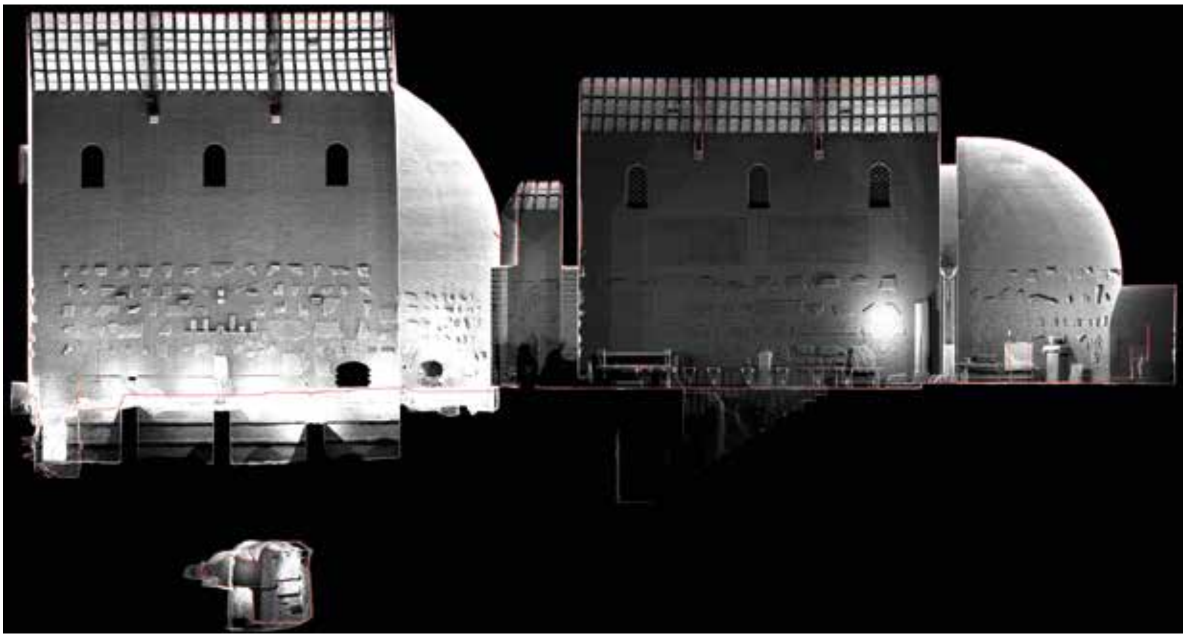

Fig. 4. Longitudinal section of the complex of the Basilica of St. Silvestro from the cloud of points *Source Photographic Archives of the Pontifical Commission for Sacred Archaeology.*

4

Fig. 5. The result of 3D model of the marble sarcophagus. *Source Marco Pucci.*

5

supports multiple languages. The database was developed with PostgreSQL and includes information about each fragment of the sarcophagus. This application used Django[5], a free and open source Python Web framework. Despite the fast progress of the performance of mobile devices, performance is still constrained, and 3D visualization is possible only using optimized native applications. This requires an order of magnitude more effort, and will restrict even more the devices supported.

A 2D interactive interface for each fragment allows access to a database so that the user will be able to be read and retrieve added information even while going through the collection as in a real visit [Pecchioli, 2011b; 2011c] (fig. 6).

3D web application using ISEE software

The museum has a considerable complexity in being able to be reproduced as a three dimensional model. For this reason, only some areas of the model will be accessible.

An important aspect with internet usage is the optimisation of the 3D model. In our case it has been achieved creating a low poly 3D mesh with the application of normal maps generated with a baking process of the high poly 3D model. In this way we have optimized for the Web and the interactive use. The Web application is based on software called "ISEE"[6] [Pecchioli *et al.*, 2011a] to meet the requirements of an adaptive and intuitive interface to access information connected with a spatial region. The method provides an intuitive interaction and allows the user to access the information through navigating in a 3D environment [Bowman *et al.*, 2005] (fig. 7). ISEE ranks the relevant information by means of its position/orientation in 3D space as a viewer. The list is automatically upgraded moving through the virtual environment [Pecchioli *et al.*, 2012].

Conclusions

Digital technology has contributed massively to our project with the important role of integrating and completing the visit. Where the antique and the new met, unless there were fundamental functionality issues, the priority has always been to preserve and enhance the antique.

6

Fig. 6. 2D interactive interface.

7

Fig. 7. MuPriS: 3D web application.

The optimization of the model is an essential phase to obtain a retrieval in real time of the information in the 3D context and must not be undervalued in the beginning when defining the aim of a project. The possibility to retrieve information in its context represents another important aspect that improves the user experience. We have aimed to use the technology like an instrument to fix a real problem and to improve the accessibility to a common user and for future use. The 3D model will soon be uploaded.

NOTES

1. AR (Augmented Reality).
2. http://mupris.net/.
3. See below, section "Database and 2D interactive interface".
4. Area 3D s.r.l. Livorno: www.area3d.com.
5. https://www.djangoproject.com/.
6. The basic idea is to enable information retrieval by simply looking inside a 3D environment, since moving and looking in the real world are basic modes which all viewers use. It ranks the relevant information by means of its position/orientation in 3D space as a viewer [Locatelli *et al.*, 2012]. Normally we use the Unity 3D technology to visualize and interactively navigate 3D models. The Unity plug-in is available for all the major browsers (IE, Firefox, Safari) and platforms (Windows, OsX).

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ABSTRACT

MUPRIS: MODERN TECHNOLOGIES MAKING MUSEUM OF SARCOPHAGI CONTENT MORE ACCESSIBLE
The paper details a technological approach applied in the museum project MuPriS to display the museum sarcophagus fragments in the Basilica of St. Silvestro at the Catacombs of Priscilla in Rome. MuPriS is a museum of classical archaeology realized with a new and innovative concept of accessibility and interaction with the information to better promote classical archaeological information even to non – specialist users. In-depth information relative to each section of the visit can be retrieved thanks to QR-codes and by means of a 2D interactive interface for each fragment with a database online. A 3D web application based on software called ISEE allows exploring of the most important pieces of the museum. As an intuitive online interface and easy archaeological description, it can become part of instrument tools of communication and of sharing in the restoration field.

MUPRIS: LE TECNOLOGIE MODERNE RENDONO PIÙ ACCESSIBILE IL CONTENUTO DEL MUSEO DEI SARCOFAGI
Il contributo descrive un approccio tecnologico applicato nel progetto museale MuPriS, per visualizzare i frammenti dei sarcofagi del museo nella basilica di San Silvestro alle catacombe di Priscilla a Roma. MuPriS è un museo di archeologia classica realizzato con un nuovo e innovativo concetto di accessibilità e interazione all'informazione e per meglio promuovere il tipo di informazione in archeologica classica anche per utenti non specialisti. Informazioni dettagliate relative a ciascuna sezione della visita possono essere recuperate grazie ai QR-codes e tramite un'interfaccia interattiva 2D per ogni frammento con un database online. Un'applicazione web 3D basata sull'uso di un software chiamato ISEE consente di esplorare i pezzi più importanti del museo. Come un'interfaccia intuitiva online e una facile descrizione archeologica che può diventare parte dei dispositivi strumentali di comunicazione e di condivisione nel campo del restauro.

KEYWORDS

database online, Django, sarcophagus, ISEE software, QR-code, Structure-from-Motion, digital survey, 2D interactive interface, 3D web application

database online, Django, sarcofago, software ISEE, QR-code, Structure-from-Motion, indagine digitale, interfaccia interattiva 2D, applicazione web 3D

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TORNA AL SOMMARIO

ACCESSING AND INFORMATION SYSTEM

Structure-from-Motion (SfM) technique in the Catacombs of Priscilla in Rome

Improvements in the conservation, the safety and the fruition

Marialuisa Mongelli, Irene Bellagamba, Giovanni Bracco, Beatrice Calosso, Silvio Migliori, Antonio Perozziello, Samuele Pierattini, Andrea Quintiliani, Barbara Mazzei

The Roman catacombs are the most important early Christian monuments in Rome and they are visited by thousands of pilgrims every year. Their underground nature affects their state of conservation and these specific conditions cannot be changed without compromising their integrity. The only viable solution would seem to be found a form of sustainable conservation. For this reason, we have undertaken many and diversified experimentations in the recent years [Mazzei, 2015].

Since 2015 ENEA is involved in a project, named "COBRA" ("Sviluppo e diffusione di metodi, tecnologie e strumenti avanzati per la conservazione dei Beni Culturali, basati sull'applicazione di radiazioni e di tecnologie abilitanti")[1], which focuses on disseminating and transferring advanced instruments, IT services, innovative technologies to SMEs aimed to protect and conserve the cultural heritage.

The paper shows the use of the Structure-from-Motion (SfM) technique in the archaeological complex of Priscilla's Catacombs, on different case studies and for different applications, in order to promote the valorisation, the fruition and the conservation of the archaeological finds that have been investigated.

From the point of view of the technological transfer, which represents the principal aim of the COBRA project, this technique can be easily used in museums or archaeological sites, in order to produce multimedia videos of the archaeological finds and their digital archiving for future share with end-users.

In this regard, the ENEA ICT team has recently developed an innovative system of cloud-storage and data sharing, named "ENEA Staging Storage Sharing (E3S)" [Iannone *et al.*, 2017]. It is based on the OwnCloud[2] open source technology, that guarantees the secure storage and sharing of the in situ measurements results and the heavy photogrammetric models.

The photogrammetric reconstruction process requires huge hardware and software resources for images processing and data analysis. In this context, E3S guarantees the network access to the computational capabilities of the CRESCO (Computational Research Centre for Complex Systems) High-Performance Computing system [Mongelli *et al.*, 2017a]. Computer graphics tools are available within the distributed virtual lab, whose access is guaranteed by the E3S GPU application server, through a graphical interface named "FARO2 (Fast Access to Remote Objects)". Moreover, images, videos, reports, documents and 3D reconstructions are archived in the ENEA AFS and GPFS storage areas for future dissemination and elaborations.

The Catacombs of Priscilla

The Catacombs of Priscilla are located on the Via Salaria, an ancient road leading north out of Rome. They are dug in a vast quarry used for Christian burials from the late 2nd century through the 4th century. The central region, which is the most ancient, winds along in a series of galleries; the walls are full of *loculi*, the most common kind of tomb, closed by bricks with simply painted inscriptions. The Cryptoportico with the Greek Chapel is a large underground masonry area that originated as a noble family burial ground that was later connected to the Catacombs. Thanks to the number of martyrs buried here as well as its sheer size, the underground cemetery was an important pilgrimage site throughout the Middle Ages [Giuliani, 2016].

The SfM technique: general principles

The Structure-from-Motion technique allows to obtain a 3D model of an object under the form of "points cloud" or "polygonal model" (mesh), starting from the acquisition of 2D images, that can be post-processed using specific photogrammetric software, based on computer vision methods [McCarthy, 2014]

The SfM technique is founded on the photogrammetric principles and in particular, on the fundamentals of optics, descriptive geometry and the inverse perspective theory. The so-called "close-range photogrammetry" is generally applied for the reconstruction of architectonical elements, archaeological finds or structures with the purpose to carry out, in a fast, contactless and easy way, structural investigations and non-invasive monitoring.

The images were taken by the close range photogrammetry method and the Agisoft PhotoScan Pro software was used to obtain the 3D models. Agisoft PhotoScan is a stand-alone software that performs photogrammetric processing of digital images and generates 3D spatial data. It is remotely available accessing the ITACHA virtu-

TORNA AL SOMMARIO

al lab, completely dedicated to the cultural heritage and developed for accessing the graphics codes, by means the FARO2 GUI, to handle heavy jobs for photogrammetric reconstructions.

The first step of the PhotoScan elaboration process is the "image alignment": by means, the SIFT algorithm and the multi-stereo matching process, the position and the orientation of the camera shots are detected and a "sparse cloud" of the object is created. Subsequently, a "dense image matching" algorithm allows extracting the "dense cloud" model, thanks to a depth comparison between all the images. PhotoScan also allows reconstructing the polygonal model, made of faces and vertices, which can be obtained from the point belonging to the dense points cloud. Then, a texture process is performed, to obtain the final "texturized" model. The code provides a fast and automatic way to scale the models, starting from the assignment of a single reference measure of the real structures. The final 3D model can be used to detect the geometrical data of the structure in terms of shape and size.

The SfM technique at the Catacombs of Priscilla: case studies

According to the Pontifical Commission for Sacred Archaeology, the Structure-from-Motion technique was applied to three different cases and for three different purposes at the archaeological complex of Priscilla's Catacombs [Yilmaz, 2007].

The first one was the monitoring over time of a biological attack that affected a surface of the "Greek Chapel", which represents one of the most important archaeological sites of Priscilla's Catacomb, richly decorated with fresco paintings. The second purpose was the use of the photogrammetric reconstruction for the virtual fruition of the "Sarcofago delle Muse". The last case study aims to propose the use of the SfM technique for the structural monitoring of a damaged masonry element.

The Greek Chapel and the Sarcofago delle Muse are situated in the Cryptoportico area of the archaeological site (fig. 1), while the masonry wall is located along the itinerary that conducts to that area. A NIKON D60 digital camera was used to produce 2D images with a 3872 x 2592 px resolution and 5 MB each for all the case studies above mentioned.

SfM for a virtual fruition: Sarcofago delle Muse

One of the most important sarcophagi finds in Priscilla's catacomb is the Sarcofago delle Muse. It was reconstructed from many marble fragments in the early twentieth century and is 2.30 meters long and 1.10 meters high. The front of the Proconnesian marble sarcophagus shows five Muses, set in a decorative arcade with spiral columns. Two

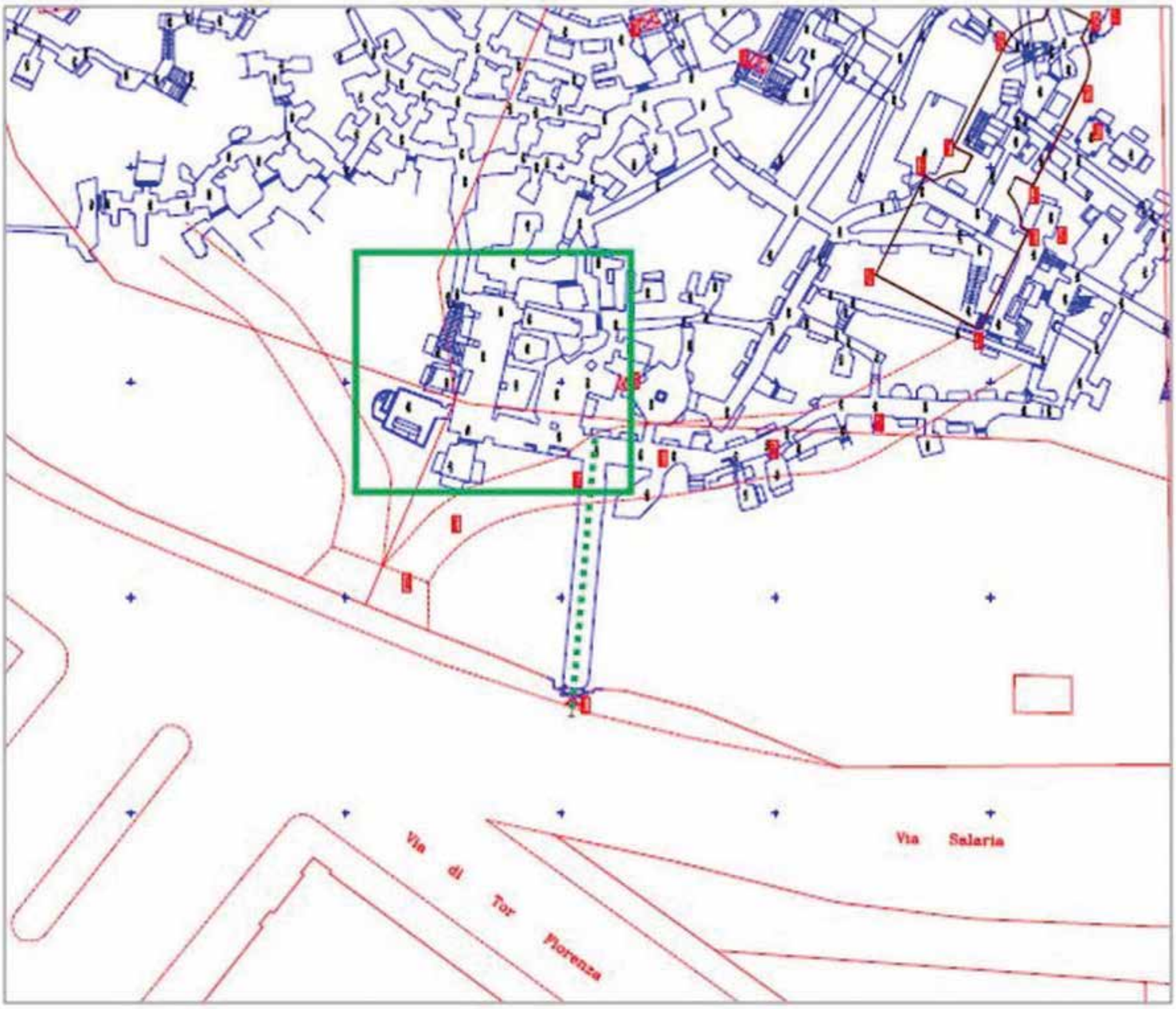

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Fig. 1. The Cryptoportico area at the Priscilla's Catacombs.

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Fig. 2. Sarcophagus polygonal mesh 3D model.

Fig. 3. Sarcophagus textured 3D model.

other Muses had to be on each side. All the Muses may be easily identified by their attributes. The sarcophagus is dated to the beginning of the fourth century according to the style [Speier, 1954].

Unfortunately, the tourist does not have the possibility to see this archaeological find because it is situated in a critical area not accessible to visitors for security reasons.

In order to create multimedia videos of the sarcophagus that the tourist can observe in the museum during their visit at the Catacombs and also with the aim to guarantee its remote fruition, exploiting its greatness and beauty to researcher and specialists, a SfM 3D reconstruction was performed. The photogrammetric reconstruction was carried out starting from the acquisition of digital images of the sarcophagus: 80 images have been captured, but only 67 were processed. Since the SfM technique is unfortunately sensitive to light variations, when an archaeological good is poorly lit, the image acquisition procedure represents a fundamental step to ensure a good result of the reconstruction. For these reasons, due to the poor lighting of the area in which the sarcophagus is situated, some LED lights were used in order to capture clear images, uniformly brightening the surfaces and avoiding optical distortion. The results of the reconstruction are shown in the following three ures, that represent the 3D model under the form of points cloud, polygonal (fig. 2) and textured (fig. 3) model.

SfM monitoring of a biological attack: Greek Chapel

The Greek Chapel is a barrel-vaulted room that widens into a triapsed hall and it is connected to the Cryptoportico. The Greek Chapel owes its importance to the very ancient cycles of pictures decorating it (second half of the third century) [De Bruyne, 1970]. The fragility of its painting decorations (in particular the delicate ones in the trilobate hall on a red background) demands a continuous monitoring system to preserve the integrity of the frescoes.

The goal of this study has been to show the effectiveness of the SfM 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 the ENEA IT infrastructure.

Unlike other diagnostic and monitoring techniques with moisture-sensitive electronic components such as laser scanners, the photogrammetry reconstruction is not influenced by environmental conditions of low temperatures and high humidity. For this reason, it must be emphasized that it was the only technique able to produce the full acquisition of the Greek Chapel and to return a 3D real scaled model. More than 400 images were acquired and 364 of them were post-processed. A photogrammetric scanning of more than 300 images produced a high-density cloud of 48110500 points and a polygonal mesh of 9622300 faces; the 3D digital reconstruction of the Greek Chapel gave a very detailed textured model (figs. 4, 5).

Fig. 4. Greek Chapel longitudinal section: left side.

Fig. 5. Greek Chapel longitudinal section: right side.

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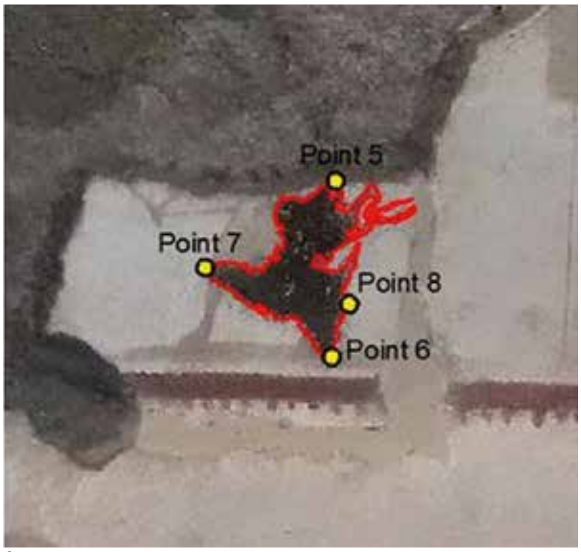

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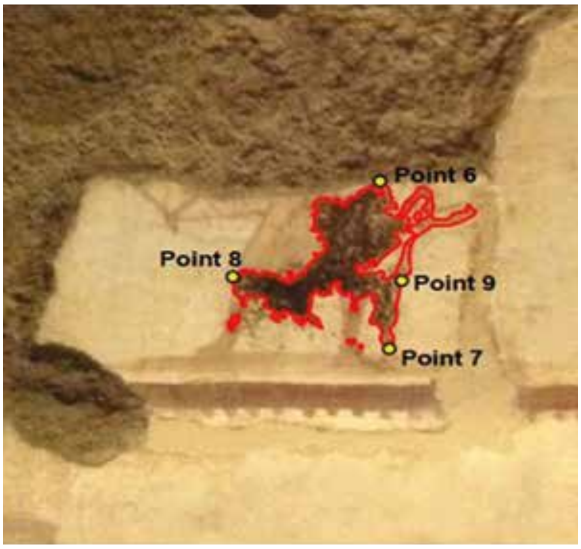

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Fig. 6. Biological attack reconstruction of June 2016.

Fig. 7. Biological attack reconstruction of November 2016.

The reconstruction by SfM was also used to show the possibility to apply this technique for monitoring and checking the evolution over time of the biological attack (figs. 6, 7) at the top on the right side. With this purpose, two photogrammetric reconstructions were performed: in June and in November 2016. In order to detect their dimensions and their total area, the two models of the biological attack were geometrically scaled in PhotoScan, starting from the scaling of the Greek Chapel model, based on a real single distance physically measured. As shown in figures 6 and 7, the biological attack in June presented different shape and dimension if compared with the 2nd reconstruction, made in November.

The results obtained from this application intend to underline the importance of the use of this monitoring technique, especially when the environmental conditions make difficult the use of other instrumentation, which is generally sensitive to low temperatures and high humidity [Mongelli *et al.*, 2017b].

SfM for crack patterns definition and monitoring: damaged masonry wall

The last application of the SfM technique concerns the photogrammetric reconstruction of a damaged masonry element, situated along the way that conducts to the Cryptoportico area of the Catacombs, in order to detect its crack pattern. In fact, the surface of this masonry element is characterized by lots of important cracks that are already monitored by a traditional glass sensor, but this instrument is not able to detect the real geometry of the entire pattern.

The SfM technique represents an easy-to-use instrument that is able to reconstruct the whole masonry element and to map the cracks, detecting their extension and taxonomy [Arias, 2015; Mongelli *et al.*, 2017c]. Starting from these results it was possible to execute a classification of the damage associated to each crack, with the aim of monitoring the cracks patterns evolution over time. The crack patterns detection, based on SfM, allows assessing the Structural Health of the damaged masonry wall, with the purpose to create a finite element model and to execute a seismic analysis, in order to evaluate its conservation status, its dynamic behavior under seismic actions and the influence of the cracks on its mechanical resistance.

For the photogrammetric reconstruction of the entire model 300 images have been acquired and 250 of them were post-processed by PhotoScan Pro. The final model of the wall, like "point cloud", consisting of 19438228 points and "polygonal mesh" of 3547077 triangle elements. Starting from the 3D model, previously scaled on the basis of a single reference measure, a map of the cracks was completely detected (fig. 8) 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).

The main advantage of the use of SfM methodology for this specific application lies in the fact that it is periodically repeatable allowing to check and to verify the evolution of the damage extension.

Technological transfer by E3S-Owncloud system (storage and sharing)

One of the principal aims of the COBRA project is the transfer to MSEs of all the diagnostic and monitoring results achieved during the experimental campaigns. In order to face a large number of images, documentation, scientific data and in particular, the heavy results size obtained by the photogrammetric reconstruction, the ENEA ICT team has developed an innovative methodology that allows to store and share with end-users, project partners and restorer, all the results obtained within the COBRA project.

The ENEA Staging Storage Sharing system is an IT architecture based on the OwnCloud framework. It guarantees a remote distributed access to the folders in which the experimental results of the photogrammetric reconstruction are saved and stored. The E3S architecture is mainly able to store and share experimental data, aiming at data integrity, security and reliability, and it uses the potentialities of the ENEA pre-existing services for data sharing, based on the AFS and GPFS file system.

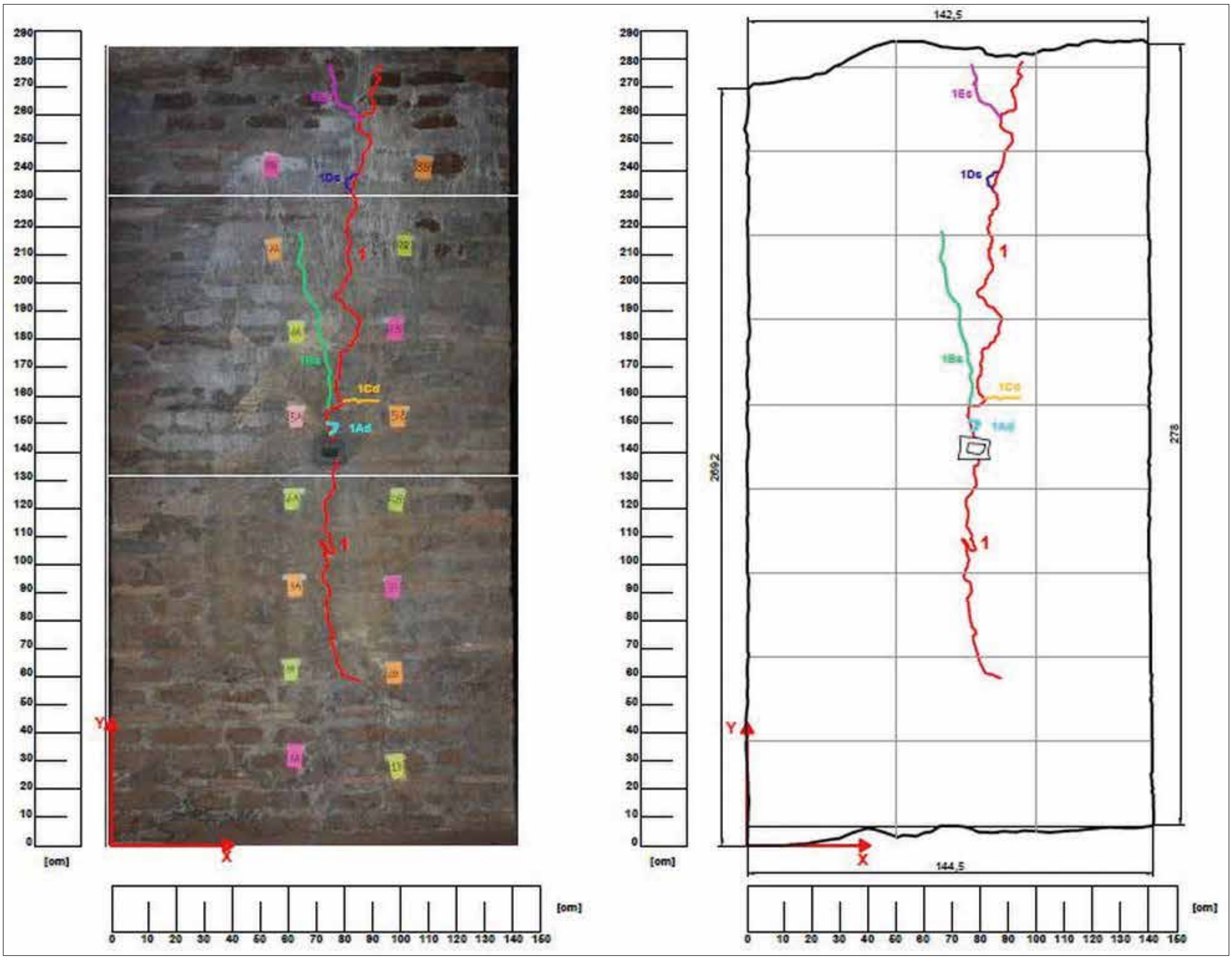

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Fig. 8. Crack pattern (left) and taxonomy (right) of the masonry element.

In this way, Catacombs restorers and conservators have the possibility to visualize images, videos, reports, documents and photogrammetric reconstructions performed during the project, by the use of the OwnCloud GUI, accessible from Web or alternatively, by means the OwnCloud client, which can be installed on any device. This architecture gave the possibility to improve the collaboration between the ENEA researchers, art experts and restorers of Priscilla's Catacombs involved in the project. In fact, all these experts have been able to cooperate in order to identify the best solutions for solving structural problems (as in the case of the masonry element) and proposing non-invasive methods to preserve the artistic goods (as in the case of the Greek Chapel) from environmental deterioration.

Conclusions

The applications presented in this paper shows as the use of the photogrammetric reconstruction by SfM technique can be used for different purposes, related to the conservation, the safety and the improvement of the fruition of cultural heritage. Its strength lies in the fact that is possible to execute a fast, easy-to-use and low-cost investigation on different archaeological finds and/or structures that show specific deterioration problems (e.g. structural damage, surface attack) and that are situated in areas not easily accessible. It should be also underlined that photogrammetry is very useful where it is not easy to introduce other sensitive instruments, but at the same time, it should be applied by integrating with other monitoring technique and/or diagnostic instruments in order to return the best results if used together.

The goal of the presented studies was to show the effectiveness of the SfM technique, to produce a 3D metric-corrected model of an archaeological find or structure in a low-cost way, and also with a not very specialized staff, simply using the hardware and software capabilities of E3S architecture and the CRESCO computational resources. In addition, thanks to the possibility to access the OwnCloud repository, the catacombs staff, restorers and art experts can visualize in every moment all the documentation, images and the results of the reconstructions for executing their own post-processing and/or evaluations.

NOTES

1. http://cobra.enea.it/english.
2. https://owncloud.org/.

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ABSTRACT

STRUCTURE-FROM-MOTION (SfM) TECHNIQUE IN THE CATACOMBS OF PRISCILLA IN ROME
IMPROVEMENTS IN THE CONSERVATION, THE SAFETY AND THE FRUITION

In the last years, the ENEA RC is involved in the COBRA project, which promotes the dissemination to SMEs of innovative and non-destructive monitoring techniques for the conservation, the valorization and the fruition of cultural heritage.
Within this project, the Structure-from-Motion (SfM) technique has been applied to the archaeological complex of Priscilla's Catacombs. SfM is a low-cost and non-destructive methodology which can represent a good alternative to obtain, in a contactless and fast way, 3D information of archaeological finds, especially where areas to be inspected are not easily accessible and when it is not possible to use other instrumentation.
This paper describes the application of the above-mentioned technique for three different objectives: the monitoring of a biological attack that affected a surface of the so-called "Greek Chapel", the virtual fruition of a sarcophagus named "Sarcofago delle Muse" and the structural monitoring of a damaged masonry element.

LA TECNICA STRUCTURE-FROM-MOTION (SfM) NELLE CATACOMBE DI PRISCILLA A ROMA
MIGLIORAMENTI PER QUANTO RIGUARDA LA CONSERVAZIONE, LA SICUREZZA E LA FRUIZIONE

L'ENEA, nell'ambito del progetto COBRA finanziato dalla Regione Lazio, ha aperto i propri laboratori alle PMI promuovendo la diffusione di tecniche di monitoraggio innovative e non distruttive per la conservazione, la valorizzazione e la fruizione del patrimonio culturale.
All'interno di questo progetto, per le catacombe di Priscilla insieme ad altre tecnologie è stato proposto l'utilizzo della fotogrammetria e in particolare la ricostruzione 3D da immagini digitali 2D mediante la tecnica Structure-from-Motion (SfM). La ricostruzione 3D fotogrammetrica rappresenta una metodologia speditiva, economica, non a contatto, che consente di ottenere una ricostruzione 3D metricamente corretta ed è utilizzabile laddove non è possibile introdurre altre strumentazioni più sofisticate per motivi di accessibilità o condizioni severe di umidità e temperatura.
Il contributo descrive l'applicazione della tecnica succitata per tre diversi casi studio: il monitoraggio di un attacco biologico che ha interessato una superficie della cosiddetta "Cappella Greca", la ricostruzione 3D del "Sarcofago delle Muse" per favorirne la sua fruizione poiché attualmente non inserito nel percorso di visita museale e il rilievo del quadro fessurativo di un elemento in muratura al fine di controllare l'evoluzione del suo stato di danneggiamento nel tempo.

KEYWORDS

Structure-from-Motion, cultural heritage, 3D survey, catacombs, 3D reconstruction, technology transfer, COBRA
Structure-from-Motion, patrimonio culturale, rilievo 3D, catacombe, ricostruzione 3D, trasferimento tecnologico, COBRA