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RESTAURO, CONSERVAZIONE E TUTELA DEL PATRIMONIO CULTURALE

107

Applications of 3D technology in cultural heritage

Digital survey and 3D digitalization

Digital reconstruction, 3D - printing and Augmented Reality

Accessing and Information System

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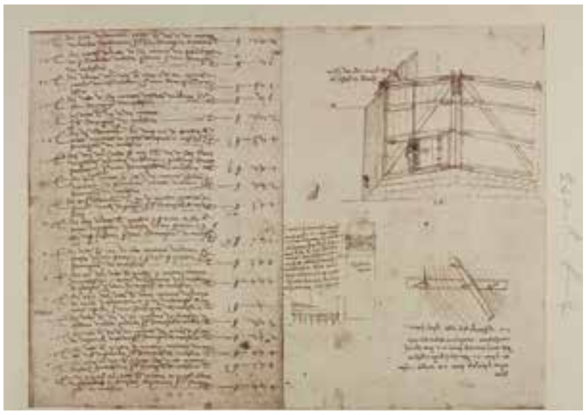

ACCESSING AND INFORMATION SYSTEM

Notizie e informazioni

DIGITAL SURVEY AND 3D DIGITALIZATION

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

In the framework of the National Training School "Science and Cultural Heritage: From Non-Invasive Analysis to 3D Reconstruction" organized by the Department of Mathematical and Computer Sciences, Physical Sciences and Earth Sciences of the University of Messina, in cooperation with the Department of Geosciences of the University of Malta we studied the Church of SS. Pietro and Paolo d'Agrò (fig. 1). It is a fortified church, the merlons and crenels undoubtedly indicate the function of the fortress over the centuries. Is one of the most important architectural work of the whole valley of the river Fiumara d'Agrò.

The Church was rebuilt in 1117 by Norman Roger II and, as reported in the epigraph on the façade, was restored in 1172 after an important earthquake in 1169. Without substantial retrofits it came to us, its architectural style is a synthesis of Byzantine, Arab and Norman architecture. The plan is a fusion between a typical basilical layout and a central plan church with Byzantine influences. There are three naves, a narthex between two towers with stairs, and three apses on the opposite side. The Church has two domes, the smallest one on the crossing, the other one in the middle of the principal nave.

The façade is polychromic with alternation of bricks and volcanic stones. The interior is characterized by absolute austerity, with no decorations or frescoes. The Church has been the subject of numerous studies over the years [Bottari, 1995; Calandra, 1938; Ciotta, 1976; Crupi *et al.*, 2018]. It has recently been officially proposed to UNESCO to include this monument in the list of human heritage assets.

3D integrated survey

The 3D survey is an integrated survey method based on image-based and range-based techniques [Canciani, 2011; 2013]. In this case, we used photogrammetry (image-based) and GPR (range-based) to create a complete 3D models of our case study. Image-based techniques used in the SS. Pietro and Paolo Church are based on Structure-from-Motion (SfM) pipeline.

Image-based techniques: photogrammetry and SfM

Nowadays fully automated methodologies can process large image datasets and deliver 3D models with a good quality of detail and variable precision according to specific applications [Crandall *et al.*, 2013; Snavely *et al.*, 2008]. Even if the process is almost simple and the level of automation is reaching very high standards, it is very import-

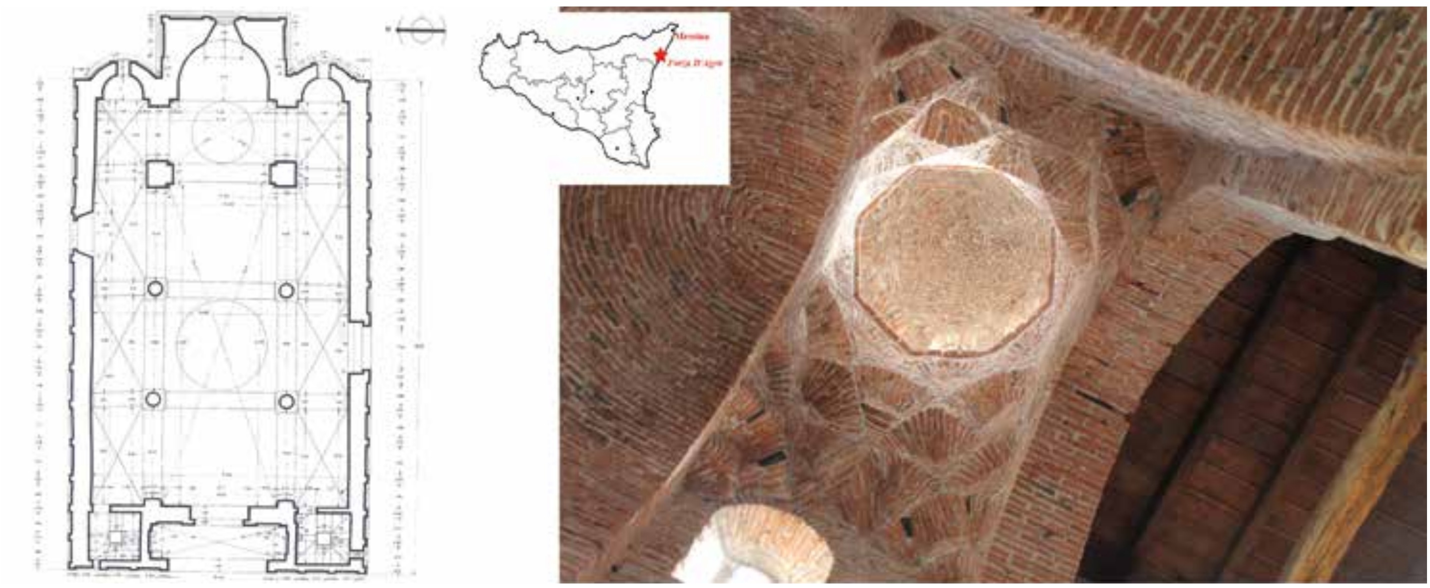

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Fig. 1. SS. Pietro e Paolo D'Agro Church in Casalvecchio Siculo, plan [from Bottari, 1995], and small dome on the crossing.

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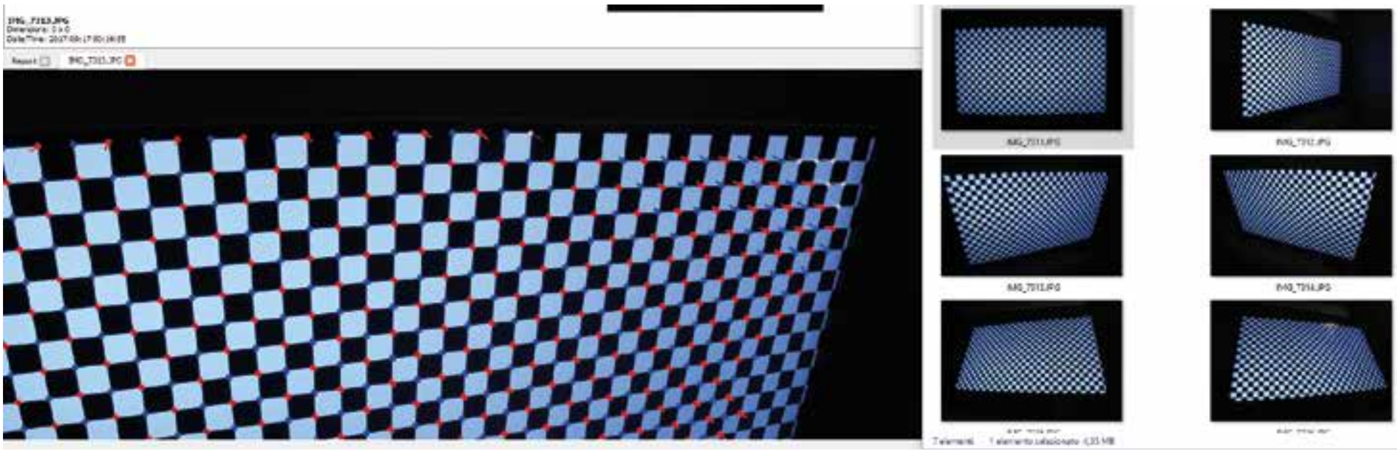

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Fig. 2. Calibration panels for Canon EOS 600D with a 18-55 mm lens.

ant to control quality and results as highlighted in a recent article [e.g. Remondino *et al.*, 2017].

For this case study, we used a reflex camera, Canon EOS 600D, with an 18-55 mm lens calibrated using a commercial tool developed by Agisoft Lens [© 2013 Agisoft LLC]. We performed camera calibration according to the guidelines, a set of eight photos was used to estimate focal length and distortions (fig. 2).

According to the visibility and accessibility of the Church, we make several sets of photos to acquire external and internal data. A lot of methodologies are well known to make a good set of photos, we used the Nicolas Martin-Beaumont protocols [Martin-Beaumont *et al.*, 2013]. All around, and inside, the building we took "master images", "associated images" and "intermediary images".

The state-of-the-art of the image-based techniques are well described by Fabio Remondino [Remondino *et al.*, 2017], and is based on image pre-processing [Verhoeven *et al.*, 2015], key-points extraction [Hartmann *et al.*, 2016], bundle adjustment [Schoenberger *et al.*, 2016], dense points clouds generation [Remondino *et al.*, 2014], mesh modelling [Maiti *et al.*, 2016] and model orientation and scale.

Pre-processing start "reading" images to find out features that could be used to match image each other with a lot of different algorithms [Miksik *et al.*, 2012; Apollonio *et al.*, 2014; Lowe, 2001; Bay *et al.*, 2008; Rosten *et al.*, 2010; Calonder *et al.*, 2010; Rublee *et al.*, 2011; Strecha *et al.*, 2012; Tombari *et al.*, 2015]. As results, we can observe tie points (fig. 3) that are used to estimate all unknown parameters, camera positions, interior camera parameters, with Bundle Adjustment process.

Fig. 3. Image correspondences, or tie points, detected on a church interior photo.

3

Each tie point, measured on the image has two corresponding and aligned point that creates an "optical ray". One is in the projection centre, the other one is the real 3D point. Bundle adjustment process [Triggs *et al.*, 1999] is an iterative process that arranges a "bundle" of optical rays to reconstruct the 3D scene and camera parameters. Once estimated camera position, tie points could represent the 3D scene as a sparse cloud (fig. 4). To transform this first point cloud into a continuous 3D model there are two more steps. The first one produces a colourized 3D dense cloud using a pixel-based matching algorithm [Rothermel *et al.*, 2012; Furukawa *et al.*, 2010; Hirschmüller, 2008].

The second one is the mesh modelling, that use interpolation on 3D points to create a continuous mesh model with texture. There are various pipelines, and software for this step using different surface reconstruction algorithms (Poisson reconstruction or Ball-pivoting algorithm) and different control parameters of these algorithms which affect the quality and computation time of the model [Maiti *et al.*, 2016]. The last step of the pipeline is the orientation and scale of the model whit the measurement made onsite during the survey.

Range based techniques: GPR investigations

During the school, different georadar prospections were also carried out inside the Church. Prospections have been performed by using a Ris-Hi mode system equipped with a dual antenna at the central frequencies of 200 and 600 MHz and made along stripes with 40 cm spacing. The data processing involved a zero timing, background removal on all tracks, a gain in-depth, a one-dimensional Butterworth filtering and a Kirchoff migration [Persico *et al.*, 2018; D'Amico *et al.*, 2017; Persico *et al.*, 2016].

The average propagation velocity of electromagnetic waves in soil turned out to be about 11 cm/ns based on the diffraction hyperbolas. Since the anomalies of pos-

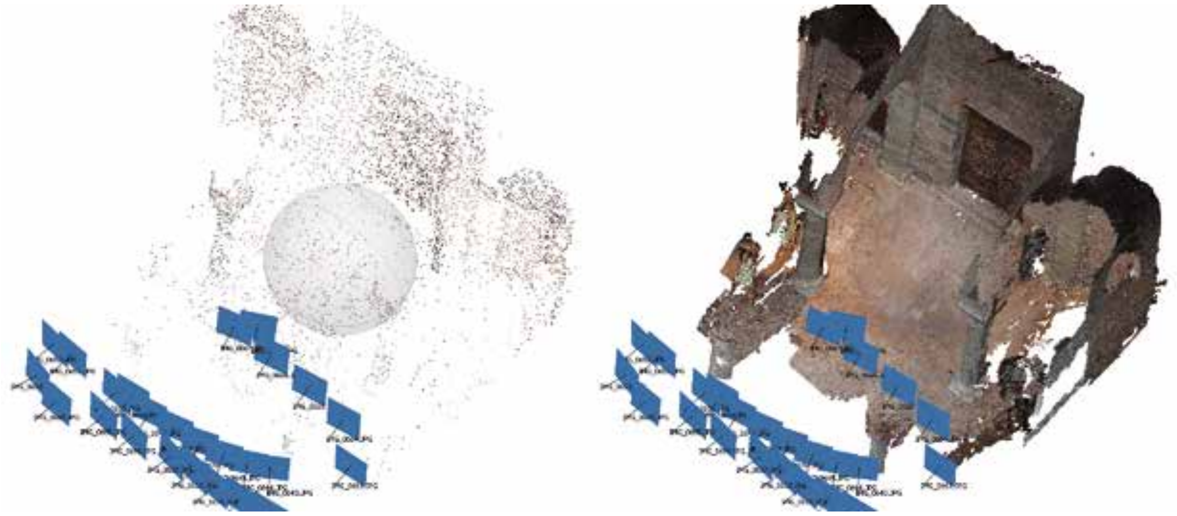

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Fig. 4. Sparse cloud made by tie points (left); dense cloud (right).

sible interest were provided to be relatively superficial, we show below a result relative to the antenna 600 MHz.

In figure 5 we show the main results through horizontal slices from the depth of 18 cm to the depth of 88 cm, docked to the plan of the site. Several anomalies are present and further investigations are needed for the best interpretation if the results.

Beside the geophysical exploration, another important goal of this project is to create a preliminary 3D model combining both the 3D photographic survey and GPR data.

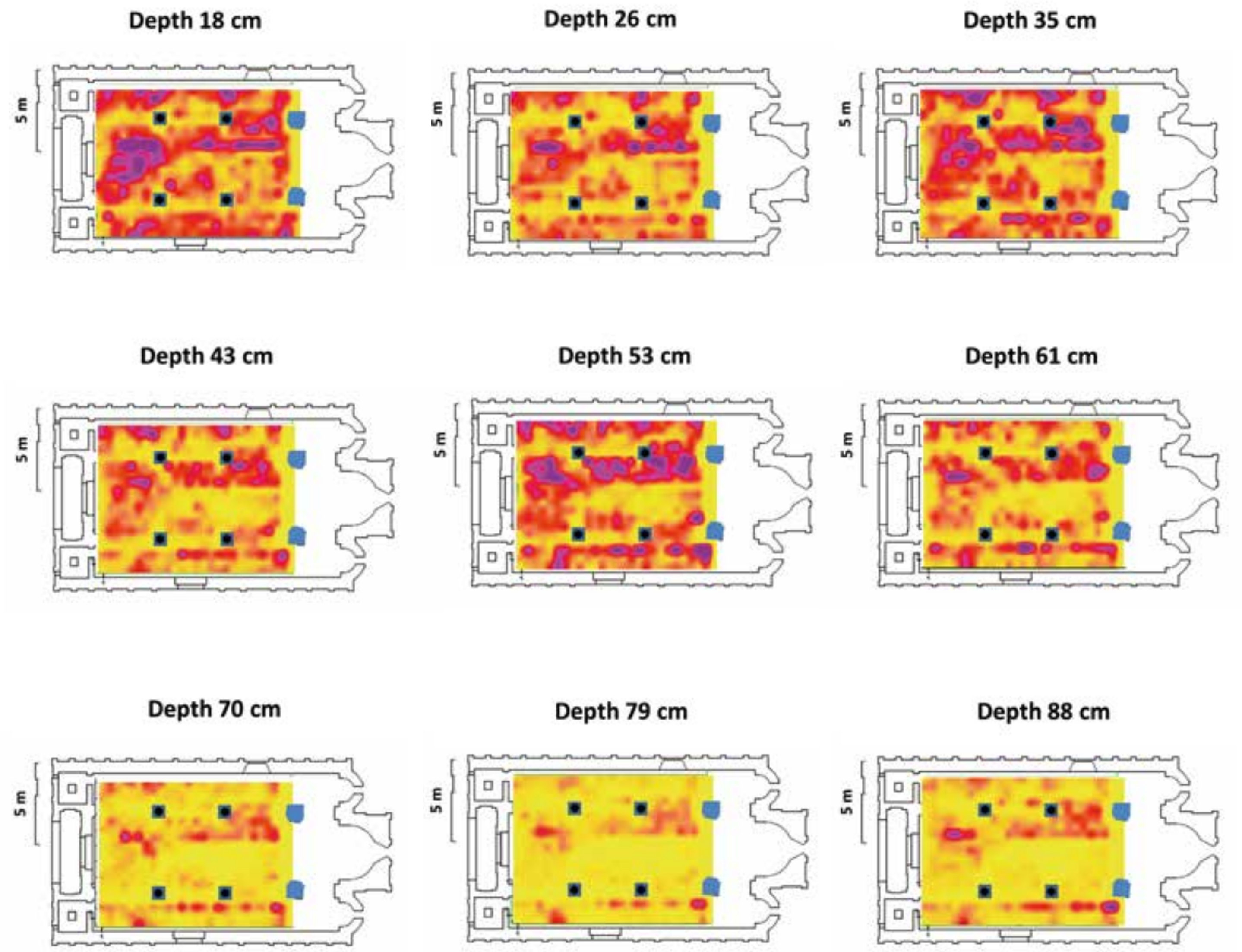

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Fig. 5. Example of GPR investigations in SS. Pietro and Paolo Church.

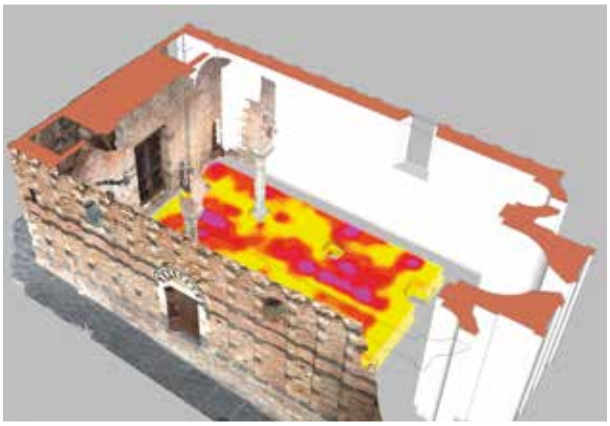
Fig. 6. GPR investigations in combined 3D models (a/b).

6a

6b

7a

Fig. 7. Relevant anomalies converted in 3D surface models (a); internal and external model of the Church with GPR information (b).



7b

Thus, GPR 2D data were interpolated and converted into a 3D model [Agrafiotis *et al.*, 2017].

The first step is to convert each horizontal slice into a vector layer using Potrace algorithms [Selinger, 2003] that converts bitmapped images into vector graphics. Each layer retains dimensions, positions, and colours information so it is possible to insert this kind information with the 3D model. The second step is to merge layers and information into a mixed 3D model that contains: church plan and photogrammetric model (fig. 6a).

3D analysis of superimposed information could be useful to select and verify GPR data. In this case, only the most important anomalies marked with purple and red (fig. 6b) are converted into 3D surface models using a pipeline composed by multiple vertical sections, curve detection and surface modelling (figs. 7a/b).

Concluding remarks

Using reality-based 3D models it was possible to derive metric data that are useful for several kinds of investigations such as the generation of ortho-images, detailed site maps, archaeological excavations and mapping, and segmented high-resolution 3D models to highlight construction techniques, sequences, restorations, etc. The photogrammetric techniques require experience and a correct acquisition of images. The technique used in this paper represents a good compromise in terms of cost effectiveness and a valid substitute for a laser scanner survey which can be very expensive in terms of equipment and/or external surveys. Field application of a laser scanner also requires a lot of time and experience during laboratory post-processing stage.

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ABSTRACT

3D SURVEY AND GPR FOR CULTURAL HERITAGE
THE CASE STUDY OF SS. PIETRO AND PAOLO CHURCH IN CASALVECCHIO SICULO
The development of 3D survey has produced a lot of new possibilities to study cultural heritage. 3D data acquired with conventional and low-cost cameras can be used to document, investigate the full appearance, materials and conservation status, to help the restoration process and identify intervention priorities. Integration with GPR investigation could be interesting to mix the visible and the invisible part of the monument using 3D models made with photogrammetry and GPR results converted into a 3D model.
The SS. Pietro and Paolo D'Agrò Church in Casalvecchio Siculo, was studied in the framework of the National School "Science and Cultural Heritage: From Non-Invasive Analysis to 3D Reconstruction" organized by the Department of Mathematical and Computer Sciences, Physical Sciences and Earth Sciences of the University of Messina, in cooperation with the Department of Geosciences of the University of Malta. In here we present the results obtaining by combining the 3D underground model and the 3D photogrammetric reconstruction.

RILIEVO 3D E GPR PER IL PATRIMONIO CULTURALE
IL CASO STUDIO DELLA CHIESA DEI SS. PIETRO E PAOLO D'AGRÒ A CASALVECCHIO SICULO
Lo sviluppo del rilievo 3D ha creato molte nuove possibilità di studiare il patrimonio culturale. I dati 3D acquisiti con fotocamere convenzionali e a basso costo possono essere utilizzati per la loro documentazione, per esaminarne l'aspetto completo, i materiali e lo stato di conservazione, per aiutare il processo di restauro e identificare le priorità di intervento. L'integrazione con l'indagine GPR potrebbe essere interessante per combinare la parte visibile e quella invisibile del monumento usando modelli 3D realizzati con fotogrammetria e risultati GPR convertiti in un modello 3D.
La chiesa dei SS. Pietro e Paolo D'Agrò a Casalvecchio Siculo è stata studiata nell'ambito della Scuola Nazionale "Scienza e Beni Culturali: dall'analisi non invasiva alla ricostruzione 3D" organizzata dal Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra dell'Università di Messina, in collaborazione con il Dipartimento di Geoscienze dell'Università di Malta. Qui presentiamo i risultati ottenuti combinando il modello sotterraneo 3D e la ricostruzione fotogrammetrica 3D.

KEYWORDS

geophysics, GPR, 3D reconstruction, photogrammetry, Sicily
geofisica, GPR, ricostruzione 3D, fotogrammetria, Sicilia

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DIGITAL SURVEY AND 3D DIGITALIZATION

3D archaeological field recording in Ostia

Axel Gering, Laura Pecchioli, Marco Dehner, Bendegúz Takáts

3D acquisition technologies such as Structure-from-Motion (SfM) or LiDAR have led to a recording revolution, as these methods are increasingly applied to field archaeology. In recent years SfM (essentially digital photogrammetry) became a very relevant tool to manage and record 3D information in archaeological sites [Alamouri *et al.*, 2010].

3D methods are today an essential part of the archaeological toolkit. Together with classical documentation methods like photography, hand-drawn plans and profiles, SfM provides an additional technical method of documentation, which produces high quality data that can also be revisited during post excavation examination. These methods allow accurate and precise recording with a relative minimum of field time. Also, the quality of digital photography has increased in recent years, as the technical equipment of better quality became more affordable. The potential to create photorealistic and spatially accurate representations of objects or areas of interest has opened up new horizons in 3D recording [Guidi *et al.*, 2009] and archaeological projects have made increasing efforts [Ortiz Sanz *et al.*, 2010; Al-Kheder *et al.*, 2010; Olson *et al.*, 2013; Verhoeven *et al.*, 2011].

The advantages of SfM for research as well as its technical issues have been widely discussed by researchers from different disciplines [e.g. Green *et al.*, 2014; Chiabrando *et al.*, 2015; Benavides Lopez *et al.*, 2016; König *et al.*, 2016, Leier *et al.*, 2017].

Interesting new applications for tablets and even smartphones are discussed by Bruce Hartzler and recently also by Noel Hidalgo Tan from the Australian National University[1]. Tan from the Australian National University. Both are showing the potential even in the usage of tablets to record on field[2]. In particular *iDig*[3] can help to record excavation data more easily and accurately[4]. In most cases the best method for documenting is the combination of different techniques.

3D acquisition in situ

In an archaeological excavation different types of information are produced in a relatively short amount of time. Recording of the *status quo* before an excavation goes on is essential. The objects are lying in situ and have to be documented in varying light conditions. Therefore, it is necessary to find an appropriate method and settings.

In 2016 and 2017 we used Agisosft PhotoScan[5] software, which is a reliable and affordable tool especially for archaeological fieldwork and post excavation examination, well known for its accuracy and easy access [Green *et al.*, 2014; Benavides Lopez *et al.*, 2016: 496; Koenig *et al.*, 2016:

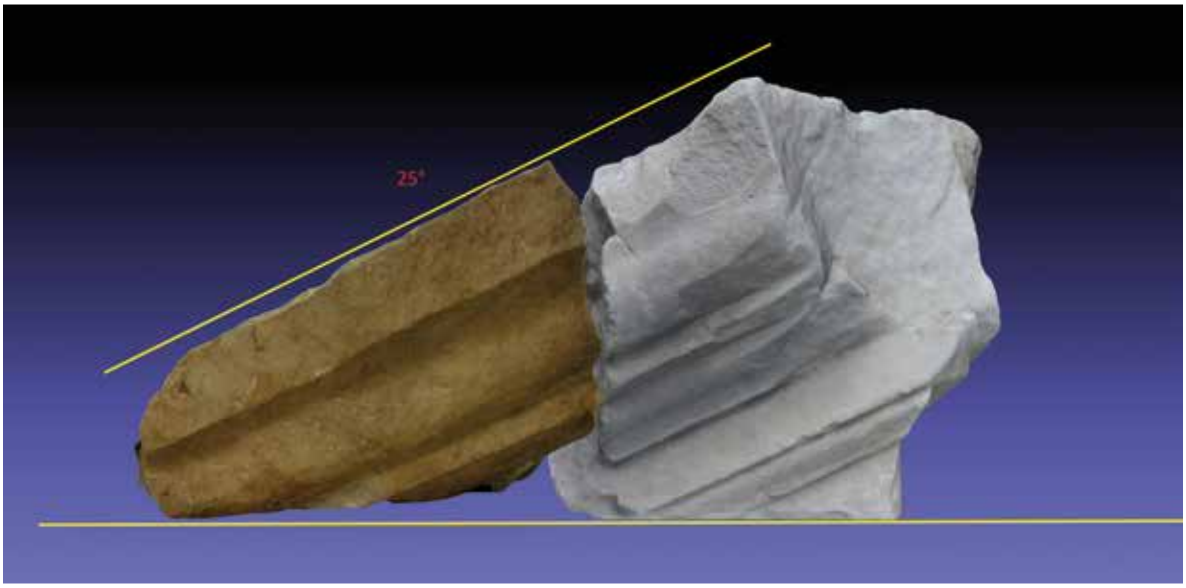

Fig. 1. Two 3D models of marble fragments reunited in MeshLab. *Source Axel Gering.*

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28]. It is used to document the progress of the excavation and to record each archaeological evidence ("context or stratigraphical unit") individually. In both campaigns Canon, Sony and Nikon digital cameras, iPad Pro 12.9-inch and a Tripod 360°[6] have been our photographic devices, as well as aerial photography with a Phantom III-Professional drone. For different material and purposes (from small finds to huge buildings) we adopted several methods/ approaches to our needs with a maximum of flexibility.

Method

The advantages of digital photogrammetry can be summarized as follows: low-cost and portable equipment, easy and fast in creating an archive for future needs, providing 3D models from small objects to large complex objects such as buildings or archaeological sites, varying high accuracy depending on the needs of the project, providing metric and vector data of the texture of the object due to its image-based nature [Hassani, 2015]. These methods were applied to the Forum of Ostia by the Ostia Forum Project since 2010 [Gering, 2011; 2014; 2017]. Below we illustrate the different methodologies and approaches used by the OFP team.

Recording small finds and marble fragments with Canon camera

The number of photographs needed depends on the features of the block, for example finely carved ornamental features need additional photographs to be taken from various angles. Light conditions are a very important factor while recording the photographs to create and texture 3D models of high quality, especially in an outdoor environment. It is necessary that the photographs show as little shadowed parts as possible in order to avoid gaps in the mesh.

Given that the camera settings, in this case a standard DSLR camera Canon EOS 550D with a standard lens used, are adjusted to the light conditions, the object can be recorded within 5 to 10 minutes. It is advisable to keep the same settings for the lens (in this case 32 mm) and not to use varying zoom settings. Recording an object with the same settings makes it easier for the SfM technique to identify corresponding points in order to connect specific features on the surface of the object and generate an accurate dense point cloud. Each block is documented in two steps. After a first documentation with 30-40 pictures (fig. 1), the block is rotated by 90° and the documentation has to be repeated. For both recorded views a separate dense point cloud will be generated in PhotoScan. After masking the object, both views (or chunks) can be merged (in the menu workflow 'Merge chunks') by using markers. A full 3D model of high quality can be calculated out of 60 to 80 photographs altogether, with an average size of 5000000 faces.

iPad Pro 12.9-inch to support archaeological fieldwork

Mobile computing (tablets and even smart phones) is becoming more and more widespread. These devices have an integrated camera. The quality of the camera is still less than a dedicated device, but they have computational power and storage to process the images, and do other computational tasks. This makes them interesting to collect, map and archive information also in archaeological research. One can combine GPS, mapping, software for databases and other tasks. The whole method of field-documentation has changed aiming for a completely digital workflow [Berggren *et al.*, 2015].

The simple convenience of displaying maps, taking quick notes or adding all kinds of digital information to a database with the same device is a big advantage. This can help to eliminate errors commonly encountered during the transfer of information from paper forms to a digital database. The disadvantages of tablet computers in the field is normally that the glare or reflection become invisible in the screen in direct sunlight. Several types of proprietary anti-glare (and screen protector) kits are available.

In 2016, the iPad Pro 12.9-inch was introduced as an on-site digital experiment to collect all photos, to record every phase of excavation and to create 3D models. The results have showed that tablets – or in this case the iPad – can be an ideal tool for field archaeology. Different applications can be interconnected on the iPad, some general purpose applications like Pixelmator or Filemaker.

In particular the photo quality achieved with the tablet's onboard camera proved more than sufficient for documenting both the terrain features under investigation and most of the archaeologically relevant material that team members located within that terrain. Additionally, wherever we required especially detailed photographic records, a high-quality digital camera was also available. In our marble-deposits in Ostia the iPad it has provided an excellent covering of the object or context (100-150 snapshots) with high detail and in less time[7] to create 3D models (fig. 2)[8]. High-resolution images on a big screen bring out details not visible to the naked eye. In this regard the tablet has been very useful to study the objects on-site in all perspectives by immediately reviewing the images [Pecchioli, 2018].

The experiences of the field-campaign 2016 showed that tablets are appropriate tools for recording most of the informations and working-processes on-site, but of course it doesn't cover all purposes. Additionally other digital cameras and for fast processing and bigger storage capacity also laptops with external harddrives are needed in order to optimize methods and the workflow on site.

Recording larger surfaces with Sony cameras

The main part of marble and ceramic objects in 2017 was recorded with Sony cyber shot RX100 mark I and mark III. The Sony mark remains our favourite camera for every-day 3D photo taking, producing excellent photos with 28 mm in the advanced automatic mode. The room TFR_2, which was the focus of the work in the seasons 2016 and 2017, has a surface of roughly 25 square meters. The surrounding brick walls are 2-3 meters high. This gave us the opportunity to take photos also from about 4-5 meters above the ground level, not only from inside the room,

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Fig. 2. 3D model of surface structures of a closed archaeological context (2016). *Source http://ostiaforumproject.com/chapter-2-temple-votives-and-kitchen-gear-an-inventory-of-the-capitolium-cult-and-its-predecessors/*

where some supplementing detail-photos helped to avoid gaps in the model underneath the overlapping stones of the marble-deposit.

Recording buildings with Phantom III drone and supplementing ground-based photos

In 2016 Bendegúz Takáts from the Pázmany Péter Catholic University used for the documentation of the room's surfaces a Phantom III drone and its included camera.

Beside single objects and little but detailed 3D documentations of important single-contexts[10] the main focus was to document the several stages of the excavation of the room TFR_2 by overall models. Here we used a range from 300-350 pictures, aerial views and photographs taken additionally from inside the room to cover all complex details. In 2017, when almost all stones were removed, a flat surface had to be recorded. Most of the pictures were taken from all four sides above the walls, while only deeper pits or structures were photographed by walking inside the room. The excellent contrast quality of the Sony-sensor allowed to get all details even from above even in light conditions of the early evening, when no direct sunlight came into the room anymore. Using high quality for aligning and medium quality for the cloud-building, calculation time of the dense cloud still was 16 hours (with a quadcore i7 of 7th generation and 16 GB RAM). Several 3D-models of a superficial ceramic depot next to a well could be brought together with the same tags in one overall 3D-model with different colouring in MeshLab (fig. 3).

Fig. 3. Several 3D models of a building pit with a well and a superficial sacrificial deposit next to it. *Source Axel Gering.*

3

Measuring points were taken in 2016 and 2017 by our Hungarian cooperation partners. Their first TFR_2 model photographed from the drone, georeferenced by more than 36 measuring-points with Agisoft PhotoScan Professional, was the fundament to incorporate all further models of the room (for further stages of the ongoing excavations). The aim was to document every main step of the excavation in an overall 3D model at the end of every two or three working days, supplemented by detailed models of all important contexts. Based on an orthographic screenshot of the rooms surface, all context plans were drawn during and after the campaign 2017 (fig. 4).

The question remains: how to use 3D models for classical publishing? PhotoScan allows to capture and export views (as screenshot-jpg) also with a high resolution of 12000 pixels x ca. 6100 pixels. Taking the screenshots in the orthophoto-mode (no perspective for plan-drawing) directly from the Agisoft-project files guarantees no loss of quality which definitely cannot be avoided when exporting the model to object- or ply-files and using other programmes like MeshLab or Cloud Compare. Only the "original model" screenshots guarantee a sufficient resolution when these orthophotos were taken as background for drawing the plans with Photoshop and Adobe Illustrator 6.0.

Beside our recording of TFR_2 the main focus since 2016 was the complete documentation of all remains of the Temple of Roma and Augustus (TRA) in the south of the Forum (fig. 5). 699 aerial photographs were taken with RPAS recording WGS 84 coordinates with every picture using its on-board GPS receiver producing an average of 1609084 meters of total error. A real time kinematic GNSS Base was set over the geodesic point at the Capitolium. Six 12-bit A4 targets were placed on the temple's podium, measured by a Leica GS14 GNSS and CS15 Field controller. Out of six targets, the measurements proved to be accurate at five resulting in an average of 0.034691 meters total error, thus greatly improving the accuracy of the georeferencing.

699 photos were aligned with "High accuracy", the default 40000 Key point and 4000 Tie point limit, "Generic" and "Reference" preselections deselected. The targets used on field were identified by the software using the "Detect marker" command.

Results

Marble fragments can show some problems for 3D documentation linked to the light subsurface dispersion, which is a robust challenge for the digital survey: almost all our marble fragments fortunately had a patina, problems with a glancing surface did only occur with one Egyptian object which was made from extremely polished black stone.

The model for the room TFR_2 was georeferenced, and all data are considered in Gering's orthophoto-based context-plan showing the sequence of several steps of our work emptying the marble-deposit. Ceramic- and marble-objects in 3D files are kept on three sets of external hard-disks for post-excavation-work. Sections for publications were drawn basing on the 3D models. An implementation of reduced 3D models for web-based access via our webpage[11] is planned.

The final orthomosaic of the temple TRA with 8217 x 9102 pixels with written alpha channels for further GIS and CAD use was used to be the background of the temple's reconstruction. Further 3D models of single finds provide the advantage of simple measuring, even if the desired object is almost out of reach or too high: In Pisa's main church, a side-door ("Porta Santa") was decorated still in the 11th century with *spolia* brought from Ostia. The orthophotos showed for the first time their exact measurements, an estimated intercolumnium of minimal 282 cm and with the fitting capital put on top a measured intercolumnium (fig. 6) of 10 Roman feet (296.4 cm).

By projecting the podium underneath the plan (fig. 6) also several mistakes which had occurred during the building-process, could be seen clearly (different positions for the pronaos' columns which resemble a possible change of plan or architect and a deviation of 1.3° of the supporting wall underneath the west row of inner columns). Obviously, the building stood at least four centuries, so the podium's concrete vaulting underneath the inner columns has proofed to be sufficient even with this mistake. The exact measuring of more than 250 relevant finds so far (roughly 12000 marbles were systematically checked to find them [Gering, 2017]) attached in the plan allowed to reconstruct the illumination system of this temple which seems to be unique: small windows of 21 cm width open directly into the back-wall of the four niches of each longitudinal wall[12].

The architrave in Pisa recorded in 2018 forced us to reconsider our former reconstruction-hypothesis of five full columns inside the cella[13]. Thanks to the Pisa-evidence we can reconstruct now the only possible position of the cella-blocks underneath the niches. The result is quite surprising: the method of illuminating indirectly the statues in the niches of the temple's longitudinal walls does not have a correspondence before Antonine age, so this Augustean temple marks an important innovation in the history of architecture.

Still work in progress is the full reconstruction of the temple with sketch-up including its implemented possibilities of reconstructing the temple's inside-illumination according to different daytime and a data-base for all relevant fragments belonging to the actual temple-reconstruction[14].

Unfortunately, the future accessibility for 3D data remains unknown. The situation has improved lately with open standards becoming more widely used, especially in mobile platforms, but it is still a complex issue. Text, html, and jpeg or png images are quite "future-proof", and preserving them is a good option at least for SfM to allow one to later recreate again a 3D model if the original one cannot be read anymore.

Fig. 4. 3D model of a room-surface immediately below a marble deposit with coloured contexts of several sacrificial deposits and votive pits. *Source Axel Gering*.

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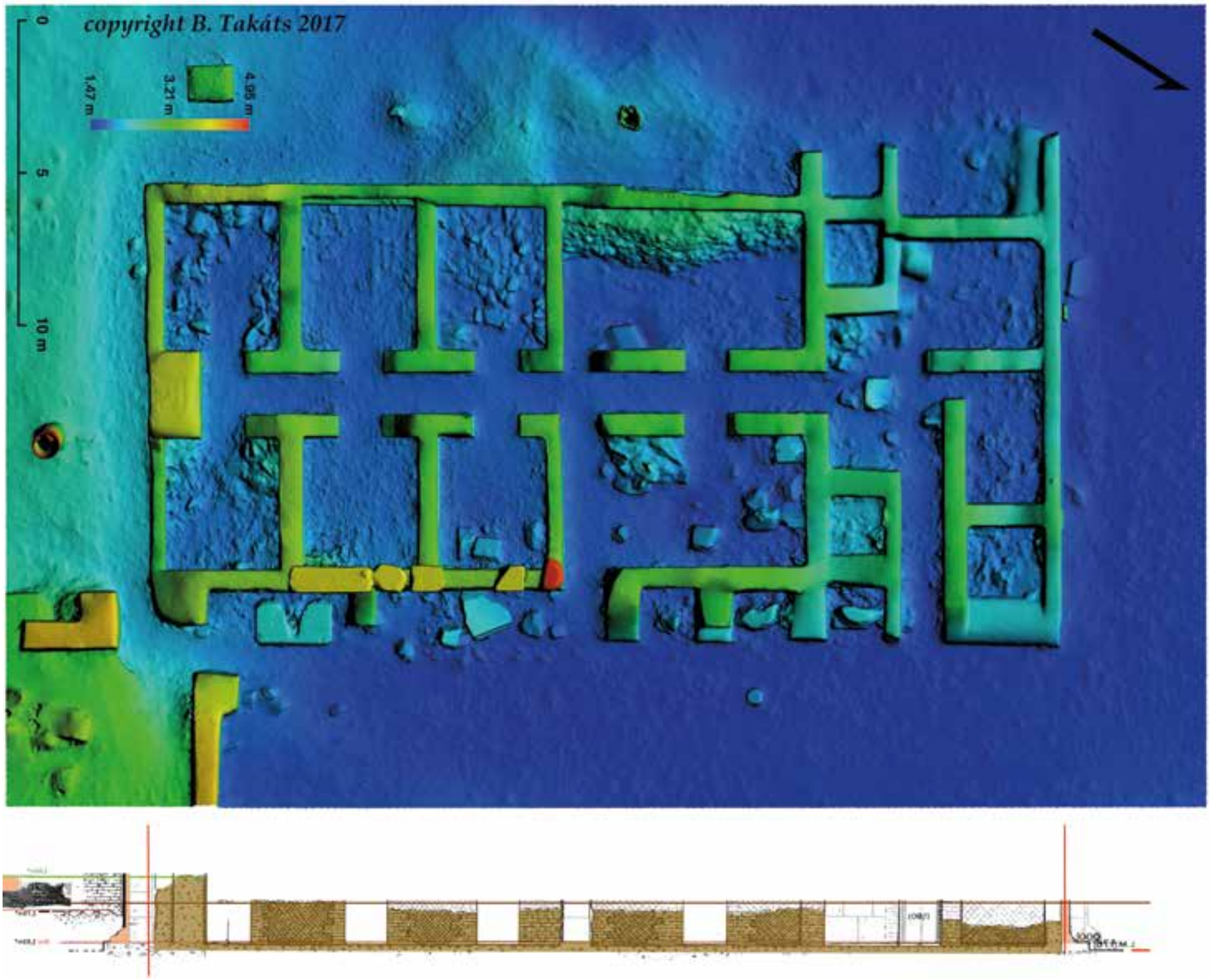

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Fig. 5. False coloured elevation model based on 3D model of a temple podium. *Source Bendegúz Takáts*.

Outlook: using URLs and QR-codes to identify objects

How can we identify documented fragments/evidence in the post-processing? We found our solution: labels with QR-code point to a unique webpage for each fragment.

This does not just give unique identifiers to the fragments, but does allow us to set up a web page to describe them. Furthermore, automatic analysis of the photo assigns them to “their” fragment. Images can be stored in fragment specific folders using this method.

Making the data available through the web also without plugins or javascript is probably one of the best ways to ensure future accessibility.

Conclusions

The different recording methods developed for the requirements of the Ostia Forum Project are promising in their flexibility and cost efficiency. Also, the standards for photogrammetric photography and basic camera settings were set for future campaigns. The results show the potential of the current generation of SfM technique and the accuracy in 3D documentation in situ.

Finally, the generated 3D models are convincing in their accuracy and also the appearance of the digitized architectural elements is satisfying. All plans were drawn based on the models.

The final results, edited and optimized in different solutions for multimedia presentation and prototyping are soon ready for further usage, like the implementation in the multimedia detail database.

NOTES

1. IT Specialist for the Agora Excavations in Athens; http://agathe.gr/.

2. Noel Hidalgo Tan has presented a paper at the Australian Archaeological Association on his use of tablets to record the location and motif details of rock art in Thailand: http://www.southeastasianarchaeology.com/2011/12/07/ipad-record-rock-art/.

3. http://idig.tips/.

4. http://www.ascsa.edu.gr/index.php/news/newsDetails/bruce-on-idig.

5. We used VisualSfM, MeshLab, CloudCompare, Photoshop and Adobe Illustrator in PostProcessing. Beside using Agisoft PhotoScan as our favorite 3D tool we tested earlier different types of 3D acquisition methods: 123D Catch is a good free app that lets to create 3D scans of virtually any object, but in field it does not ensure complete coverage and has some offline mode problems. Sketchfab offers an efficient web-based platform for creating and sharing 3D content. Nor-

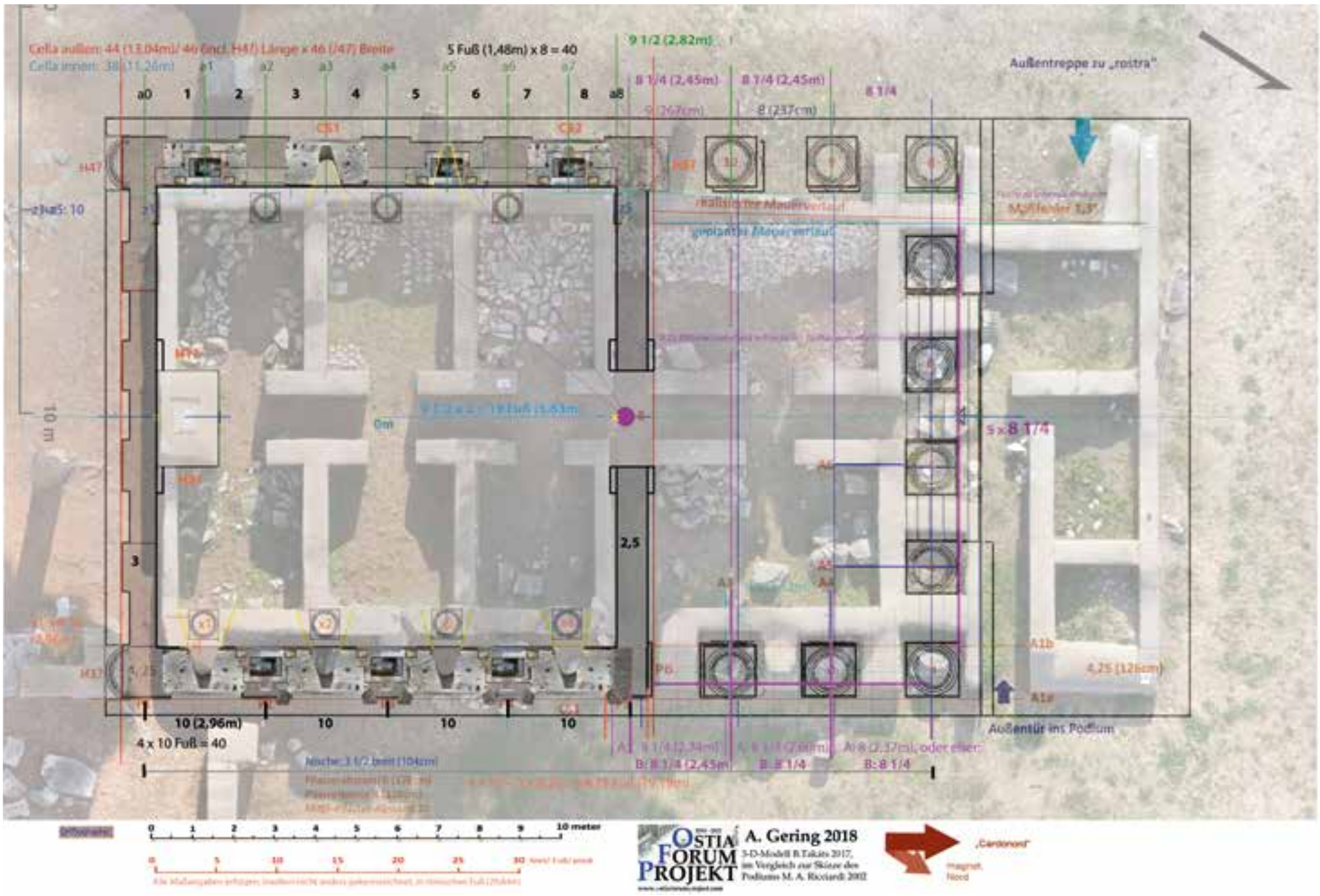

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Fig. 6. Reconstruction of the complete layout of a lost temple based on the 3D model of its podium remains and single marble fragments.
Source Axel Gering.

mally one can upload especially small objects: http://www.hypergridbusiness.com/2016/08/sketchfab-offers-nearly-a-million-vr-models/.

6. In order to use this construction in wood, a relatively flat horizontal area is needed, but owing to its weight, a fast repositioning is no problem, also in case the light conditions change. The installation for the monopod provided the possibility to spin the camera around the object at a constant height and distance, while the object was centered. Also, the camera could easily be moved up and down to get photographs from top or bottom angles. However, because of its light-weighed construction this framework was not solid enough to carry architectural elements larger than 30 x 20 x 20 cm. While moving the camera around the object, every 20 to 22 degrees a shot was made with the whole object in focus, getting 48 pictures of one view (realized by Fawzi Mohamed and Laura Pecchioli).

7. https://rangitotoarchaeology14.wordpress.com/tag/ipad-archaeology/.

8. As frequently found in temple-contexts of the whole Graeco-Roman world, these lits once covered little ceramic bowls in which the meat of the sacrificed animals could have been served to the spectators. So, it is hardly another coincidence that we have found in one room-corner a surface of a bone-deposit, which seems to have consisted of several big bones of bulls, maybe even with cutting-marks on the bones themselves. Due to reasons of conservation after fotographing we left the bones covered in their original context waiting for further specialized analysis.

9. http://arch-pad.blogspot.de/2012/.

10. See Pecchioli's contribution to context "Method" and others.

11. http://ostiaforumproject.com/.

12. Compare the contribution of Daniel Damgaard in this volume: the possibilities of further illumination of the roof is dicussed there.

13. East longitudinal wall.

14. *Idem* in note 9.

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Thanks to the courtesy and hospitality of the directors of the "Scavi di Ostia", Angelo Pellegrino, Cinzia Morelli and Mariarosaria Barbera, and the Superintendence of Rome and Ostia we had the chance since years to work up all material from old and recent excavations regarding the Forum. We like to thank Paola Germoni and the Humboldt-University-team too and our Hungarian colleagues: thanks to Gabor Bertok, Zsolt Wagner, Bendegúz Takáts, Zsombor Györffy-Villám, Fawzi Mohamed (Fritz Haber Institute, Berlin) and all other members of the team: http://www.ostiaforumproject.com; http://www.iovia.eu.

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ABSTRACT

3D ARCHAEOLOGICAL FIELD RECORDING IN OSTIA
Since 2010, the Ostia Forum Project of the Humboldt-University of Berlin (Winckelmann-Institute) involves 3D documentation methods. In 2010 we cooperated with the German Aerospace (DLR), in 2011 with TOPOI Berlin (https://www.topoi.org/home/about-topoi/) using laser scanners. Since 2012 photogrammetry became more accessible and efficient every year so we tried it on our own, and since 2015 with the help of our new Hungarian cooperation partners from Pázmany Péter Catholic University at Budapest. This article lines out our actual 3D work and digital workflow during the archaeological campaigns 2016 and 2017 in Ostia Antica, starting from modelling small finds, archaeological contexts and catalogue with QR-codes to rooms, buildings and the whole site.

DOCUMENTAZIONE 3D IN SITU A OSTIA
Dal 2010, l'Ostia Forum Project dell'Università Humboldt di Berlino (Winckelmann-Institute) prevede metodi di documentazione 3D. Nel 2010 abbiamo collaborato con il Centro Aerospaziale Tedesco (DLR), nel 2011 con TOPOI Berlin (https://www.topoi.org/home/about-topoi/) utilizzando scanner laser. Dal 2012 la fotogrammetria è diventata più accessibile ed efficiente ogni anno, di conseguenza l'abbiamo impiegata e, dal 2015, con l'assistenza dei nostri nuovi partner di cooperazione ungheresi dell'Università Cattolica Pázmany Péter di Budapest. Questo articolo illustra il nostro attuale lavoro 3D e il flusso di lavoro digitale durante le campagne archeologiche del 2016 e del 2017 a Ostia, partendo dalla modellazione di piccoli reperti, contesti archeologici e dal catalogo con QR-codes per ambienti, edifici e per l'intero sito.

KEYWORDS

3D acquisition, Structure-from-Motion, PhotoScan, Ostia, QR-code, URLs, iPad
acquisizione 3D, Structure-from-Motion, PhotoScan, Ostia, QR-code, URLs, iPad

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DIGITAL SURVEY AND 3D DIGITALIZATION

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

This paper is focused on the 3D documentation of cultural objects, in the framework of a multidisciplinary study on a pair of wooden gates belonging to a water channel lock, now preserved in the National Museum of Science and Technology Leonardo da Vinci (MUST) in Milan.

The primary goal of our project was to promote those gates, reintegrating them into the collective heritage of the city, giving them back their historical and artistic dignity. For reaching this aim, we investigated the objects considering their overall life cycle, starting from the acquisition of the raw materials and their processing, through the production and distribution, use, reuse and discard. Such investigations studied how, where and when the objects were made, where they were distributed, their utilization and diffusion.

Answering these questions requires a holistic approach that takes full account of the fact that production, distribution, and use, are correlated with each other and, therefore, interact with the associated environmental, economic, social, political and technological contexts.

Following this approach, our attention was focused on the history of the canals and waterways of Milan. Since 1400 the Lombardy region, Milan, in particular, has been a technological center of excellence; the scientific research, started in Renaissance courts with the work of Leonardo da Vinci, continues nowadays into Milan Universities. Between 1457 and 1471 the ducal engineer Bertola da Novate built the Martesana Canal. In the following years, some locks were incorporated

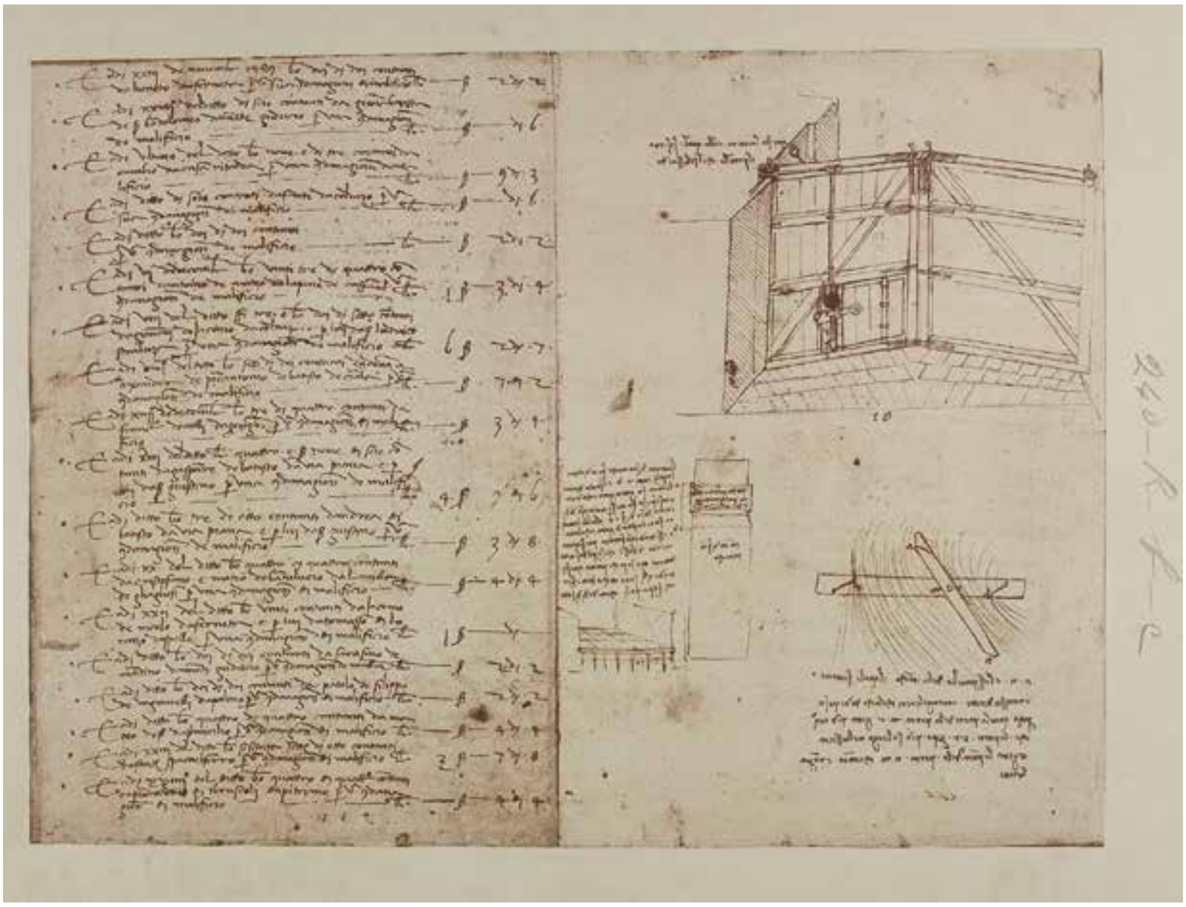

Fig. 1. Leonardo da Vinci, the lock near San Marco, from the *Codex Atlanticus*, folio 656r-a (ex 240r-c), in the version published by the Lincei Academy (1894-1904), National Museum of Science and Technology Leonardo da Vinci, Milan.

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and documented by Leonardo da Vinci in his drawings. All the wooden locks of the Milan canals Navigli, are derived from this cultural tradition. The study of such artifacts, due to the interdisciplinary approach needed, was a challenging scientific investigation in the field of conservation.

The Museum of Science and Technology contains different elements related to various locks of the Milan canals system. The components we examined include: i) a complete pair of gates belonging to the same lock, each one with a small controllable aperture; ii) a set of pieces from a wooden dismounted gate, and iii) some stone components probably representing the submerged structure blocking the gate rotation when the door was closed.

The focus of our work was then directed on the pair of gates that are better conserved. Each gate is 3 meters large and 1.5 meters tall, with a thickness of 0.4 meters, so its weight is in the order of hundreds of kilograms. For this reason, a complicated system for their movements was used. The gates have been placed on specially designed structures as to facilitate access to any part by the operators in the diagnostic phase and to ensure the possibility of intervention for future restorations.

Our research team, through a wide range of in-depth and multidisciplinary studies, tried to solve the problems related to the diachronic reconstruction, structural evolution and to determine the state of conservation of the gates.

The significant historical research was first aimed at investigating the history of the artifacts and at solving issues related to the origin and the circumstances of their arrival at the museum. In support of such humanistic research, a diagnostic campaign has been developed, involving different technical analyses.

A historical reconstruction of the wooden components has solved the doubts about the age, the role of the constituent parts of the artifacts. Micro samples from both gates were taken according to the particular indication of the restorers. The wooden fragments were subjected to radiocarbon dating by the Department of Materials Science, University of Milan-Bicocca [Poldi *et al.*, 2009].

The same collection of samples was assessed to study the state of degradation of the wood material by the Department of Environmental Sciences and Earth Sciences, University of Milan-Bicocca. In particular, the wood species through DNA analysis and the material preservation status was assessed.

Some X-ray surveys have been carried out with the aim of determining the structural and technological evolution of the gates. The study was performed by using a portable X-ray tube at the museum, by the Department of Physics at the University of Milan.

A high-resolution 3D survey made by Politecnico of Milan has completed the technical documentation of those artifacts by accurately capturing their shape with digital photogrammetry. The first paragraph describes the documentation available regarding the history of the gates, from their design to their arrival in the museum; the next one shows how the 3D digitization was achieved and which were the technical choices for obtaining enough details from the model. The third paragraph shows how the 3D model was used for this project and the last one includes a discussion, conclusions and some considerations for possible future developments of this research.

Historical context and placement in the museum

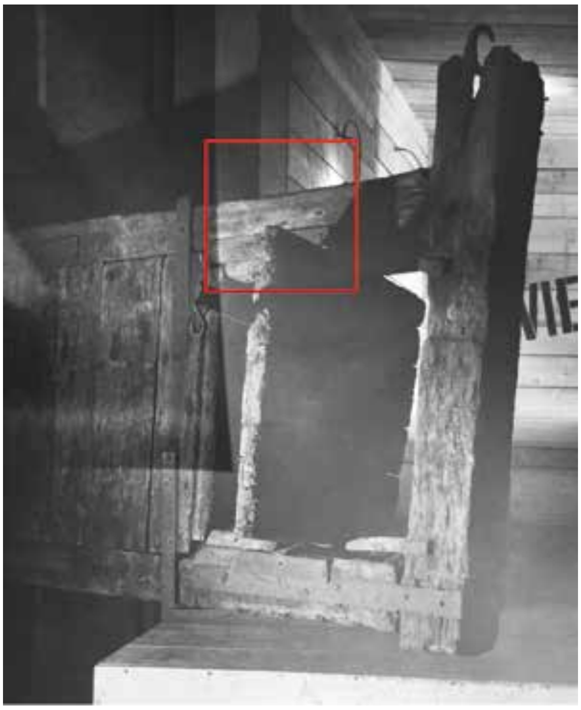
The wooden lock of the Navigli canals, preserved in the National Museum of Science and Technology Leonardo da Vinci in Milan, is considered to be an excellence of the 15th century Lombardy cultural heritage. The historical research has allowed to reconstruct the entangled chronological steps of the artifact and to gather a coherent identification of them. The lock was a technical device that allowed continual navigation through the Milanese canals and thereby giving rise to a flourishing commerce. This matter, amongst others, was of interest even to Leonardo da Vinci. From the beginning of his arrival in Milan in 1482, he studied the subject in depth to understand its hydraulic engineering. In this way, he was able to offer precious improvements to solutions already in existence in the surrounding territory [Calì *et al.*, 2015][1]. The most direct referral is the well-known drawing for the lock of San Marco, found in the *Codex Atlanticus* on folio 656r-a (ex 240r-c) dated 1493-95[2] (fig. 1). Trace of this past has come to us thanks to a careful management of Milanese waterways over the centuries as evidenced by the historical documents housed in the Milan State Archives[3]. When the Navigli network was discarded, and the inner Canal was covered over from 1929-30, the authorities had the Martesana locks preserved as they were of historical interest.

So, in 1935, the lock gates of San Marco were removed and later those coming from the lock of Cascina dei Pomi in 1967. Following various relocations[4], the two lock gates reached the MUST areas[5]. In order to identify them, a comparison between the lock gates and the documentation in the recovered archives was carried out both photographically and technically[6] (figs. 2a/b). Both comparisons reinforced the opinion that the most appropriate thesis identifies the lock gates studied at the museum with that removed from the supporting beams of San Marco. The conclusion enhances the concept of “Leonardo’s legacy” and the historical excellence of the artifact, establishing an ideal connection with the lock described and represented by Leonardo on folio 656 of the *Codex Atlanticus*.

3D digital survey and modeling

One of the crucial points of the study conducted over the gates was their 3D digitization and modeling aiming at:

– producing a digital replica of them to be used as a geometric reference for accurately measuring the artifact and its components, as a visual reference being texturized at high resolution, and as “3D notepad” for attaching on his surface annotation and results coming from other analyses;



2a

2b

Fig. 2. Images of a gate of the lock: picture of the 1950s representing a gate of the San Marco's lock (a); picture of the gate studied in this research, apparently the same shown in the previous image (b).

- virtually slicing the artifact for studying the thickness and the deformation of the various wooden planks composing each gate;
- position the two gates in a single reference system for verifying the real belonging of them to the same lock, also simulating the relative movements of the different components.

Given the objectives of this study, we choose to digitize the artifact with a photogrammetric approach using the Structure-from-Motion/Image Matching (SfM/IM) technique that does not involve the use of specific and cumbersome equipment on the field. This choice was motivated by the practical difficulty in handling such heavy objects and the need of interacting in the same places with other research groups trying to minimize any interference with their work.

The 3D survey was carried out by acquiring a set of images at the museum. A 3D resolution of 1 mm and a measurement uncertainty better than 0.25 mm were identified as optimal for the aims of the general study on this old lock.

Given these requirements, the photographic parameters have been set. The camera used was a Sony Nex 6 equipped with a Zeiss 24 mm f/1.8 lens. Such camera employs an APS sensor sized 23.5 mm x 15.6 mm featuring 4912 x 3264 pixels, providing, therefore, a pixel size of 4.78 x 4.78 µm.

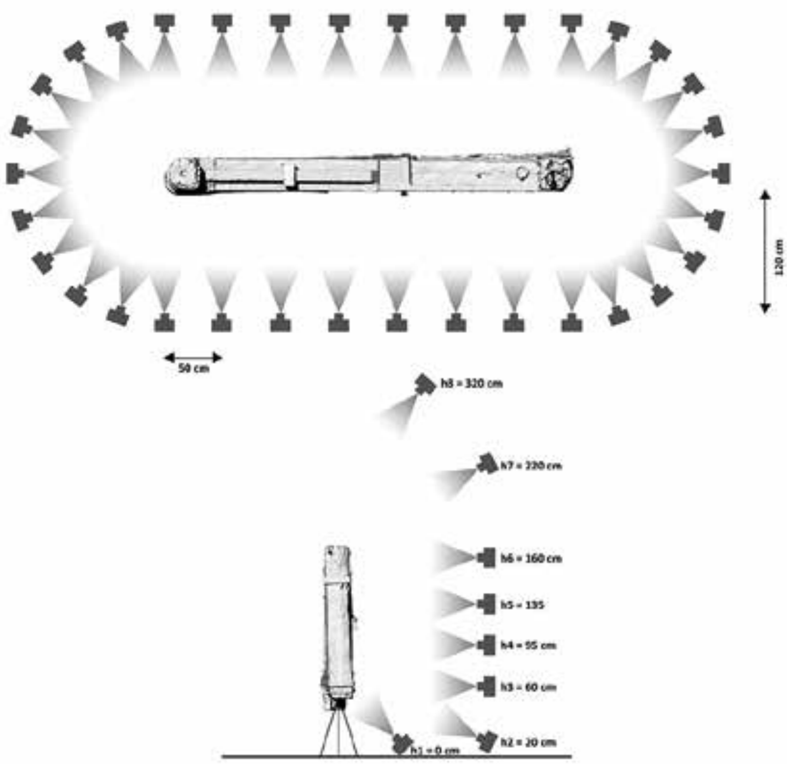
Given the characteristics of this large artifact, we decided, in agreement with all the other researchers of the group, to employ a spatial resolution of 1 mm.

The photogrammetric processing was made with Agisoft PhotoScan with a setting, for the Image Matching phase, which involves the generation of one 3D point every four image pixels (Medium quality). Therefore, the spacing between adjacent pixels on the pictures used for the photogrammetric survey, i.e., the Ground Sampling Distance (GSD), was set at 0.25 mm. As a consequence, considering the focal length of the lens used (24 mm) and the pixel size (4.78 x 4.78 µm), the camera-to-object distance was set equal to 120 cm, as shown in figure 3.

Ten pairs of coded targets were located around the artifact, automatically recognizable by the photogrammetric software. A few target-to-target distances were measured and used as references for scaling the photogrammetric project.

Each gate was captured with about 250 landscape photographs taken at 1.2 meters of camera-surface distance.

Fig. 3. Horizontal and vertical shooting scheme for the optimal coverage of the objects surface, including the required image overlap.



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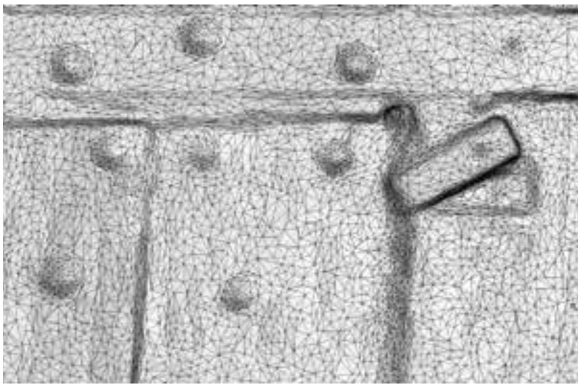
TORNA AL SOMMARIO


4a

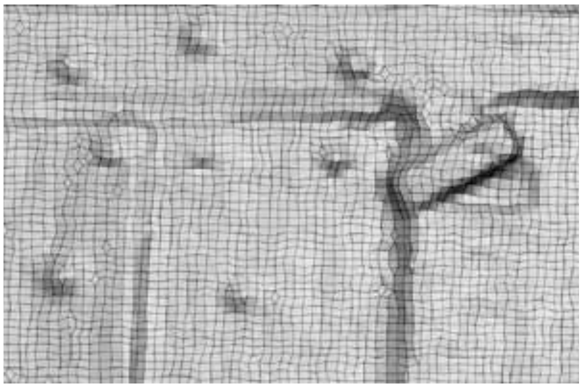

4b

Fig. 4. Details of the model: triangular mesh resulting from the 3D dense cloud originated by the photogrammetric acquisition (a); quadrangular mesh arising out of the re-topology step (b).

The set of images was generated by displacing the camera 0.50 meters horizontally all around each gate, creating image loops at a different height. The camera was then displaced vertically by 0.35 meters for generating different image loops. In this way, an image-overlap of at least 60 % was guaranteed.

In addition to these images, for each artifact, a few pictures from a long distance were taken (up to 3 meters) in order to frame the photo shot including all targets. Finally, a few high-resolution images were taken at about 0.5 meters camera-surface distance, for documenting unique features and points of particular interest such as the connections between different wooden elements or the presence of metallic components.

The acquired images have been then processed with SFM, that automatically detect image features through the SIFT algorithm, identifying those with correspondences in other images leading to the identification of more than 100k tie points, reduced to 23k after cleaning the points too far from the scene and those with a re-projection error above 0.5 pixels.

In this phase, the photogrammetric project has been scaled with some long target-to-target distances, using the short target-to-target distances for quality check. In this way, a maximum error of 0.425 mm was found, with a standard deviation between the various reference data of 0.250 mm.

With the resulting oriented images, a dense cloud has been generated by the Image Matching process, originating a 12 million points 3D colour cloud. Starting from this dataset a 2.5 million polygon mesh was produced.

One of the purposes of the 3D model was to generate video-animations for showing the functioning of the lock for managing water levels. A particular post-production work has been done for: a) the optimization of the acquired 3D model; b) the semantic subdivision of the different parts and c) the keyframe animation.

The 3D models obtained through digital acquisition have in general high quality, but they are made of a mesh with a huge number of polygons. A high polygon density involves that the model cannot be easily used for rendering due to its geometrical complexity and the following significant amount of memory required for managing it.

The optimization process aims at reducing the number of polygons of the 3D model when redundant, maintaining the metric coherence to the original one. The high-resolution 3D model made of a dense mesh of triangular polygons, featuring possible holes and topological incoherencies, has been then re-topologized with a brand-new structure of quadrangular polygons arranged over the original mesh in such a way to follow the object features and adapt their size to the scale of the underlying features. In this way, a quasi-planar area will be described by large polygons while small details will require a far greater number of tiny polygons. The resulting optimized mesh is therefore much smaller in file size, still maintaining the geometrical information of the original one [Guidi *et al.*, 2016]. Also, the re-coded model is made by quadrangular elements instead of triangular, with no holes and no topological errors (figs. 4a/b).

Each simplified mesh model, even when very detailed, is made of a single mesh with no distinctions between the various components. For this reason, after the simplification, every model has been segmented into parts according to semantic criteria, to obtain different independent digital objects starting from the same unique mesh. Such segmentation has been important also for producing the animation of the lock, explaining how its mechanical movements work.

The result of the semantic subdivision of the whole lock originated a 3D model made of four levels, each containing a single mesh model: left gate, left gate mechanism, right gate, right gate mechanism. In this way, this model could show each component separately moving, becoming therefore suitable for the following animation production.

Applications of the 3D model

The high-resolution 3D models obtained according to the process described above, have been employed in different ways for supporting the scientific investigations of the other teams of the research group or for making visible to a public of non-specialists the results of the reconstruction hypotheses.

First of all, the mesh models, both texturized or not, have been used by the conservators for making an accurate analysis of the lock. Considering the size and weight of each gate, the movement of each of them was definitely out of the question, but also the access to each object from a human operator was relatively limited. Thanks to the digital 3D model the scholars have had the opportunity to turn around the objects to be studied by every possible direction, looking at it from the point of views more convenient for their particular purposes. Due to the high resolution of the geometrical model and the associated texture, and thanks to the inherent flexibility of the 3D visualization, the model could be easily zoomed even above the 1:1 scale. In this way also details hardly evident to a direct view on the real artifact with the standard illumination available at the museum, could be put in great evidence.

The digital version of the lock and its components have been used for example for correctly relocating the different parts differently from the way they were arranged in the exhibition, with the two gates of the lock not close to each other, and with one gate upside down to the other.

Thanks to its high level of detail of the 3D model have been suitable for evaluating the conservation conditions of the object. The "shade" visualization mode, where the model is shown in one uniform colour and with no texture, has been particularly functional for estimating the co-planarity of the different wooden planks making the gate, the possible breaks into the wood, or the presence of metallic fixtures as nails or hooks.

Other sub-products have been then extracted by the 3D model of the lock.

The first and most typical document is the high-resolution ortho-image of each face of the two lock's gates. It is a metric image, suitable for being loaded into a CAD system for annotating possible zones needing restoration, possibly measuring their area.

Also, a set of curves originated by the intersection of each gate's model with a set of horizontal and vertical parallel planes spaced 10 cm each other, has been extracted (fig. 5). Such curves represent an alternative way of analyzing some specific 3D features of the lock, just working on the 2D domain of the section curve.

One of the most interesting points in using three-dimensional models is the possibility to use them for performing various types of simulations.

Thanks to these models it was possible for example to simulate the movement of the different parts, the main gates and the small doors within any gate, during the various phases of the management of water levels in the passage of watercraft from an upper level to a lower level and back.

Once the simulation clarified how the lock used to work, a video animation has been produced for explaining such result to the public. The technique used was the keyframe animation where the different components of the 3D model are set in specific configurations correspondingly to particular time instants, and the software interpolates the various positions between them providing in this way a moving scene. A few frames of the video are shown in figures 6a/b.

Discussion and conclusions

As demonstrated in the literature by several pieces of research involving studies in depth on specific historical architectures [Micoli *et al.*, 2013] or archaeological sites [Clark *et al.*, 2006; Micoli *et al.*, 2017], the use of interdisciplinary approaches is crucial for discovering new information on a heritage asset that a single discipline alone would not allow obtaining. In this paper, we have shown the same concept transferred to a single artifact. Reality-based 3D modeling based on the accurate digital acquisition of the shape and visual aspect of the object under

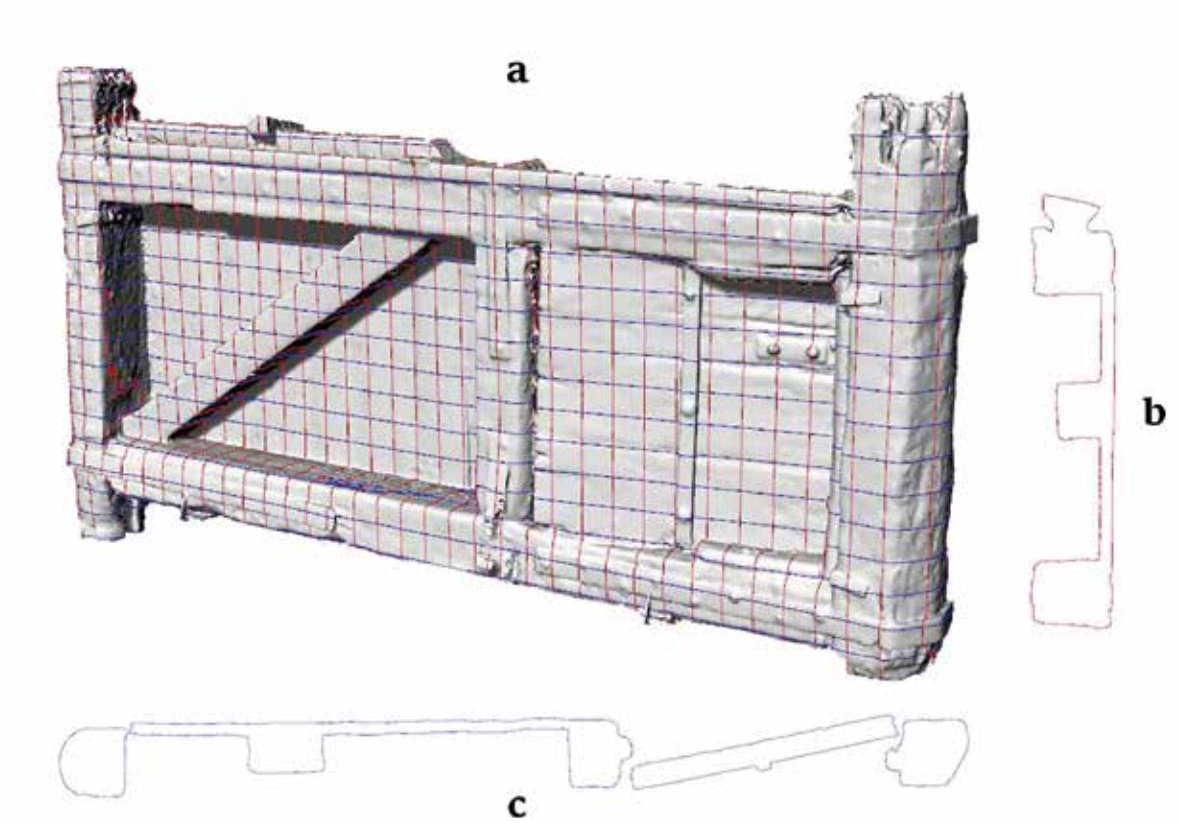


Fig. 5. Right lock's gate: 3D model visualized with no texture (a); vertical section taken at 0.75 m from the gate left end (b); horizontal section taken at about half of the gate height (c).

6a

6b

Fig. 6. Movements of the gates when a watercraft is passing the lock coming from a stretch of water at the higher level and has to reach the lower level. Frames of the animation produced, associated with different phases: the lock completely closed (a); the lock closed with the two internal mechanisms open for lowering the water level in the locked area (b).

study [Guidi, 2014] has been demonstrated to be an essential tool for supporting this approach. It can be in fact utilized as a reference for associating different analysis to the same artifact, such as RX images, C14 dating, DNA mapping of the organic materials involved, etc.

However, the investigation on the lock's gates conserved at the MUST demonstrates how, even on artifacts of limited size, a digital 3D model is a highly useful form of documentation in itself. As a matter of facts, being a metric representation, it can be used as an element for accurately analyzing the shape and size of the object of the study. Also, especially for an object like the lock examined in this paper, made by different components each of considerable weight whose movement would involve cumbersome equipment and not-negligible costs, the presence of a 3D model allows to quickly test different positioning of the components just in a digital space. This flexibility represents a significant help in general. But it is especially useful for artifacts that are poorly conserved and are broken into several parts that need to be reconnected in space for regaining their original sense.

Therefore, the work done till now on the most well-conserved parts of the locks that have been studied in the present research could be in the future be extended to other sparse fragments conserved at the MUST on which much more philological doubts arise.

For example, a great group of wooden components of the same kind of those used in the lock shown in this paper, are stacked in a closed area of the MUST. As a possible future research, the 3D acquisition of any single fragment would allow attempting a virtual reconstruction of the original artifact through the solution of a 3D digital puzzle. Such kind of works could rely on the results of other significant research projects dealing with the automatic digital reconstruction of fragmented items starting from the 3D models of each fragment [Papaioannou *et al.*, 2002; Koller *et al.*, 2006]. The composition of this virtual puzzle would allow verifying if those elements all belong to the same lock and if the resulting artifact is similar to the other better conserved and shown in this paper. It would also allow making further historical hypotheses on the provenance of the lock and its possible relationship with Leonardo da Vinci that designed some similar ones.

Another group of objects that could be studied is represented by a group of stone blocks conserved in the backyard of the MUST. Those blocks nowadays seem just random pieces of rock on the ground. But, according to the historical documents studied in this research, they should have arrived at the museum together with the artifacts considered in this paper and were generically tagged as structural components of a lock. No clues are available if these are part of that particular lock or another one. The 3D scanning of each part and their virtual recomposition with the existing wooden gates would allow checking different historical hypotheses gaining new pieces of knowledge.

In conclusion, the works done confirms that the accurate reality-based 3D modeling of an artifact is a crucial step for studying a heritage object whose origin is unclear, especially when it is made by different parts whose geometric coherence can confirm or not particular historical hypotheses.

Once the model has been used for its "functional" role, it can also be employed as a visual tool for explaining the heritage object, including its dynamic behavior, not easy to be understood on the static object conserved at the museum.

Such model is also important as a support to interdisciplinary researches for his role of 3D map of the artifacts, which could be simply transformed in 3D notepad where several pieces of information can be annotated in correspondence of the specific location where they have been gathered.

For example, in the present work, this occurs for all those analyses associated to point samples like radiocarbon dating or DNA analysis, but also results of methods providing results associated with specific areas such as RX imaging.

All these reports, useful in general for studying the origin and the historical profile of a heritage object, are also a supporting documentation for any future restoration action. The association of such data with the 3D model would further improve the readability and the usability of such pieces of information.

NOTES

1. More in-depth analysis of Leonardo's hydraulic studies can be found in [Pedretti, 2007].

2. For the data from folio 656r-a (ex 240r-c) of the *Codex Atlanticus*, it refers to [Capurro, 2014].

3. Originals found in the State Archives in Milan, Government Acts, Ancient Waters, files 981-982.

4. For the documents referring to the removal and successive move of the artifacts to the museum one should consult the Archives of the Didactic Naval Museum in MUST, the Historical Supervision of the Arts Archives in Milan, the Civic History Archives, the Siloteca Cormio Archives, housed in the Natural History Museum in Milan.

5. For an accessible knowledge of the history of MUST, see [Curti, 1972].

6. An analysis of the lock gates housed in the museum has been used for an accurate comparison through a series of photographs of the Lock of San Marco on exhibit in 1963 in Milan [Giobbo, 1963: 56]. For dimensional comparison, the researchers compared the lock gates in the museum with a series of road surveys taken from technical documents of the urban area of San Marco Street, resulting from 1935-36. See the Acts of the Municipality of Milan, files 31-1939 found in the Public Works, Historical Archives of Milan.

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KEYWORDS

3D digitization, 3D modeling, multi-disciplinary analysis, wooden artifact, Leonardo da Vinci's studies

digitalizzazione 3D, modellazione 3D, analisi multidisciplinare, manufatto ligneo, studi di Leonardo da Vinci

ABSTRACT

3D DOCUMENTATION OF AN ANCIENT WOODEN LOCK OF THE NAVIGLI CANALS IN MILAN, BASED ON DA VINCI'S STUDIES

This paper presents an example of multi-disciplinary research for investigating a couple of old gates belonging to the same canal lock, used for raising and lowering watercraft between stretches of water of different levels on one of the waterways of Milan, better known as Navigli. Those objects, conserved at the National Museum of Science and Technology Leonardo da Vinci (MUST) in Milan, have been assessed regarding their origin, their story, their structural integrity, the conservation status of their materials and the explanation of their functional aspects. The study has been carried out together with a three-dimensional documentation and modeling of the two gates. The resulting 3D models represented a valuable support for analyzing the geometrical structure of the studied artifacts. Such models have been used for communicating the research results through sections and drawings, useful for the comprehension of functional aspects. Finally, the same models could be used as a detailed 3D map for linking together the collected conservation data including X-Ray images, radiocarbon dating, DNA analyses and historical studies.

DOCUMENTAZIONE 3D DI UN'ANTICA CHIUSA LIGNEA DEI CANALI DEI NAVIGLI A MILANO, BASATA SUGLI STUDI DI DA VINCI

Questo articolo presenta un esempio di ricerca multidisciplinare volta a studiare una coppia di antichi portelli appartenenti alla stessa chiusa di un canale, usati per far transitare imbarcazioni tra acque a livelli differenti lungo un corso d'acqua nella rete navigabile di Milano, meglio nota come Navigli. Di tali artefatti, conservati presso il Museo Nazionale della Scienza e della Tecnologia Leonardo da Vinci di Milano, è stata indagata l'origine, la storia, l'integrità strutturale, lo stato di conservazione dei materiali e gli aspetti di carattere funzionale. Lo studio è stato effettuato tramite la documentazione tridimensionale e ricostruzione digitale dei due portelli. I risultanti modelli 3D hanno rappresentato un valido supporto per l'analisi della struttura geometrica e dello stato di conservazione dei manufatti studiati. I modelli sono stati utilizzati per visualizzare e comunicare i risultati della ricerca attraverso sezioni e disegni, utili per la comprensione degli aspetti funzionali. Infine, gli stessi potrebbero essere impiegati come una mappa 3D dettagliata per collegare tra loro i dati relativi alle altre indagini scientifiche svolte, che includono le immagini a raggi X, la datazione al radiocarbonio, le analisi del DNA e approfonditi studi storici.

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DIGITAL SURVEY AND 3D DIGITALIZATION

3D application in Estonian cultural heritage

Benefits and considerations based on the Chr. Ackermann Investigation Project

Andres Uueni, Hilkka Hiiop, Fabrizio Ivan Apollonio

State-of-the-art: 3D solutions for cultural heritage documentation

The several points of interaction between Information and Communication Technology Applications (ICT) and the preservation, research and dissemination of cultural heritage are important in the conservation workflow, heritage management and studies of particular artifacts. Over the past couple of decades, instrumental studies, imaging, survey methods and technologies have developed very rapidly due to wider knowledge and available ICT solutions. A combination of non-invasive (e.g. infrared photography) and (semi-) destructive surveys (e.g. collecting fragments of pigments or pieces of artifacts) provides enriched information about heritage artifacts that may greatly benefit conservation and heritage specialists in decision making, interpreting and understanding works of art.

A Web-based platform can provide an efficient method of data-gathering, organisation and management of information related to CH. Such enriched information helps to reconstruct the evolution of artifacts over time and consequently to design a correct approach to conservation, maintenance and dissemination activities. The main chal-

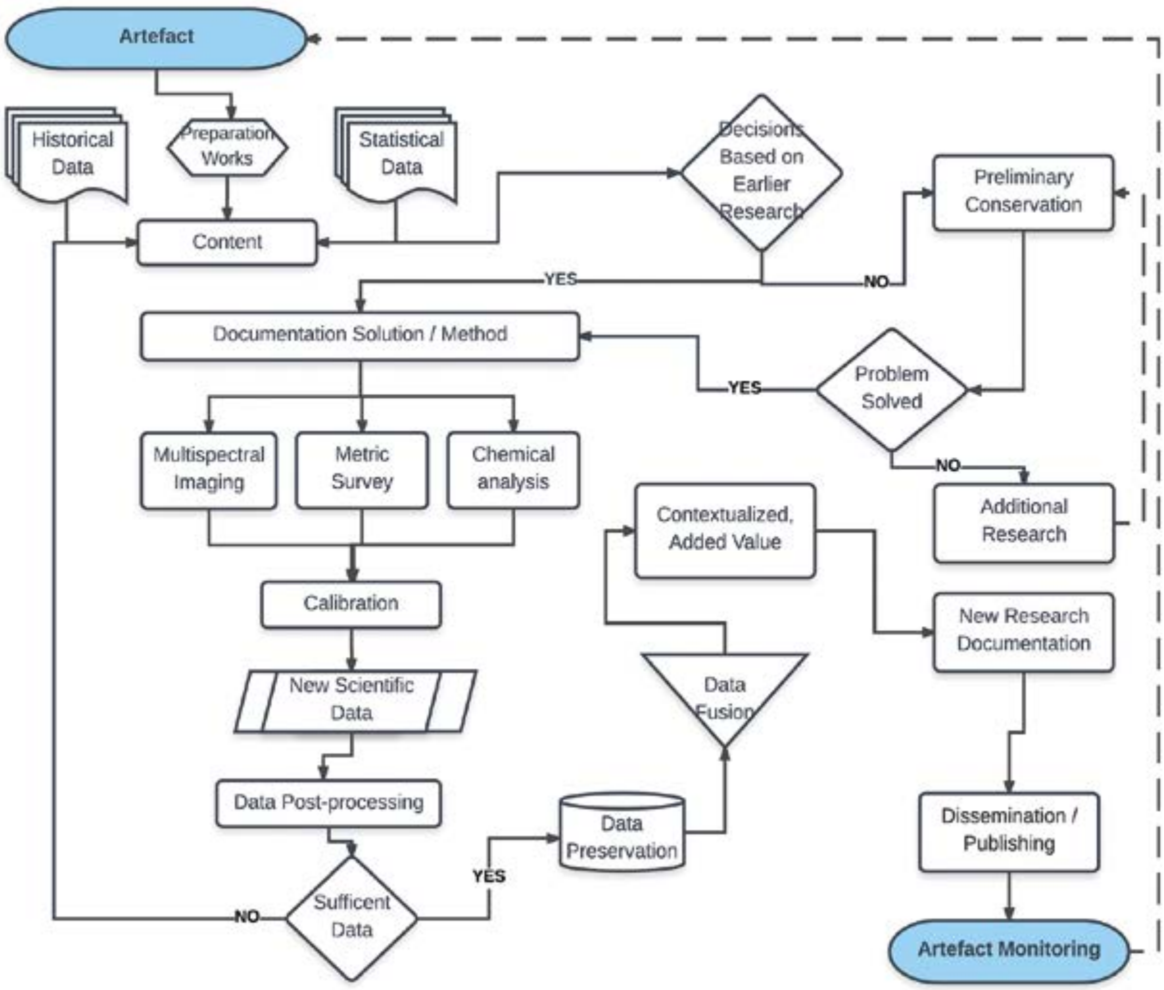

Fig. 1. Artifact documentation process schema.

1

lenges derive from the large amount of heterogeneous data collected from a site (3D models, images, photos, drawings, written documents, etc.) and from differences among users (researchers, archaeologists, architects, managers, tourists, etc.).

Although geometrical surveys are more complicated than ordinary photography, these solutions can be adapted for a broader use, e.g. in the conservation and investigation workflow. ICT also provides the opportunity to concentrate, contextualise, visualise and archive large volumes of different types of CH research data. The results obtained can be used to develop scientific knowledge [Pamrat *et al.*, 2017] and to broadly popularise results [Stanco *et al.*, 2011].

3D documentation in cultural heritage

Different 3D technologies and their combinations have been in use within the field of documenting CH since the early 1980s [Boulanger, 1988; Pintus *et al.*, 2015]. Since then it has become possible to combine different data from different domains for better access and understanding. The development of Web standards since the mid-2000s has provided the opportunity to implement this idea in real workflows.

3D documentation is a method in which a physical artifact is converted into a point cloud in the initial phase of data collection, using, for instance, photogrammetry, and extra value is created or added, such as combining data from other domains and having interactive access. In combination with other data, different 3D capturing technologies make it possible for modern documentation to contribute significantly to conducting research and to better preserving or presenting information concerning a work of art. By carrying out repeated surveys, it is possible to add the fourth dimension of time to 3D documentation, in order to produce time-varying content [Kyriakaki *et al.*, 2014]. It has become possible to document the appearance and historical events around a particular environment and structures that have evolved.

Modern ICT and imaging technologies provide better and more detailed trustworthy output for heritage specialists. 3D offers the benefit of presenting more information on complex artifacts than ordinary sets of photos [Arayici, 2017]. But 3D survey and multispectral imaging data fusion is able to provide even more: the heritage (building) information model HBIM. Web-based 3D documentation provides a unique opportunity to heritage specialists for the wider analysis of complex artifact documentation, mapping, visualising and archiving information [Logothetis *et al.*, 2015; Apollonio *et al.*, 2012; Nettuno, 2017].

Based on earlier experience and knowledge, we decided to mainly use photogrammetry during the Chr. Ackermann project, as it makes it possible to achieve precise results with wooden sculptures in a cost-effective way. Thus, it is possible to precisely map out on a 3D model previous data, such as the results of an instrumental analysis, underdrawings, other paintings, information associated with dendrochronology and other data.

As photogrammetry is accessible, when possible we test and implement in art historians' and conservators' workflow 3D documentation solutions [Pavlidis *et al.*, 2007; Remondino, 2011]. A lot of these solutions are still under development and different projects have been working with these issues to provide open-source web-based solutions [Janvier-Badosa *et. al.*, 2015].

During this project, there are considerations regarding the 3D data quality, especially the colour information, usage and accessibility of numerous 3D models at the same time via the web. There are 3D data long-term preservation issues as well [Koller *et al.*, 2009].

Such a solution can be important to represent the characteristics of CH artifacts in terms of shape and appearance. It is very important to achieve and design solutions to provide the user (e.g. conservator specialist, teacher or student) with an intuitive interaction approach without losing the quality of details, i.e. maintaining high precision in level-of-details (LOD) [Stanco *et al.*, 2009].

"Christian Ackermann – Tallinn's Pheidias, Arrogant and Talented" project 3D documentation (2016-20)

Recently, there has been wide interest in using 3D documentation methods and in implementing modern technological possibilities in the conservation workflow to support conservation work and to disseminate the knowledge gathered during research (e.g. 3D-COFORM, CARARE, CASPER and V-MUST).

Our first test of using 3D models during the conservation workflow was the application in the "Rode Altarpiece in Close-Up" project (2013-16) [Rode, 2016] of such solutions as photogrammetry, 3D scanning, multispectral, ultraviolet and radiographic, panoramic photography and reflectance transformation imaging [Hiiop, 2015; Uueni *et. al.*, 2016; 2015].

The St. Mary's Cathedral's retable (1694-96) by Chr. Ackermann is a heritage artifact with great public and research interest. This masterpiece provides an excellent opportunity for the wider information analysis of complex artifact documentation, visualisation and archiving. Since November 2016, Estonian Academy of Arts, Cultural Heritage and Conservation Department experts, in co-operation with the Art Museum of Estonia, Rändmeister LLC and Archaeovision LLC, have had a unique opportunity to gather and disseminate scientific information during research on the works of Chr. Ackermann's workshop. During the project, the main target has been the documentation and examining of the sculptor's masterpiece – the retable of the Tallinn Cathedral – but work has also been done on rural church altarpieces and pulpits (e.g. in Martna, Karuse and Lihula and many other churches, all together around 20 artworks) attributed to Ackermann's workshop.

In the course of the project, contemporary methodology and technology, as well as critical re-reading of historical sources, are being employed to re-evaluate retables, pulpits, baptistery and other artistically valuable artefficts attributed to Ackermann. Top specialists are participating in the examination of the materials used for Ackermann's carvings and cabinetmaking, along with the style, typology, techniques and polychromy [Ackermann, 2017].

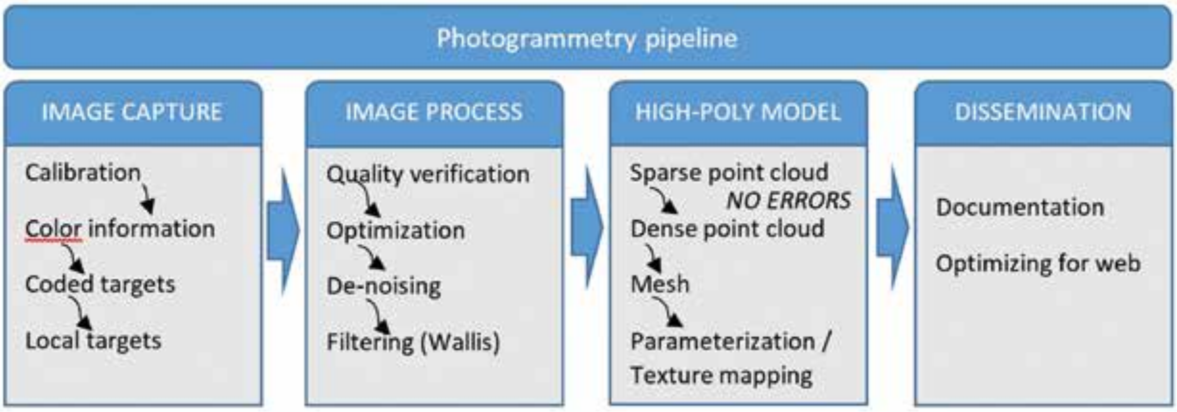

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Fig. 2. Following the photogrammetry pipeline helps to ensure repeatable results from the same image datasets.

For further use and implementation, methods and techniques are crucial: how the data has been acquired and how the raw data is processed, how imaging capture workflow can be adapted in different cases, how to reduce errors of the final results and how to optimise the general workflow and processes (fig. 1).

An important part of the ongoing project is to collect and provide high resolution photogrammetric 3D models for art historians and conservators. During the photogrammetry processing, different software, quality levels, the accuracy of the colour and processing methods were tested [Coffey, 2012]. To achieve higher quality 3D models, a combination of "natural" and coded targets was tested and used. To achieve repeatable results, the photogrammetry pipeline was followed (fig. 2). To capture exact material properties and to process all kinds of images, data manipulation was avoided, including enhancing filtering [Barazzetti, 2010; Mathys *et. al.*, 2015; Potenziani *et. al.*, 2015; Remondino, 2014].

During the investigation, it was determined that all of the 17th century sculptures had been repainted in the following centuries. The earlier, Baroque era, construction has been proposed by conservation experts and the colour palette of the sculpture will be collected in combinations of non-invasive analytical techniques, such as X-ray fluorescence (XRF), to determine the elemental composition of materials, and invasive cross-section techniques, conducted by conservators and professional chemists. Based on the gathered information, there are plans to create a hypothetical reconstruction of the retable's original shape and polychromy. The purpose of the virtual colouring (fig. 3) is to provide, both for the wider public and specialists, examples of the retable's details, in the way it might have been presented in the Baroque era.

The other important target during the virtual colouring is to test different software tools to achieve the most optimal results [Fernández-Palacios, 2013: 19; Gaiani *et. al.*, 2016; Guidi *et. al.*, 2014].

Visualising data and data accessibility: www.ackermann.ee

For the Chr. Ackermann research and conservation project, the plan is to implement ICT solutions which can be used by conservators during the conservation and survey. The 3D digital models of the solutions will allow conservators to use a dedicated user interface to re-check data and make decisions during the conservation work.

All information entered can be explored and also connected with the 3D models and images of the various elements noted by conservators (fig. 4).

The data information system, based on open-source database tools, is the Estonian Academy of Arts Cultural Heritage GraDoc Information System [Eesti, 2017], which implements the classic features of documentation: a time log of all operations, and a repository for different docu-

3

Fig. 3. 3D models compared in MeshLab: current colour of the sculpture (left), virtually coloured 3D model (right).

4

Fig. 4. To present accurate multi-resolution 3D models, the Sketchfab platform has been implemented, e.g. a Web interface of ackermann.ee makes it possible to combine 3D models, and via local interests points connect textual and image data.

ments (images and text) that are associated with various interest points.

The 3D models are useful for scientific research and presentation/dissemination. Analysing and making more than hundred sculptures comparable via web 3D models can also provide valuable information for proposing more accurate attribution. The CH documentation 3D models help to capture a particular moment of the life-cycle of the artifact, to make decisions during heritage management, and to gather new materials (fig. 5).

The planned 3D model publishing solution will combine Sketchfab and 3DHOP [Potenziani *et. al.*, 2015]. Both solutions use the latest web standards, based on the *SpiderGL* JavaScript library and *jQuery*, which is able to provide an optimal method for the visualisation of 3D models via the web.

Conclusions

During the conservation phase, there are several important factors the CH specialists need to check and decide on based on visual information. ICT solutions should provide accurate data for the CH specialists for better understanding and accessibility. Developments in ICT and metric survey make it possible to use solutions that are considerably more cost-effective and universal than earlier technologies. Regardless of which technology is used, the precision and comprehensibility of the information gathered are always important. Modern CH documentation is a practical way to capture information concerning artifacts. It provides the opportunity to collect, contextualise, visualise and archive large volumes of different types of research data that accompany the study of CH. The results obtained can be used to develop scientific knowledge and to broadly popularise results [Meyer *et. al.*, 2007].

In addition to research, web-based solutions for presenting and processing data are important in modern CH management, including access and the opportunity to reuse those solutions, which is extremely important in broad-based analysis and further interpretation. This is especially important in the case of 3D and multispectral data because the volumes of data are large and, depending on the solutions, they may require special server solutions. The objective over the course of this project has been to create a web environment that assembles most of the large and diverse information that accompanies conservation work and research.

The expected impact of this trans- and interdisciplinary approach can supplement imaging and information technology solutions and make them more accessible to researchers and general users. Moreover it can provide workflow and an opportunity for wider use of different research methods, and the creation of synergies among specialists from different fields.

Fig. 5. Artifact documentation and the preservation of heritage depend on many different sub-elements.

5

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ABSTRACT

3D APPLICATION IN ESTONIAN CULTURAL HERITAGE BENEFITS AND CONSIDERATIONS BASED ON THE CHR. ACKERMANN INVESTIGATION PROJECT

Information, communication and 3D survey technology applications are important in cultural heritage preservation, research, management, conservation and dissemination of the results. Cultural heritage requires continuous scientific investigation and preservation to gather valuable information from our history and to provide better understanding for future generations. Based on the Chr. Ackermann project, this paper focuses on the state-of-the-art in Estonia, and implementations, plans and considerations during the documentation process.

APPLICAZIONI 3D NEL PATRIMONIO CULTURALE ESTONE VANTAGGI E CONSIDERAZIONI SULLA BASE DEL PROGETTO DI RICERCA CHR. ACKERMANN

Nel settore del patrimonio culturale, per quanto riguarda la conservazione, la ricerca, la gestione dei dati e la diffusione dei risultati sono importanti le applicazioni di rilievo 3D, così come le tecnologie applicate all'informazione e alla comunicazione. Il patrimonio culturale necessita di ricerca scientifica e di conservazione continua per poter ricavare dalla nostra storia quelle informazioni preziose e fornire una migliore conoscenza per le future generazioni. Basato sul progetto Chr. Ackermann, questo articolo tratta dello stato dell'arte in Estonia, e delle implementazioni, dei piani e delle considerazioni svolti durante il processo di documentazione.

KEYWORDS

3D survey, photogrammetry, imaging, conservation, 3D model, 3D documentation, access

rilievo 3D, fotogrammetria, imaging, conservazione, modello 3D, documentazione 3D, accesso

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DIGITAL SURVEY AND 3D DIGITALIZATION

3D imaging system for the digitization of the Argentine museums' collections

Mercedes Morita, Gabriel M. Bilmes

The 3D image acquisition techniques most commonly used for 3D recording of museum objects are the laser or structured light scanning. These techniques are usually expensive and some complex for handling. But since a few years ago, results obtained with digital photogrammetry and appropriate image processing software are leaving behind traditional techniques, with the advantage of a lower cost, easy access and simple execution. This new option allows a really massive access to the use of the 3D resource and it is beginning to impact very strongly in diverse areas, such as cultural heritage.

In the latter case, 3D images are increasingly used in the museums of the entire world for documentation, for monitoring the state of conservation of an object, for the recording of deteriorations that are not detectable, for carrying out virtual reconstruction of lost elements and for dissemination. They also allow real-scale measurements without the need for physical manipulation and the production of copies from originals.

Although these applications have been carried out for a long time at an international level, in Latin America and particularly in Argentina the use of these technologies is still very limited. In the Argentine museums, documentation and dissemination systems are generally photographic and do not include recording by 3D images. This is the case of more than 400 museums of the Province of Buenos Aires. Given this situation, in recent years, the Laboratory of Laser Ablation of the Centro de Investigaciones Ópticas (LALFI-CIOp) has been investigating the use of 3D technology in cultural heritage and since the beginning of 2017 is carrying out a four-year project called "Digitization of Cultural Heritage by 3D Images". This Project is funded by the Scientific Research Commission of the Province of Buenos Aires and the Ministry of Culture of the Nation.

In this context, the LALFI has developed a 3D recording system for museums, based on digital photogrammetry and free software. This system, called "Mu3D", is very accessible to conservators.

The overall objective of the project is to produce an innovation in museums by incorporating the 3D digitization of their collections, transferring to them the Mu3D system developed, training their staff in the use of this technology and offering advice for the implementation of digitization programs and conservation actions. Also, this project contemplates virtual access to the museum collections, allowing visualizing in 3D, for example, objects that are not exhibited. On the other hand, museums often need to study the state of the objects of their collections and to do restoration strategies and material analysis. In the majority of cases, these museums do not have access to the appropriate techniques to perform these tasks, due to lack of knowledge or budgetary reasons. In this sense, the project also aims to provide advice and service for this type of studies, making the infrastructure of the LALFI-CIOp available to the museums in order to apply novel photonic techniques.

The Mu3D system

The developed 3D recording system, Mu3D, is based on digital photogrammetry and 3D image processing using free software. It consists of a user manual that includes procedures for 3D recording of collections and the software required for processing and visualization.

Digital photogrammetry is the most suitable option, compared to other techniques such as laser or structured light scanning, for the digitization of museum collections. It has the advantage that only a standard camera and a computer are needed, it does not require a complex setup and it can be easily implemented by museum employees not specialized in image processing techniques. In addition, digital photogrammetry reaches the same resolution as the laser scanning technique using low-cost instruments [Morita, 2017]. The procedure is very easy: the user takes a sequence of photos of an object in different positions and angles, and with a software provided by the system he can generate a 3D model with colour texture.

One of the most appropriate techniques to automate the process of photogrammetry is Structure-from-Motion (SfM) [Snavely *et al.*, 2008], which was used in our project. There are several pieces of software for performing this technique. In the Mu3D system, the VisualSfM software [Wu, 2011] is used to make the correspondence between the images and to generate a 3D point cloud; the CMP-MVS software [Jancosek *et al.*, 2011] is used to make a textured mesh from that point cloud; and the MeshLab software [Cignoni *et al.*, 2008] is used to edit the models, visualize them interactively and perform damage mapping and virtual measurements, among other things.

In order to apply the SfM technique, many images of the object are taken in a wide range of orientations and positions, with an overlap of more than 70 %, a fixed focal length and a depth of field that allows having most of the object in focus. The lighting should be diffuse and uniform, making sure that the images are very clear and have high resolution. The algorithms in the SfM software detect common characteristic points among all the images and calculate the position of each one in the form of three-dimensional coordinates. The result is a point cloud. By using image processing techniques, it is possible to transform that point cloud into a textured mesh, which will be the final 3D model. MeshLab's surface and texture reconstruction filters [Hoppe, 2008; Dellepiane *et al.*, 2010] or the CMP-MVS software can be used for this purpose.

A user's manual for museums was elaborated and distributed to the institutions that participate in the project that contains a protocol to perform the photogrammetric recording and post-processing of the 3D models. Also, a flash drive that contained the software and theoretical material on the SfM technique and the photographic practice was also distributed to the participants.

Training of the museum staff

In order to participate in the Project, the museums have to fulfill the following conditions:

- an institutional compromise to participate in the project;
- the designation of a suitable person for the digitization tasks who could also participate in the training course;
- the selection, by the museum management, of the type of collection and the estimated number of objects to be digitized within a period of two years;
- having a camera and a computer with an appropriate processor and graphics card for 3D image processing.

Till the date, 25 institutions have participated, exceeding expectations for the first period of the project. Table 1 shows the list of the institutions that took the training course.

Two training courses were offered on the use and possibilities of the Mu3D system. The first edition was carried out at CIOp on July 2017 (fig. 1). The second one was in the Ferrowhite Museum, Bahía Blanca, Buenos Aires, on August 2017. In both courses, theoretical contents and practical training in computers were given (16 hours in total), to which they were added the tasks of the individual practical work of those trained, required for the approval of the course.

Tab. 1
List of institutions that have participated in the project "Digitalization of Cultural Heritage by 3D Images"

No.	Institution / Museum
1	INCUAPA (Instituto de Investigaciones Arqueológicas y Paleontológicas del Cuaternario Pampeano), UNICEN
2	Museo de Arte Contemporáneo Latinoamericano (MACLA)
3	Museo de Instrumentos Musicales Emilio Azzarini
4	Facultad de Bellas Artes – Área Museo, exposición y conservación
5	Museo Taller César Bustillo
6	Dirección de Museos y Preservación Patrimonial de la Provincia de Buenos Aires
7	Museo de Ciencias Naturales de La Plata
8	Museo de Bellas Artes Provincial Emilio Pettoruti
9	Complejo Museográfico Provincial Enrique Udaondo
10	Quinta de Perón – 17 de Octubre
11	Museo Histórico Provincial Guillermo Enrique Hudson
12	Museo del Juguete
13	Museo de Física
14	Museo de Astronomía y Geofísica de la Facultad de Ciencias Astronómicas y Geofísicas
15	MEDA Museo etnográfico Dámaso Arce
16	Museo del Cabildo y la Revolución de Mayo
17	Museo Y Biblioteca Juan d. Perón
18	Museo Libres del Sud
19	Museo Ferrowhite
20	Museo del Puerto de Bahía Blanca
21	Museo de Arte Contemporáneo / Museo de Bellas Artes de Bahía Blanca
22	Museo de Ciencias de Bahía Blanca
23	Departamento de Humanidades, Universidad Nacional del Sur
24	Habemus Grupo facilitador para museos (Bahía Blanca)
25	Museo Histórico de Bahía Blanca

The contents were:
- introduction to 3D recording. Fundaments of digital photogrammetry and the Mu3D system;
- workshop on digital photography for 3D recording;
- practice with an object provided by the LALFI-CIOp;
- Structure-from-Motion software (VisualSfM and CMP-MVS). Edition of the 3D model with MeshLab. Scale, alignment and interventions. Exercises on PC;
- discussion about the collections that each museum had proposed to digitize.

An open laboratory for 3D recording training

An open laboratory was set up at CIOp so that the participating museums could train in 3D digital photogrammetry, test their own systems and adjust the technique (photographic acquisition and data processing). The laboratory is permanently available for participants who have completed the course and it has the support of the LALFI team. The facilities are equipped with three computers suitable for 3D image processing. In addition, a laser scanner and a Reflectance Transformation Imaging (RTI) system [Mudge, 2005] were set up when required.

So far, 13 of the 25 institutions that attended the course have regularly used the CIOp laboratory to complete the training of their staff. All of them have already managed to digitize pieces of their respective collections. Figures 2 and 3 show some examples of the digitization of several objects made during the project.

Digital repository for the museum's 3D images

We developed a digital repository where all the 3D models made by the participating museums could be placed and shown next to the technical or historical information of the object. It is under construction and was designed as an independent site, linked to the museum's websites (if they have it) and with free access (find Mu3D project on the website www.ciop-cic-conicet.gob.ar).

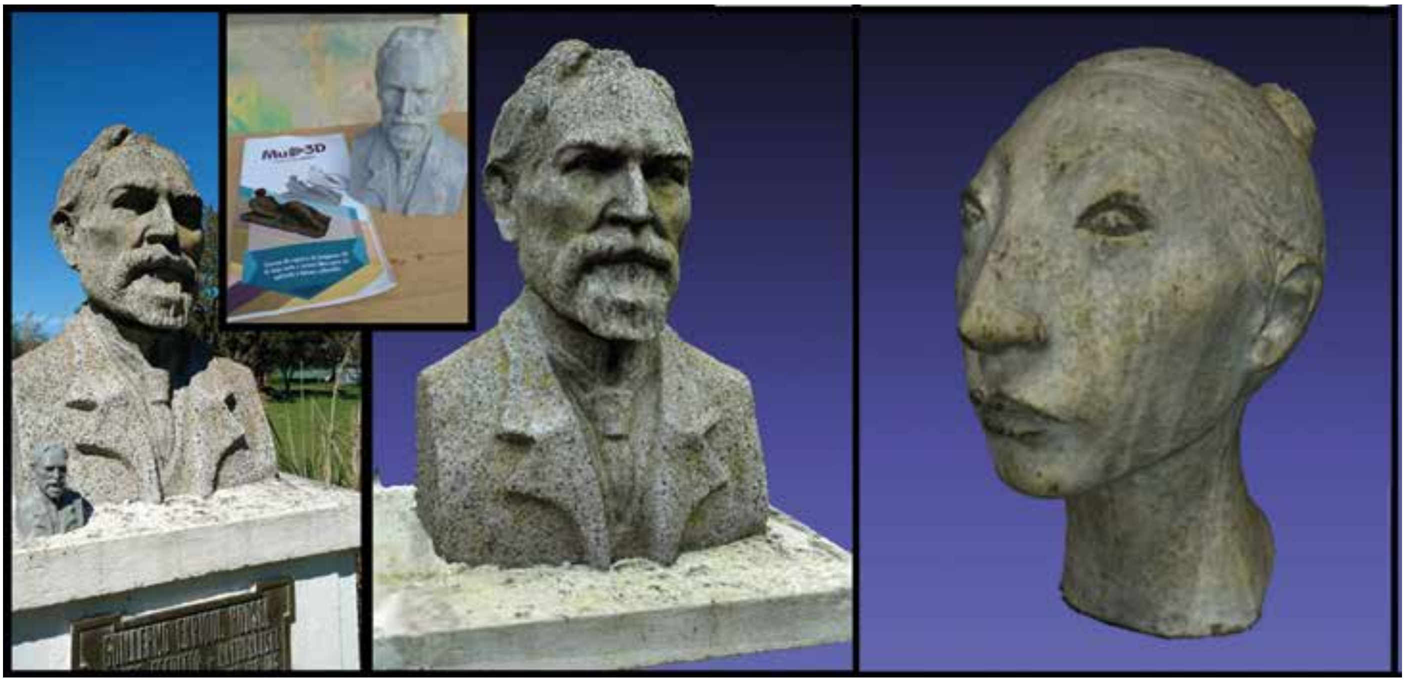
1

Fig. 1. Course given at CIOp, Gonnet, La Plata.

The 3D models could be visualized in GIF format and some of them could also be visualized using the 3DHOP interactive software, developed by the CNR-ISTI Visual Computing Lab [Potenziani *et al.*, 2014].

3D printing laboratory

A set of 3D printers will be assembled at CIOp as a facility for the production of small replicas of cultural heritage objects, support elements and containers for conservation and exhibition. This facility will be offered to museums that want replicas for educational purposes. On the other hand, the designing of support elements and containers will be explored, with the aim that museums could learn this technology and take action to implement it with their own financing.



2

Fig. 2. Monument of Guillermo Enrique Hudson next to a 3D printed replica on a small scale in the inset (left); 3D model of the monument displayed in MeshLab, made by the participants of the Museo Histórico Provincial Guillermo Enrique Hudson (middle); 3D model of a sculpture from the collection of the Museo Provincial Emilio Pettoruti de La Plata, made by participants of the Dirección de Museos y Preservación Patrimonial de la Provincia de Buenos Aires (right).

3

Fig. 3. 3D models of objects that belong to collections of some museums that have participated in the project. An archaeological ceramic from the Museo de Ciencias Naturales de La Plata (left); a molar from *Stegomastodon platensis*, Museo de Ciencias de Bahía Blanca (middle); a sculpture by César Bustillo, Museo Histórico Provincial Guillermo Enrique Hudson (right).

Non-destructive analysis service by using photonic techniques

In addition, a facility for applying photonic techniques to the study of patrimonial objects is offered to the participating institutions: in particular, Laser Induced Breakdown Spectroscopy (LIBS) [Anglos, 2001], Laser and Structured Light Scanning [Sansoni, 2009], Reflectance Transformation Imaging, Laser Cleaning [Fotakis *et al.*, 2006; Bilmes *et al.*, 2007] and Optical Coherent Tomography [Morel *et al.*, 2013].

Among the ongoing works, we can mention the one of the Faculty of Fine Arts, where the objective is to study the effectiveness of laser cleaning for the various cases of plaster patinas. Other works were developed in collaboration with the INCUAPA (Institute of Archaeological and Paleontological Research of the Pampean Quaternary) and the Recoleta Cemetery of Buenos Aires. In these studies, the Reflectance Transformation Imaging was used. In the first case, RTI was applied to the study of marks in archaeological bones, and in the second one, it was used to read the inscriptions of a tumulus, relevant for the historical identification.

Conclusions and perspectives

During the first year of the project, we achieved 90 % of the objectives and tasks proposed for this phase. A survey in order to know the opinion of the participants regarding the project was performed. Most of them were very satisfied with the contents and the dynamics of the course. Possibly this is due to the fact that training of these characteristics (free and with constant support) have rarely been offered in the cultural heritage field in Argentina.

The possibility for the participants to attend a laboratory at CIOp to use the computers allows overcoming some issues regarding the limitations of the Argentine museums, as the minimum equipment required (hardware) to work with the Mu3D system.

After having some experience of the application of the Mu3D system, we found some new challenges to work on. Some of them were suggested by the participants of the project. Therefore, we are developing new versions of this system including changes in the protocol and in the software, in order to improve it and create more possibilities.

Finally, 3D recording techniques together with Virtual Reality technologies are having a strong impact on the conservation of Media Art and installations, allowing a new method of documentation that provides virtual access to works of art rarely exhibited or already destroyed by the obsolescence of materials [Muñoz *et al.*, 2016; Morita, 2017]. We are planning to incorporate virtual and augmented reality technologies soon into the training courses and into the 3D recording protocol for museums.

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KEYWORDS

3D digitization, Structure-from-Motion, photogrammetry, Argentine museums

digitalizzazione 3D, Structure-from-Motion, fotogrammetria, musei argentini

ABSTRACT

3D IMAGING SYSTEM FOR THE DIGITIZATION OF THE ARGENTINE MUSEUMS' COLLECTIONS
3D images are increasingly used in the documentation of cultural heritage. The Laboratory of Laser Ablation of the Centro de Investigaciones Ópticas, La Plata, Argentina, is carrying out a 3D digitization project of the collections of the museums of the Province of Buenos Aires, by using digital photogrammetry. A system called Mu3D was developed, that uses free software for Structure-from-Motion (SfM) and 3D image processing. A combination of three software systems has been chosen in order to achieve a 3D model with the same accuracy of the results obtained by laser scanning techniques.
The system, including a protocol for image acquisition, is being transferred to the museums for free, by training their staff and providing them assistance for the development of digitization programs and conservation actions.

3D IMAGING SYSTEM PER LA DIGITALIZZAZIONE DELLE COLLEZIONI MUSEALI ARGENTINE
Le immagini 3D sono sempre più utilizzate nella documentazione del patrimonio culturale. Il Laboratorio di Ablazione laser del Centro de Investigaciones Ópticas di La Plata (Argentina) sta svolgendo un progetto di digitalizzazione 3D delle collezioni dei musei della provincia di Buenos Aires, usando la fotogrammetria digitale. È stato sviluppato un sistema denominato Mu3D che impiega software liberi per Structure-from-Motion (SfM) ed elaborazione di immagini 3D. È stata selezionata una combinazione di tre sistemi software così da ottenere un modello 3D che avesse la stessa accuratezza di risultati delle tecniche di scansione laser.
Il sistema, che include un protocollo per l'acquisizione di immagini, viene consegnato gratuitamente ai musei, formandone contestualmente il personale e fornendo loro assistenza per l'elaborazione dei programmi di digitalizzazione e per operazioni conservative.

TORNA AL SOMMARIO

DIGITAL SURVEY AND 3D DIGITALIZATION

Photogrammetric recording of an Early Iron Age hut tomb in central Oman

Paul A. Yule, Michela Gaudiello

State of archaeological research

The authors emphasise that the study of Early Iron Age south-eastern Arabia is underdeveloped. Advantageous would be systematic sources of images, a reason for the authors to build the pool "SKVO Oman" in the image bank heidICON. Relatively few archaeologists in this part of Arabia have cultivated high quality graphics, particularly of archaeological architecture generated by 3D scanning and/or photogrammetry [exceptions, e.g.: Yule *et al.*, 1998; Döpper *et al.*, 2014; Schmidt *et al.*, 2017]. One project recorded artifacts with a 3D scanner made of copper alloy from the EIA site of 'Uqdat al-Bakrah, a site which lies in Oman just inside the edge of the Empty Quarter [Yule, Gernez, 2018].

The terms Early Iron Age and Late Iron Age (EIA and LIA) usually are taken to refer to the time in south-eastern Arabia respectively from 1300-300 BCE and > 300 BCE-300 CE [Yule, 2016: 65 fig. 31]. In central Oman since this age is illiterate, it is considered to be prehistoric.

Criticisms published about the EIA and the LIA are notoriously inaccurate. One reads that in central Oman the graves of the Late Iron Age are similar to those of the Late Bronze and Iron Ages [Mouton *et al.*, 2014: 82], that the German team excavated 37 skeletons between 1980 and 1994 [Mouton *et al.*, 2014: no source given] instead of correctly, 191 [Yule, I, 2001: 477-480; 2017]. Colleagues who work in the United Arab Emirates generally attempt to force their own archaeological situation and nomenclature on that of central Oman. One such expert [Kennet, 2007] simply links his excavation at Kush (UAE) with sites on Baḥrain and "Période préislamique récent" sites [definition of Mouton, 2008], to represent all of eastern Arabia from the 3rd century BCE to the 8th century CE, despite the lack of similarity to Central Oman's LIA characteristics [Schreiber, 2007: 64]. However, increases in the number of sites and the documentation of the Samad LIA assemblage increasingly disable this agenda [most recently Yule, 2016]. One expert lapidarily opines that one cannot assign biological sex on the strength of burial goods [Magee, 2016: 254], which we never do, and that, Yule's chronology, "is not widely accepted" although both of his points can be and have been easily countered [e.g. Yule, 2017]. It would certainly help the discussion, if the colleagues would simply read and cite the texts as they are published. The discussion regarding the EIA is a continuing one in search of a dialogue and less so brachial value judgements.

Clearly, the main burial structure in EIA central Oman is the hut tomb, which prior to 1970 in the pre-archaeological days, here and at other sites around the Gulf came to be known first as cairns, later as pillboxes, the latter term fashioned after machinegun emplacements of WW II. Their first mention in south-eastern Arabia come from the quill of Samuel B. Miles, who mentions them in Wādī Jizī [Miles, 1966: 534] and Bertram Thomas [Thomas, 1931: 167, 177], who refers to them as *buyūt al-jahalā* (houses of the illiterate). Until recently, in neighbouring places in the Gulf littoral any pile of stones was termed a pillbox or a cairn. Donald B. Doe corrected this in his systematic surveys of Oman in which he differentiates different kinds of cairns [Doe, 1976: 148-149]. Gerd Weisgerber first mentions EIA hut tombs in a concrete way [Weisgerber, 1980: 101-102 fig. 72 ("Musfa grave city"); Weisgerber *et al.*, 1981: 182-183 fig. 6.6].

Once the second Samad project of the German Mining project got on its feet in 1987, preliminary grave typology developed along the lines set out by Weisgerber [Yule *et al.*, 1988: 13 fig. 3.5 (a hut tomb)]. Subsequent studies of pre-Islamic funerary structures in the SE Arabia set out to establish a standard nomenclature which arrived at 28 different grave types up to and including the Islamic period [Yule *et al.*, 1993; Yule, 1994; I, 2001: 27-45]. The three studies cited are similar, with slight successive corrections over the years. Regarding a survey of large stretches for the Bāṭinah Expressway one author and evidently his editors reduce the number of grave types from 28 down to six [Saunders, 2016: 8-14]. In this Anglocentric text many previously known types are omitted in part because they did not occur in the areas surveyed. However, among the difficulties of this study is the unfamiliarity of the authors with the specialist literature which is insensitively cited.

For example, tomb type 2 hut tombs [Saunders, 2016: 10 figs. 9-10] reflect only indirectly the occurrences (tab. 1) and characteristic form of those in central Oman. Type 6 Wadi Suq cist graves omit any mention of the best known source for these, 64 "end-wall graves" excavated and published in Samad al-Shan [Yule, I, 2001: 31]. Moreover, the conclusion of one of the authors in this otherwise useful volume to omit all mention of previous literature regarding physical anthropology, "The limited information presently available for populations from the Bronze and

Tab. 1
Published mentions of EIA hut tombs in the central part of the Sultanate of Oman

Site	UTM E.	UTM N.	Publication	Comment
al-Feg	673242	2569218	Doe, 1976: 151	coordinates incertain
al-Ḫawd, Ḥur al-Ḏabaʿ	622206	2608537	Gaudiello, Yule, 2018: 76	
al-Maysar gr M2716n	614985	2522250	Yule, I, 2001: 228-231, pl. 19	–
al-Maysar gr M8	615274	2522321	Yule, I, 2001: 225-228; II, 2001: pl. 11	partial LIA re-use
al-Nibāʾ	671064	2514475	Doe, 1977: site 49, 49, 51 fig. 13	coordinates uncertain
al-Šūwwaʿī 13.72	607259	2516001	Weisgerber, 1980: 101; Yule, I, 2001: 370; II, 2001: pls. 479, 582, 596	
Bāṭinah gr L3-32	510288	2631231	Saunders *et al.*, 2016: 89-90 figs. 187-191	–
Bāṭinah gr L3-17	513135	2628675	Saunders *et al.*, 2016: 32-34 figs. 55-59	–
Bāṭinah gr L3-18	513184	2628871	Saunders *et al.*, 2016: 34-36 figs. 59-62	–
Bāṭinah gr L3-20	513094	2628765	Saunders *et al.*, 2016: 37-38 figs. 66-68	–
Bāṭinah gr L3-32	510288	2631231	Saunders *et al.*, 2016: 89-90 figs. 187-191	–
Bāṭinah gr L3-34	514289	2626833	Saunders *et al.*, 2016: 27-29 figs. 42-47	–
Bāṭinah gr L3-35	513155	2628822	Saunders *et al.*, 2016: 39-40 figs. 69-72	–
Bāṭinah gr L3-55	513090	2628640	Saunders *et al.*, 2016: 40-42 figs. 73-76	–
Bilād al-Maʿādin	628528	2542193	Weisgerber *et al.*, 1981: 209, 190 fig. 12; Yule, 1993: 396-398, pl. 8; 1994: 545-547 fig. 8, pl. 20b; I, 2001: 370; II, 2001: pls. 479, 582; 2014: 34-35 fig. 13.3	
Kurīyā Murīyā site 1	391274	1934016	Weisgerber *et al.*, 2014: 146 figs. 276, 158; Yule, I, 2001: 39 note 259	
ʿMusfaʾ (Ǧebel al-Ṣalāylī site 1)	631901	2536305	Weisgerber, 1980: 102 figs. 71-72; Yule, I, 2001: 383; II, 2011:pl. 587 below	
Nigid Busfa	675238	2518093	Doe, 1977: site 48, 48-49, pl. xviia	coordinates uncertain
Rawdah/Muqata gr Mu1	626992	2531404	Yule, I, 2001: 396; II, 2001: pl. 531	LIA re-use
Samad gr S101200	617426	2521161	Yule, I, 2001: 286; II, 2001: pl. 229	–
Samad gr S10669	617513	2521188	Yule, I, 2001: 245; II, 2001: pl. 71	–
Ṣūr Maṣīrah/Ǧebel Ḥamr site 8	701822	2275800	Weisgerber *et al.*, 2014: 67; Yule, I, 2001: 39 note 259	–
Ṣūr Maṣīrah/Ǧisr Ġas site 22	677808	2259323	Weisgerber *et al.*, 2014: 74; Yule, I, 2001: 39 note 259	–
Ṣūr Maṣīrah/Wādī al-Šwāb site 25.1	675889	2257287	Weisgerber *et al.*, 2014: 75; Yule, I, 2001: 39 note 259	–
Wādī Gheiran/Ṣīāʿ	673677	2569210	Doe, 1976: site 6, 152-153 fig. 28, pls. 13-14	attribution uncertain
Wādī Jizī	457102	2698463	Phillips, 1971: 55-56; Yule, I, 2001: 386; II, 2001: pl. 592	coordinates uncertain

Iron Age in this region emphasizes the importance of this study and analysis" [Caine, 2016: 134] is bad news for those who publish their results and hope for them to be cited. Based on a fragment of the data for central Oman, William Deadman concludes that "hut graves do form a discrete class" [Deadman, 2016: 192], although aspects such as the orientation for the definition are ignored (tab. 2) and prior to this hut tombs were already defined as a discrete artefactual group.

Table 1 summarises the state of research for EIA hut tombs, which shows most of published examples in our region. A few from the rescue excavations of packages 3 and 4 do not appear listed, not a result of any ill-will, but rather because we selected only the best-preserved ones for mention.

In any case, the majority of hut tombs in central Oman are flat at one end and at the other may be rounded, in plan like a horse-shoe. They range considerably in size from some 0.60 cm to 1.70 cm in height. A given group may have a single orientation, different groups may vary from each other. The EIA south-eastern tomb group at Bilād al-Maʿādin shows different axis orientations.

Tab. 2
Height and orientation of the entrances of the hut tombs of the south-eastern group at Bilād al-Maʿādin.
From Yule, I, 2001: 40 pl. 4.9.

	Inter. height	Exter. height	Orientation
1	1.0 m	1.9 m	N
2	0.6	0.9	N
3	0.8	1.7	N
4	0.8	1.3	ENE
5	0.8	1	NE
6	0.8	1.4	E
7	0.35	1	W
8	0.85	1.6	NE
9	0.8	1.3	NE
10	0.85	1.2	NE
11	0.85	1.5	SE
12	0.9	1	NE
13	0.9	1.4	NE
14	c. 0.8	1.5	E
15	0.8	1.1	E
16	0.7	1.5	E
17	1.1	1.6	W

Method

We simply searched for EIA sites with hut tombs which were little documented and noted in a preliminary way the find situation, particularly the geographic position. In this way we chose the Ğebel al-Ṣalāylī site for photogrammetric recording.

Photogrammetric recording and rendering

With our short visit in January of 2018, we aimed to photograph one tomb photogrammetrically. Previously in 2015, we had used a 3D scanner for recording small metallic artifacts in the National Museum, but the importation, customs formalities and the high costs for the instrument consumed considerable time and effort and required outside financing. First we searched the best preserved example. We visited ad hoc the sites at Wariya and Musfa (tab. 1), but none of the tombs were in a good condition. Skipping over nearby Bilād Maʿādin, we proceeded to a little known group at a place known first ambiguously as “Musfa” and later as “J. Salayli” [Yule *et al.*, 2018]. A more intensive questioning revealed the name of the adjacent mountain to the north actually to be Ğebel al-Ṣalāylī. To my knowledge site 1 contains the best-preserved EIA tombs (figs. 1, 2). We selected a better preserved tomb of the 46 examples. All were positioned in rows and oriented with the entrance to the west. The example which we recorded measures 2.0 x 1.60 x 1.30 meters and is made of dark grey fine granite which weathers to an ochre.

Recording parameters

Key problems involved how to deal with shadows in the photos, and use them advantageously with the Agisoft PhotoScan software (standard version, 1.4.0 build 5650 [64 bit] multi-view 3D reconstruction). A small problem is that the programme changes over time, which makes them out of tune with online tutorials. Although we found no close tutorials for such tombs, still they were useful to explain methods of recording and rendering. We were indeed a low-budget project and had limited time in the field. Following diverse tutorials in the net, we used a Nikon d7100 with an AF-S Micro Nikkor 40 mm 1:2.8 G lens. In order to keep the data to a manageable volume, instead of using RAW/NEF camera option or subsequently converting to high-resolution jpg-images, we laid down the images directly in jpg format onto the flash card. This resulted in images on the average of 1400 KB size which corresponded to our intentions. We set the camera at 100 ISO and used the camera setting automatic in addition to autofocus. Since we had no remote release, we placed the camera on a 2 meters long monopod and used the time exposure feature to record the tomb roof. The location of surrounding tombs conditioned photography distances ranging from 0.5 to 1 meters. We used no pass crosses (which our version of the programme does not support). We photographed around the tomb in spiral fashion moving upwards and counter-clock-wise.

It was a cloudless day. We arrived at the site at 09:41 and began to photograph despite the presence of direct light and shadows with the surrounding tombs cast on that which we selected. Overview photos were possible only from the south and east. This resulted in F stops c. 9.5 and an exposure time of 1/350 of a second. We used a monopod where possible. We nearly finished with some 323 photos. We returned at 17:00 when the shadows covered the entire site and the light was diffuse, but still sufficed. We made a further 14 images, which in the evening we rendered in a hotel. The thin-cloud mode of PhotoScan suggested that there were small holes in the render, which required patching. Two days later we returned and reached the site at around noon and patched

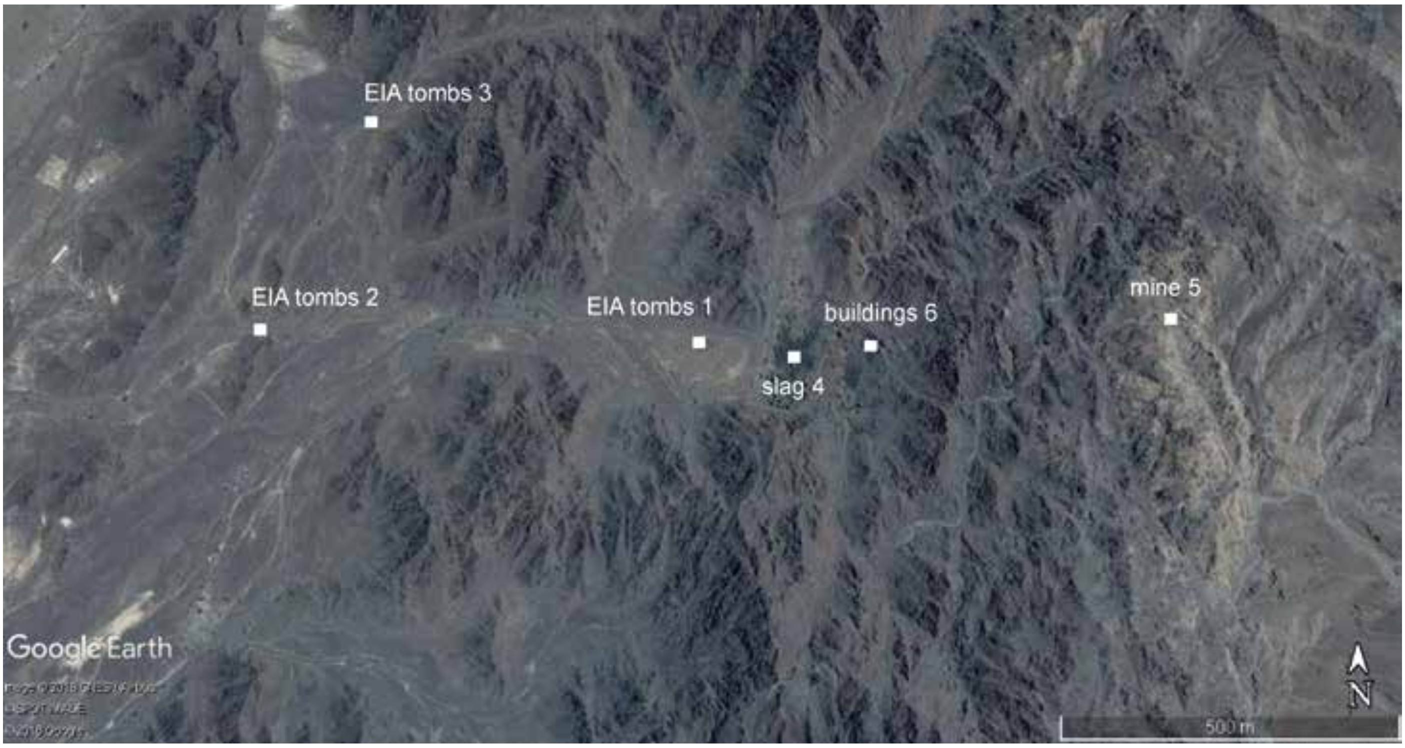

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Fig. 1. Google Earth image of the Ğebel al-Ṣalāylī cemetery 1, mining and smelting site. *Source Paul A. Yule.*

TORNA AL SOMMARIO

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the holes with 154 more photos using the same camera settings. The best photos were made in the late afternoon in shadow. However, equally good would be morning shadow light. To optimise, we could have set for a longer exposure time and a high F-stop, in order to increase the depth of field. However, owing to adequate light, this proved not to be a problem (fig. 3).

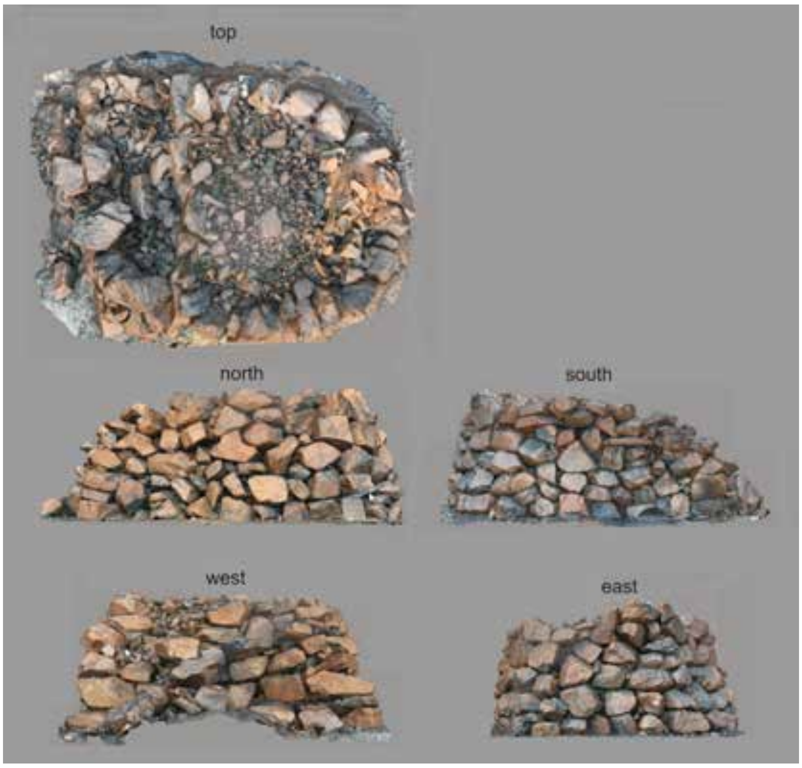
The computer used for the rendering is a Dell Optiplex desktop with the following configuration: Windows 7, Intel i7-2600 CPU @ 3.40 GHz, 16 MB RAM, 64 bit operating system, NVIDIA GeForce GT 720 graphic card. For rendering of less than 400 jpg files @ 1400 KB this configuration was adequate. The programme was factory-configured to use this hardware. But a notebook computer also sufficed for the rendering.

Conclusions

Advised in tutorials not to exceed 400 photos for the rendering, first we rendered 323 images (cameras) which yielded the following parameters: 217071 points, 891683 faces, 447614 vertices. The attempt to render all of the 491 photos of the tomb crashed the programme. Nearly all of these photos joined to each other, as we could determine from the photo feature below the modelling screen. Most showed the diagnostic orange check. Our first test was moderately successful. However, next time we would attempt to get more depth of field in the photographing. We were unable to get the ultra-high mode for rendering the dense cloud to function on our computer. Recording a second grave would be easier and go faster, having had this experience.

Fig. 2. Ğebel al-Ṣalāylī cemetery 1 viewed to the north. *Source Paul A. Yule.*

Fig. 3. Ğebel al-Ṣalāylī cemetery 1, photogrammetrically recorded tomb no. 15. *Source Michela Gaudiello, Paul A. Yule.*



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ABSTRACT

PHOTOGRAMMETRIC RECORDING OF AN EARLY IRON AGE HUT TOMB IN CENTRAL OMAN

At an alarming rate, the archaeological monuments of central Oman are going the way of the extinct Arabian elephant and Arabian ostrich before they can be recorded. Aside from a simple drawing, until now there was no 3D orthographic recording of an Early Iron Age (EIA) tomb. Thus, it was unclear how the roof was fashioned into something durable enough to withstand the test of millennia. The EIA tombs located next to the Ğebel al-Ṣalāylī in the Sharqīyah province are the best-preserved ones in Oman, but are being encroached on, and are not in any way protected. At the lower end of a wādī, they lie 400 meters west of a long-abandoned copper mine to which they probably originally owed their existence. The mine was obviously in use during Muslim times, but probably also in the EIA. This is not a scientific experiment, but rather a recording of our experience during photogrammetric recording and rendering.
Photogrammetric recording is preferable to 3D scanning owing to the logistical hurdles to get the instrument in and out of the country. Then one also needs a source of electricity, which in the field may be prohibitive. Should one manage this, scanning requires darkness which requires driving in the desert and finding a place to stay – or driving back to larger town with a hotel. By means of some 323 jpg images, we rendered one tomb using the Agisoft PhotoScan standard program.

DOCUMENTAZIONE FOTOGRAMMETRICA DI UNA "HUT TOMB" DELLA PRIMA ETÀ DEL FERRO IN OMAN CENTRALE

A una velocità allarmante, i monumenti archeologici dell'Oman centrale si stanno estinguendo come gli elefanti e gli struzzi dell'Arabia, prima che questi vengano registrati. A parte semplici disegni, finora non esiste una singola ricostruzione ortografica 3D di una tomba della prima età del ferro (EIA). Pertanto non è ancora chiaro come la copertura doveva apparire ed essere strutturata in modo da durare per millenni. Le tombe EIA individuate presso il Ğebel al-Ṣalāylī, nella provincia della Sharqīyah, risultano essere le meglio conservate in Oman, ma sono state violate e non sono in alcun modo protette. Nella parte bassa del *wādī*, queste sono state erette a 400 metri a ovest da una miniera di rame da lungo tempo abbandonata e a cui, molto probabilmente, devono la propria esistenza. La miniera sicuramente fu in uso durante l'epoca islamica, ma anche durante l'EIA. Questa nota non vuole essere un esperimento scientifico, quanto piuttosto un resoconto della nostra esperienza durante l'acquisizione dei dati e la ricostruzione fotogrammetrica.
La ricostruzione 3D attraverso fotogrammetria è preferibile all'utilizzo di laser scanner per le difficoltà logistiche nel fare entrare e uscire la strumentazione in un Paese. Altra problematica è la corrente elettrica, che sul campo è spesso proibitiva. Potendo risolvere ciò, il laser scanner richiede ombre che nel deserto implica il dover guidare a lungo per trovare un posto adatto o tornare indietro nell'albergo in città. Con 323 immagini jpg, siamo stati in grado di ricostruire una tomba utilizzando la versione trial di Agisoft PhotoScan.

KEYWORDS

central Oman, Early Iron Age, hut tombs, Agisoft PhotoScan, Salayli
Oman centrale, prima età del ferro, "hut tombs", Agisoft PhotoScan, Salayli

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DIGITAL SURVEY AND 3D DIGITALIZATION

Analysis of skylight illumination using 3D

An experimental case of the Roma and Augustus temple in Ostia

Daniel Damgaard

Axel Gering has recently put forward the hypothesis that the cella of the Roma and Augustus temple in Ostia was illuminated through several elongated windows positioned behind the inner colonnades. The bottom of the windows consists of shafts cut out into the cella socles. Remains of the shafts are preserved on two different cella socles, thus providing the adequate documentation for such a hypothesis. Roberta Geremia Nucci has already proposed that the shafts in the cella socles were utilised for illumination. However, her hypothesis concerns an illumination of the rooms in the podium beneath the cella and not the cella itself [Geremia Nucci, 2013: 64-65].

The light shining into the cella, as presented by Gering, would emerge from behind the statues positioned inside the aediculae along the inside longitudinal cella walls. In continuations to this hypothesis, ideas of illumination through the marble roof of the temple have emerged. Several research projects have been conducted on this subject around the ancient world, but mostly on Greek temples and mostly on transparent roofing [Wikander, 1983; Heile, 1990; Hopefner, 2001; Gruben *et al.*, 2002: 391-397; Ohnesorg, 2011; Hennemeyer, 2011]. In one research regarding the Demeter temple in Sangri on Naxos it was documented that thin (2 cm) marble pan tiles (lat.: *tegulae*) entailed that 5-8 % of the outside light shined through the marble tiles and into the cella, thus lightening up the interior [Hoepfner, 2001: 491-492; Ohnesorg, 2011: 92-93].

Three different options of illumination through roofs consist of skylight tiles with *opaia* (sing. *opaion* – opening in the tile), transparent roofing and the hypaethral temple [Heile, 1990]. The first option is relevant to discuss in relations to the Roma and Augustus temple. The last two options, transparent roofing and the hypaethral temple, are less likely.

The reason transparent roofing is unlikely, is due to the pan tiles found in Ostia, which are all between 3 and 4.5 cm thick. Thus, 1-2.5 cm thicker than the tiles of the Demeter temple. A typology of pan tiles in Ostia is yet to be defined, and we are therefore not certain whether the pan tiles from the Roma and Augustus temple were 3 or 4.5 cm thick. The roof tiles of the Roma and Augustus temple are made in Luna (Carrara) marble, and some research has been conducted on the geological composition of Luna marble [Herz *et al.*, 1986], but experiments on its ability to transfer light have not yet been conducted. Therefore, in the 2017 summer-campaign of Ostia Forum Project (OFP), a small experiment to test the ability of Luna marble to transfer light was conducted. It turned out that the tiles were too thick, thus, no light shined through. Another contributing factor to the inability of the marble to transfer light was that the upperside of the pan tiles all have a rough surface with remains of the dental iron. This disturbed the light-direction, which made it difficult for any transparent effect. The roof tiles of monuments that are documented to have had a transparent roof are all polished on the upperside as well as their underside, which does not only concern the pan tiles, but also the cover tiles (lat.: *imbreces*; it.: *coppi*) and the ridge tiles [Kelly, 1996:

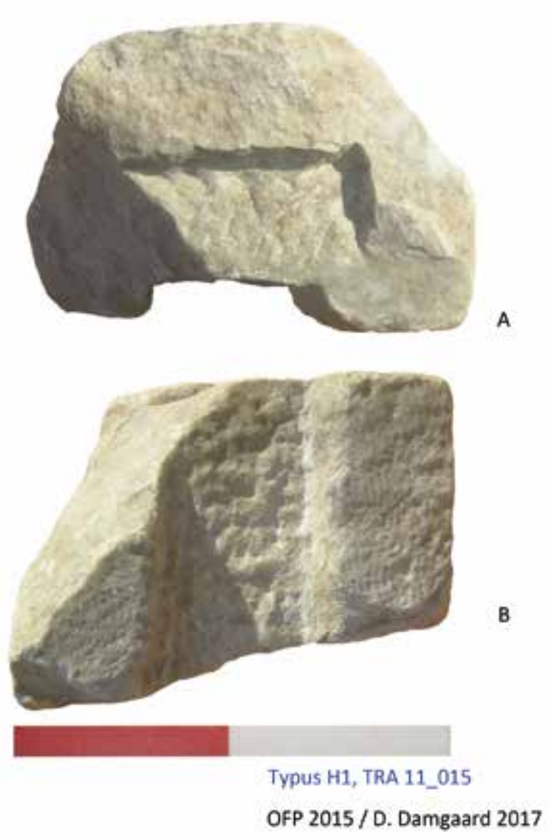

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Fig. 1. Coppo type H1 from the Roma and Augustus temple.

258-261; Cooper, 1996: 54]. This indicates that to have a transparent roof, both sides of the tiles have to be polished.

The last solution, the hypaethral temple, is even more unlikely, due to the fact that there are no recorded examples of such a roofing system in Rome, why it is also unlikely that there should be examples of it in Ostia [Vitr. *De Arch.* III, 2,8; Heile, 1990: 32].

The marble roof tiles

The roof of the Roma and Augustus temple is known as a Corinthian roofing system[1]. It consists of large flat pan tiles and cover tiles of the type H1 [Gering, 2017: fig. 5; Damgaard, forthcoming][2] (fig. 1).

We know that the Roma and Augustus temple consisted of Luna marble, and as mentioned above, even the pan tiles made in Luna differ in thickness. This difference can also be explained by the possibility of other monuments in the Forum having marble tiles made in Luna, where another thickness was utilised. However, due to the excavation history of the temple and the Forum in general, we cannot point towards one certain pan tile thickness for the temple. Nonetheless, all the pan tiles have one thing in common, and that is that they are all polished on their underside. The upper side, as mentioned above, is unpolished. Therefore, it is interesting to ask the question: why polish the underside of a pan tile? The long edges of the underside of the pan tile were resting on the rafters, where it is more likely that a rough underside would ensure more stability. Consequently, this polished underside indicates that that side of the pan tile was visible from beneath and thus possibly from the viewer inside the cella. Hence, one of the reasons for this polished underside could be that of illumination.

Illumination through the roof of the Roma and Augustus temple

Skylight tiles

Skylight tiles have been categorised into five types by [Wikander, 1983: 91-94]. They are differentiated by their architectural layout, where the *opaion* differs in shape as well as differences of the raised borders surrounding the *opaion*. Because we do not have any fragments representing a skylight tile, we cannot determine which type of skylight that hypothetically would have been utilised on the temple. However, according to the material presented by [Wikander, 1983: 85 fig. 2], one skylight tile from Kaulonia with a size measuring 92 x 59 cm is very similar in style and size to the pan tiles from the Roma and Augustus temple, which measures 90 x 66 cm [Geremia Nucci, 2013: 89 fig. 84]. Hence, this skylight tile, type Ia, will therefore be representative for the skylight tile utilised on the Roma and Augustus temple [for type I: Wikander, 1983: 91-92]. The *opaion* from the tile in Kaulonia is 25 cm in diameter, which would fit well to the tiles from Ostia.

It is unfortunately unknown how many skylight tiles that were on the roof, but we do believe that a sufficient amount of skylight tiles on each roof side would be six, thus twelve skylight tiles on the entire roof surface. They are placed strategically, based on different illumination possibilities of the cella. This will be explained and visualised in the next section.

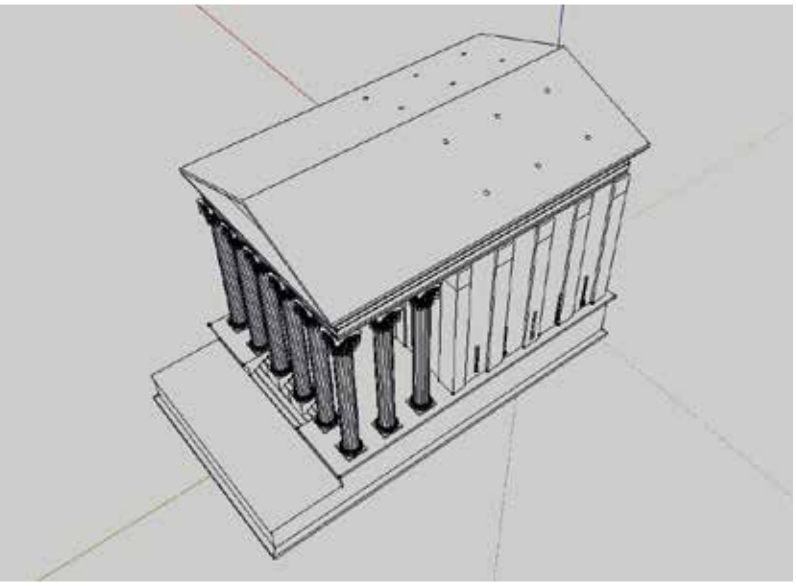


Fig. 2. Overview of the position of the skylight tiles.

Illumination of the Roma and Augustus temple

In the attempt to experiment with illumination of the cella, Marco Dehner has created a 3D model of the temple using the programme SketchUp Make 2017. The 3D model has been generated using authentic measurements from almost each individual architectural objects ascribed to the temple, thus creating an authentic model of the temple and its interior. I have inserted the twelve skylight tiles using the same programme, in which it becomes possible to experiment with the illumination. To provide different illumination angles, three different times during a July day have been chosen: morning at 10:00 AM, around noon at 01:00 PM and in the early evening at 05:00 PM.

On one roof side, two skylight tiles have been placed three vertical rows of pan tiles from the raking simas in the south-facing pediment, thus roughly 3 meters from the sima. Raking simas are the rows of pan tiles adjacent to the backside of the sima [Ginouvès, 1992: 189, pl. 83.1e]. One skylight tile is placed two horizontal rows of pan tiles, thus circa 1.8 meters, from the ridge of the roof. In the other end, one skylight tile is placed the same distance, thus 1.8 meters, above the antefixes. Two corresponding skylight tiles are placed in the same manner on the other roof side. Thus, four skylight tiles are placed above the southern part of the cella. A similar row with four skylight tiles has been placed above the other end of the cella, thus they are placed roughly in the middle of the entire roof length. They are placed in this manner, because no skylight tiles would have been placed above the pronaos. This is simply because that section of the temple is already located outside, hence no need for illumination. The last set of skylight tiles are placed in the same manner, but in between the other two rows of skylight tiles (fig. 2).

Due to the orientation of the temple with its entrance facing north, there would not be any direct sunlight on the cult statues in the southern end of the cella at any point during the year, despite four skylight tiles being placed roughly above them. The only option for direct sunlight would be if there were windows in the cella wall behind the cult statues. Roman temples in the Near East have windows in the cella walls [Ginovuès, 1992: pl. 31.3; Collart *et al.*, 1969: 67], but we do not have any indications of such a solution in Ostia nor in Rome or the Roman West for that matter. Hence, this solution is not likely here, which thus means that the cult statues were never exposed to direct sunlight. The marble revetment of the cella walls could however be polished in such a way that the light shining through the skylight tiles and the elongated windows behind the aediculae statues could be reflected towards the cult statues.

When conducting experiments with sunlight, surrounding buildings play a vital role, and one must be aware of the built environment. The Roma and Augustus temple is the oldest monument on the Forum amongst the present structures. The temple is built in 6 AD. We can therefore exclude shadows from the tall Baths of the Forum positioned to the east, due to the fact that they were constructed in the 2nd century AD. During the afternoon and evening sun, the Basilica positioned to the west was not erected either, but was built some 60-70 years later. Therefore, what we can assume is that in Augustan times, when the Roma and Augustus temple was built, it would have been the highest standing building within a large radius of the Forum – at least in the direction of the sun's movement. In addition, because we are dealing with the roof, there would hardly be any risks of shadowing at any point during the day.

The interior of the temple has been reconstructed with four aediculae on the ground floor on each side, which are divided by five columns. On the second floor above the aediculae, five smaller columns are placed[3]. Thus, in the morning, the three lowest skylight tiles on the eastern roof side would illuminate the aediculae of the western wall, while the three upper tiles would illuminate the second floor columns above the aediculae (figs. 3a/b).

Around midday, the sunlight shining through the twelve skylight tiles would direct sunlight towards the floor and the door in the north end of the cella. In the afternoon hours, the three lower skylight tiles of the western roof side would illuminate the eastern aediculae, while the three upper tiles would illuminate the second floor columns.

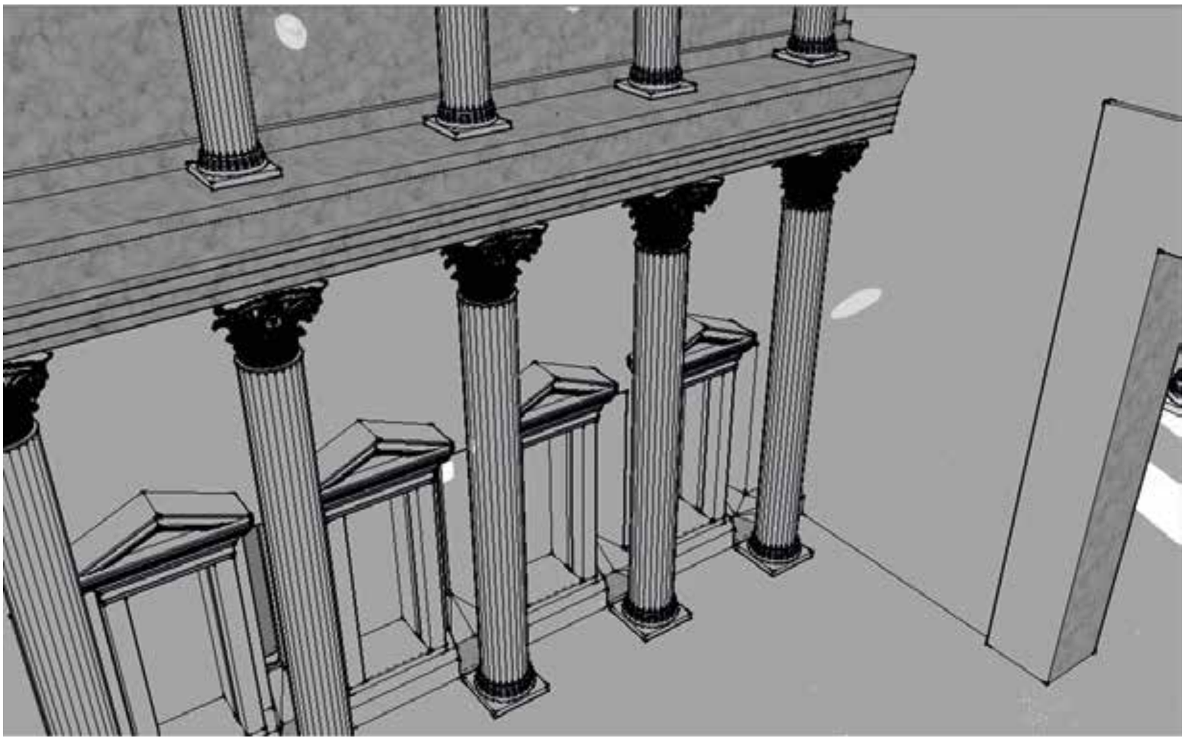
Regarding the risk of rainwater entering the cella, there are two different approaches to prevent this from happening. The first option consists of a closing mechanism, where a lit, most likely of terracotta, could be attached to the surface of the skylight tile. This would be the easiest and quickest solution despite the fact that the closing mechanism had to be moved physically by someone. However, there are different solutions to this problem, which amongst others includes a wooden stick attached to the terracotta lit, which means that the lit could be manoeuvred from inside the cella [Wikander, 1983: 92]. The second option is a so-called trough tile, which lies across the direction of the raised borders of the surrounding pan tiles. Such a tile is placed above the skylight tile, where it leads water towards the adjacent rows of pan tiles and away from the *opaion*. Such a solution can be found on the South Stoa in Corinth [Broneer, 1954: 87].

The rain falling straight into the cella could be handled by simple drains in the floor leading the rain to a drainage. On the inside of the fundament, a tube is still preserved in the *opus reticulatum* fundament walls. Originally, a pipe would have been built into the tube, thus functioning as drainage, where rainwater was transported to the sewer systems of Ostia [Geremia Nucci, 2013: 65]. The reason for this drainage is most likely connected with the shafts of the cella socles, through which rainwater could enter. Water sliding into the podium would be problematic, but the tube system in the fundament indicates that the solution to this problem was to insert a vertical drain just below the opening in the cella socles. This same architectural principle could have been utilised with water being led from a possible built-in-drain in the cella floor, and via a pipe led to the preserved pipe system leading it to the underground sewer system.

Why illuminate a temple of the Imperial cult?

It can be interpreted differently if we are dealing with religious connotations regarding the illumination of the cella and the aediculae at the different times during the day or at a certain time during the year. However, it can also merely be with the intention of lighting up the cella having certain practices in mind. Normally in temples, nobody had access to the cella except the priests. All religious and sacrificial actions happened in front of the temple by the altar. However, as the cella could have been illuminated, this indicates that the temple was utilised for something more than just priests working for the Imperial cult. One hypothesis could be that the temple could have been utilised for council meetings, which is supported by a 2nd century AD inscription [CIL XIV 353]. It is known that Ostia was governed by the *decuriones* (the city council) and that the *flames Romae et Augusti* (the priest of the cult) could have been politically active [Meiggs, 1977: 178-179]. This information combined with the newly established hypothesis that the Roma and Augustus temple was illuminated, could indicate that the temple was utilised as a meeting place for that council in Augustan times. Illumination of temples is well known in the Roman East, where there is a vast evidence of temples being illuminated through large windows. However, due to the wide variety of different cultic activities in that region, those windows are not necessarily related to these same functions. On the contrary, in the Roman West, there are hardly any known examples of temples being illuminated, which makes these findings even more extraordinary[4]. Furthermore, it is known that the podium in front of the entrance to the cella was the *rostrum* – a place where an orator made public announcements for the people. Indeed, this does not relate to actions inside the cella, but it does imply that the temple had more than one function.

TORNA AL SOMMARIO


3a

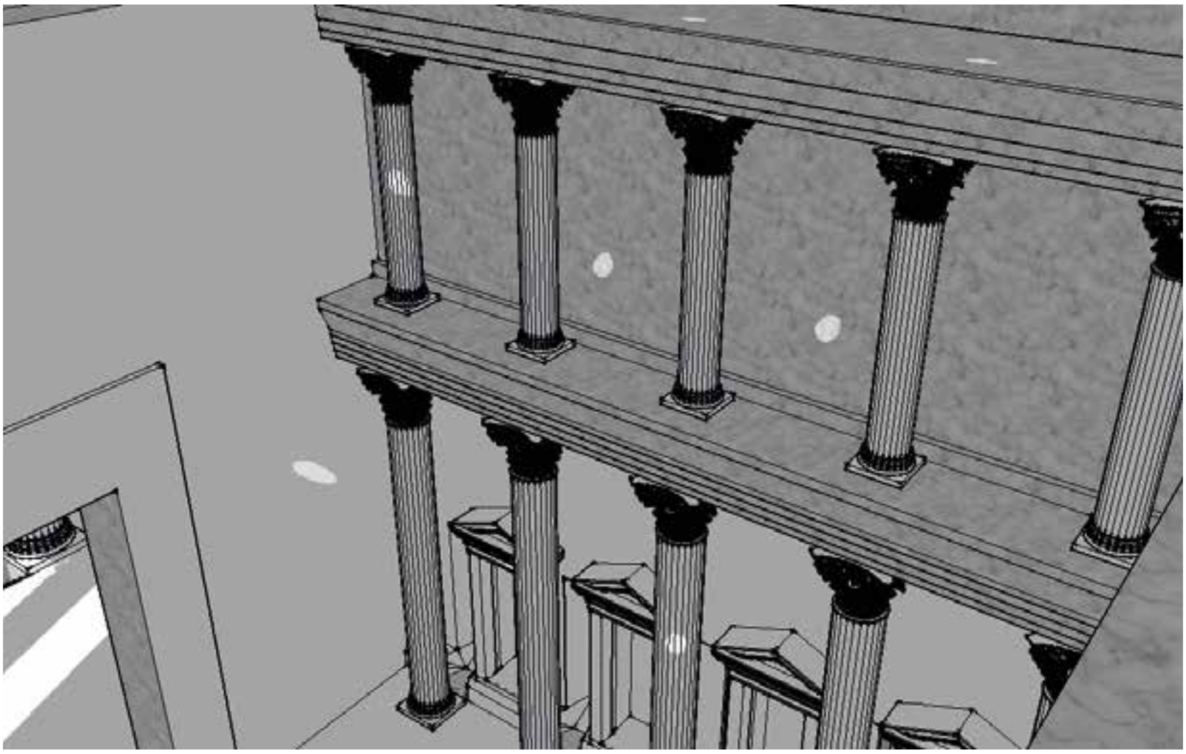

3b

Fig. 3. The morning light on the western aediculae (a); the afternoon light shining on the eastern aediculae (b).

Notwithstanding, it cannot be excluded that the cella was equipped with wooden ceilings, as it is seen in, for example, the almost contemporary Mars Ultor temple in Rome [Ganzert, 1996: 237], and in many reconstructions of Roman temples in general. This would ultimately exclude the function of the skylight tiles. Nevertheless, it is still conspicuous that the underside of the pan tiles were polished and the question "why polish the underside of a pan tile?" could be answered with the purpose of illumination.

Conclusions

The article has presented a new way of looking at the Roma and Augustus temple in Ostia. Both regarding function, but also regarding the architecture of the roof. The aim of this article has thus been to present some initial thoughts that have been visualised in a 3D room. In this way, it has been easier to interpret and analyse on not only the single skylight tile but also on the contexts and functions. In a 3D room, it is easier to change the roof and add to it, when future discoveries are made.

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Through the utilisation of 3D, it is easier to interpret on the archaeological data and to put the archaeological data into a broader perspective. Furthermore, the 3D room enables a, sometimes hypothetical, view of the ancient viewer, thus adding a much-needed perspective on visual culture.

NOTES

1. For an overview of the different marble roofing systems, see [Wikander, 1988: 215; Ginovuès, 1992: 182-196, pls. 82-85].
2. See also "Ostian Marble Roof Tiles – Aspects of Chronology, Typology and Function", Ostia Forum Project, http://ostiaforumproject.com/ostian-marble-rooftiles/, accessed the 8th of June 2018.
3. This is based on the old hypothesis of its interior. The new hypothesis is presented by Gering in this volume: Gering A., Pecchioli L., Dehner M., Takáts B., "3D archaeological field recording in Ostia Antica". However, this does not have any effect on the purpose of my work here.
4. For an overview of possible skylight tiles from temples in the Roman West, see [Wikander, 1983: nos. 15, 25, 27, 32].

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ABSTRACT

ANALYSIS OF SKYLIGHT ILLUMINATION USING 3D
AN EXPERIMENTAL CASE OF THE ROMA AND AUGUSTUS TEMPLE IN OSTIA
A recent hypothesis by Axel Gering concerns the idea that the cella of the Roma and Augustus temple in Ostia was illuminated through elongated windows positioned behind the statues in the aediculae of the cella. The purpose of this article is to contribute to this hypothesis by presenting some 3D work of illumination through skylight tiles. Some marble fragments that could resemble skylight tiles have been found in a deposit close to the Roma and Augustus temple. This initiated some ideas that the roof of the temple could have been equipped with these types of tiles. The tiles would not only assist in illuminating the cella, but also the statue-equipped aediculae along the walls. Skylight tiles of Roman temples are rarely discussed and even more rarely published.

ANALISI 3D DELLA ILLUMINAZIONE DEL LUCERNARIO
UN CASO SPERIMENTALE DEL TEMPIO DI ROMA E AUGUSTO A OSTIA
Una recente tesi di Axel Gering ipotizza che la cella del tempio di Roma e Augusto a Ostia fosse illuminata da finestre rettangolari poste dietro le statue entro le edicole della cella. L'obiettivo di questo articolo è di concorrere a tale ipotesi presentando alcune elaborazioni 3D di illuminazione attraverso i coppi del lucernario. Alcuni frammenti marmorei che potrebbero ricondursi a coppi di lucernario sono stati rinvenuti in un deposito prossimo al tempio di Roma e Augusto. Ciò ha condotto all'idea che il tetto del tempio avrebbe potuto essere munito di questi tipi di tegole. Esse non avrebbero solo favorito l'illuminazione della cella, ma anche quella delle edicole con le statue lungo le pareti. I coppi di lucernario dei templi romani sono di rado oggetto di trattazioni e, ancora più di rado, di pubblicazione.

KEYWORDS
Ostia, illumination, skylight tile, marble roofing, temple
Ostia, illuminazione, coppi di lucernario, copertura marmorea, tempio

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