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3D Reconstruction of rock paintings: a cost-effective approach based on modern photogrammetry for rapidly mapping archaeological findings

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Abstract. The work describes a cost-effective methodology for the creation of 3D virtual models with both metric and photo-realistic content developed for archaeologists who need to rapidly map new findings during their field prospections. The potential of modern photogrammetry approach, based on Structure from Motion (SfM) and dense image matching algorithms, coupled with the use of low-cost cameras is evaluated for the creation of 3D models and orthophotos of rock paintings. The case study is located in Brealito valley, in the Calchaqui basin of the Province of Salta, Argentina. In these wide areas, actually known for the naturalistic value, a huge amount of archeological remains was found and surveyed for the first time in August 2013 within a research project funded by the Italian Ministry of Foreign Affairs. A methodological approach to record the findings in a cost-effective and reliable way is defined, acquisitions are performed with common use instruments such as digital cameras (off-the-shelf and single lens reflex - SLR) and measuring tapes. The novelty of the work lies in defining, experiencing and transferring to operators a simple methodology for digitizing and mapping the archeological heritage in order to provide 2D orthophotos and 3D models. Such methodology allows anyone, archaeologists or unprofessional personnel, to be trained and easily perform a survey in order to document, survey and study the investigated site.

1. Introduction

In recent years image processing and 3D modeling are finding great application in archaeology; the documentation of the heritage is becoming more and more digital and detailed thanks to innovative technologies such as photogrammetry, computer vision algorithms, laser scanning, remote sensing and topography based on satellites (GNSS - Global navigation Satellite System). Both traditional and satellite-based topography as well as remote sensing are well known in archaeology [1]. Laser scanning is also a widespread technique in cultural heritage documentation and monitoring [2, 3], although it has limitations in wild and mountainous areas because of the heaviness, the energy consuming and the encumbrance with respect to other systems. Traditional photogrammetry is widely used in archelogy for digitally document, usually in two dimensions, the excavations and the remains. The achievement of 3D products is also well known, there are countless publications about algorithms, procedures and potentialities of this technique [4], but it requires a deep knowledge of the procedures, the ability to properly design and carry out the survey and technical skills to accordingly process the data and deliver a reliable result. Thus, it is really hard to improve the method in terms of automation, rapidness of field activity and know-how transfer to unskilled personnel. On the contrary, the modern photogrammetry based on Structure from Motion (SfM) approach [5, 6] exploits digital images that are captured from different platforms (airplanes, unmanned aerial vehicles and from the ground) and sensors barely with no rigorous rules and provides automatic tools for data processing. Thanks to such an apparent easiness in obtaining a beautiful result, this technique rapidly spread the 3D virtual reconstruction of the digital heritage [7, 8], even if the actual challenge is still to produce a 3D documentation with an accurate metric content [9, 10]. Moreover, the recent technological improvement on software that are implementing SfM algorithms and hardware to speed up the image processing, allows a quite automatic method for 3D documentation.

Since 3D photorealistic models improve the representation of archaeological sites and enable post mission detailed studies and virtual enhancements of remote sites, the goal of the research is to develop, implement and test a cost effective methodology. User-friendly portable devices are exploited for data collection so that they can be carried out by archaeologists during prospections and do not need deep technical expertise. Moreover, such methodology is characterized by high automation so that the data processing is also carried out by personnel with a minimum training. The main steps of the research, as described in the paper, deal with methods for data collection and data processing as well as analysis and cross check of results in order to establish rules for the everyday field application of the methodology.

2. The case study: rock paintings in the Argentine Andes

The Argentine Northwest, and in particular two side valleys of the middle basin of the Calchaquí river (province of Salta), are the research sites of an archaeological mission based on the cooperation among Italian and Argentine scientists. The mission can boast two records: it is the first Italian archaeological research in Argentina and the interdisciplinary team combining both humanistic and technological skills has been driving to an innovative methodology to approach the digital 3D documentation of the Andean archaeological landscape. The specific context of the research is that of the lower Calchaqui river valley, southwest of the city of Salta (figure 1), in a densely populated region during the pre-Hispanic period. In particular, the studies took place in the areas of Luracatao, Brealito and Molinos where the archaeological prospection campaigns carried out since 2012 have allowed to identify several sites of cultural interest (fortified settlements, agricultural areas, caves with rock paintings, necropolis) [11]. Any findings and documentation in this area is of particular interest as it is unknown to archeology and it is located on the ancient transit routes between the Andean area and the low Argentine lands. The case study chosen to test the cost-effective methodology lies in the rock paintings of Brealito valley (figure 2).

3. Methods

3.1. Data collection

The archaeological prospection carried out in 2012 allowed to identify several sites of cultural interest that have been approximately positioned by means of portable low-cost *Garmin* receiver. In the following field campaign, that was carried out in 2013, some of them, such as the fortified settlements and agricultural terraces, have been recorded by means of GNSS static and kinematic surveys in order to provide detailed archaeological maps.

Some other sites, particularly the rock paintings, have been mapped by means of the modern photogrammetry approach in order to collect a suitable dataset to implement and test the cost-effective methodology for rapidly document in digital 3D way the archaeological heritage during field prospections. The investigated rock paintings are twofold (figure 2): the first one illustrates several white llamas with different sizes covering multiple faces of a rock within a cave; the second one, instead, paints animals (a monkey is particularly distinguishable) and figures with the colors of white, red and dark blue over a fractured rock.

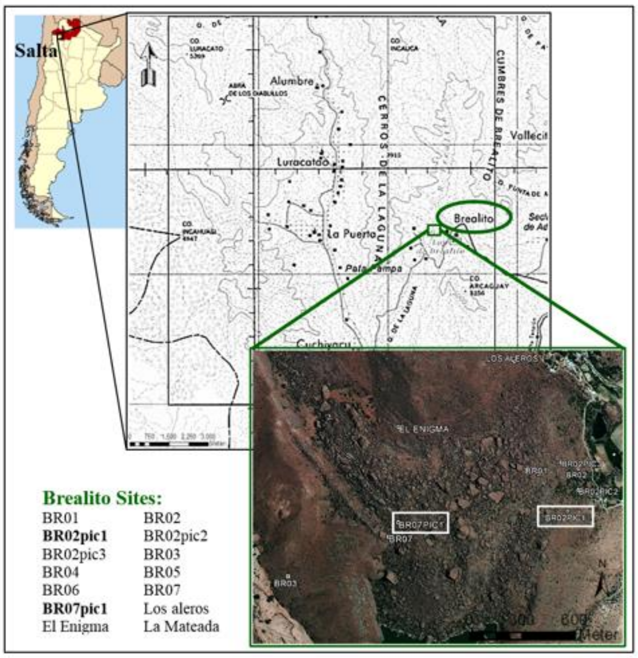


Figure 1. Location map of the study area: the Brealito valley (province of Salta – Northwest of Argentina) is included within the basin of the Calchaquì river where caves of cultural interest are found during 2012 field mission. Positions and identification codes are shown for all sites; the investigated rock paintings are BR02pic1 and BR07pic1.

Figure 2. Pictures of the investigated rock paintings with their name and identification codes. The white dots that stand out in any picture are the targets temporarily installed on the rock paintings with a double scope: to measure real distances in the field and then to properly process and give a geometric scale to the final 3D models.

In order to document the painting conservation, both the radiometric appearance and the 3D morphology of the rock are required; therefore, a 3D model with photorealistic content needs to be provided. The minimum suitable dataset consists of a proper number of images with good resolution (the higher the resolution, the better the final radiometric appearance) and a redundant set of geometric parameters. Usually, in photogrammetry, the geometric content comes from Ground Control Points (GCPs) whose coordinates are measured on purpose but this requires to carry on adequate technical instrumentation (for the specific environment, caves, the total station is the only feasible choice because GNSS receivers do not work unless in the open sky) and to own the proper competences to perform precise measurements, process the data and deliver accurate results. Very often archaeologists involved in field prospections cover wide areas by walking and examining the environment by means of only their eyes looking for evidences of past cultures; as soon as they identify any findings they have only the possibility to draw a sketch of the site on a paper and locate it by a *Garmin*. They come then back with technical equipment and topographers in case the site is of interest for excavations and full field missions. What if they could bring with themselves the knowledge and the ability to exploit mass market devices that are widely used and widely available such as a standard camera and a measuring tape? Such a minimum set of instruments is at the base of the data collection carried out in the August 2013 mission. Two different types of camera, a *Canon EOS 5DMarkII* and a *Panasonic DMC-FX60* have been tested in order to evaluate the performances of both Single Lens Reflex (SLR) and off-the-shelf cameras. Technical details of the cameras are listed in table 1.

Specific targets have been temporarily installed over the paintings in order to be included within the images and act as GCPs during data processing. Distances among the centers of targets have been measured by means of a simple measuring tape with an accuracy of few millimeters. These measurements provide the information about the real geometry and will then be used to process the data and give to the final 3D model the proper geometry and an idea of the achieved accuracy. A redundant set of distances was collected for each investigated rock painting: 39 measurements for BR07pic1 and 34 for BR02pic1. The mean acquisition distance separating the camera and the painting was about 2.5 m when testing the Canon camera with the lens at 35 mm focal length and 1.5 m when testing the Panasonic camera and the Canon one with the lens at 24 mm focal length. Concerning the pictures, images have been collected from different points of view in a convergent way and with high redundancy, paying attention to guarantee an overlap of 70% or more between adjacent images (34 images with the Canon camera and 41 with the Panasonic one at the BR07pic1 test site; 31 pictures were capture at BR02pic1 site).

3.2. Image processing

The images have been processed by means of the software *Agisoft PhotoScan v. 1.1.6*, that implements the SfM algorithm and the dense image matching, in order to obtain the final 3D models of the rock paintings (figure 3 shows the workflow of the process). The process consists of aligning the images by means of common descriptors that are found in automatic way by the algorithm over multiple images; by this way a self-calibration of the camera is performed and a first sparse point cloud is achieved. In order to improve the alignment, the manual selection of targets pairs visible in different images can be used (by this way the targets are used as tie points). Then, the dense image matching allows to provide the dense point cloud and the 3D model after meshing procedure which looks like the real object thanks to the photorealistic appearance given by the radiometric content of photos (imaging texture) despite no geometric content is included yet.

Table 1. Technical details about the digital cameras used for data collection.

Camera	Canon	Panasonic
Model	EOS 5DMarkII	DMC-FX60
Type	SLR	Off the shelf
Lens	24 mm, 35 mm	4.5 mm
Resolution [np x np [a]]	5616 x 3744	4000 x 3000
Pixel size [um]	6.549 x 6.549	1.536 x 1.536
Pre-calibrated	No	No

[a] np number of pixel

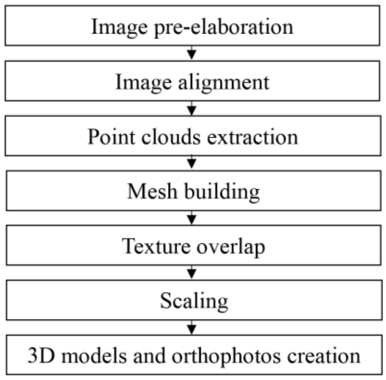


Figure 3. Workflow of the image processing procedure.

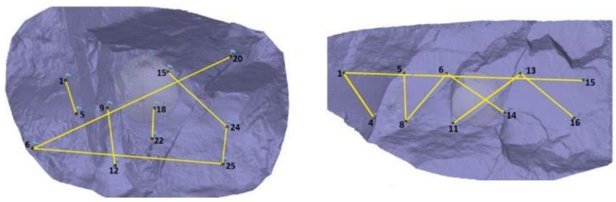
At this step, the target distances are used to scale the model and add the geometric content: the targets are identified over the 3D model and fixed to be the vertices of known segments, whose length is input in the software by the field measured distances (see figure 4). The validation of results as well as the evaluation of the final accuracy were performed by comparing the distances as measured over the obtained 3D model together with real distances measured in the field. In order to do that, the only usable field distances were the one that were not previously chosen for scaling the model. Several tests have been performed in BR07pic1 rock painting in order to evaluate the influence of the camera type and the specific focal length, the redundancy of the images dataset and the redundancy of the distances dataset. A summary of the various investigated dataset is described in table 2.

As soon as an accurate enough 3D model has been obtained, the methodology focuses on the creation of the orthophoto. Such a technical product is a 2D representation that is helpful to analyze in details the rock paintings conservation: the degradation of colours along time can be monitored thanks to the radiometric content whereas the geometric measurements that can be performed allows to check for deformations (such as thermal expansion, etc), fractures and further materic decay. The creation of orthophotos related to objects with a three-dimensional morphology requires the definition of multiple reference planes, where each one is orthogonal to the various faces of the rock in order to provide a comprehensive reliable representation. The automatic uncontrolled extraction of an orthophoto with a single plane, based on an average layout, provides a deformed 2D representation of the real geometry and furthermore any geometric analyses to monitor the conservation is meaningless. For complex morphologies a sort of unrolling of the cave has been implemented: projection planes as well as an internal coordinate system have been defined for the all painted surfaces.

Table 2. Technical parameters of data processing as modified in the various tests to evaluate the influence of camera type, lens and redundant dataset.

	BR07pic1					BR02pic1
Test ID	C35_34 [a]	C35_20 [a]	C35_10 [a]	C24_20 [a]	P4.5_41 [a]	C35_31 [a]
Camera	Canon	Canon	Canon	Canon	Panasonic	Canon
Focal length [mm]	35	35	35	24	4.5	35
N. of images	34	20	10	20	41	31
Mean capture distance [m]	2.63	2.63	2.63	1.23	1.37	2.5
Test area [m^2]	~ 4.5	~ 4.5	~ 4.5	~ 4.5	~ 4.5	~ 1
N. of targets	24	24	24	22	24	16
N. measured distances	39	39	39	30	39	34

[a] Rule for the test identification name: 1st letter relate to the camera (C=Canon, P=Panasonic); 2nd number relate to the focal length; 3rd number relate to the number of images.



BR07pic1	
Distance	Value [m]
6-20	2.441
1-5	0.44
9-12	0.69
22-18	0.377
6-25	2.165
24-25	0.422
15-24	0.887

BR02pic1	
Distance	Value [m]
1-4	0.745
5-8	0.635
6-8	0.811
6-14	0.895
11-13	1.08
13-16	0.84
1-15	2.875

Figure 4. Scaling of the 3D model of BR07pic1 (left) and BR02pic1 (right) test sites. Top: the model with highlighted the know distances that have been selected and input to add the geometric content. Bottom: tables reporting the distances that have been measured during the field survey, for each test site respectively.

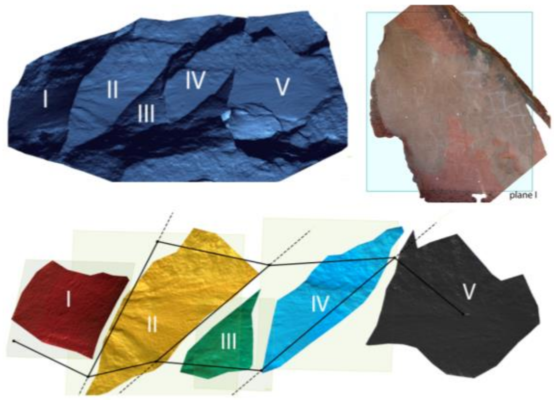


Figure 5. Orthophoto extraction: analysis of the 3D model and identification of sub-sectors where a single best-fit plane is able to describe the geometry layout (top left); computation of each best-fit plane (top right); planes and single coordinate systems to be used to perform the unrolling of the 3D model.

The area covered by paintings has been divided into as many sectors as the portions of rock that can be assimilated to a plane; each sector is then represented by an average best-fit plane (see figure 5). In order to compute the best-fit planes the 3D model has been processed with the modeling software *Rapidform XOR* (these tools are not available in *Agisoft PhotoScan*); the intersections between the planes provide the rotation axes to define the coordinate system. At this step, the coordinates of some points over these planes have been exported and introduced in *Agisoft PhotoScan* to create the coordinate system that is suitable to obtain the proper orthophoto, thus orthogonal to the surface, for the specific sector. The same procedure has been implemented for any sector, resulting in several portions of

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orthophoto that are then combined to provide the final unrolled 2D representation of the rock painting. The main characteristic of such orthophoto is a full content both in terms of geometry and radiometry.

4. Results and discussion

The technical characteristics of the 3D models obtained by the various tests of image matching process are listed in table 3: the generated point clouds have a huge amount of points and a high resolution due to the low distance of cameras from the object (that has been especially designed with respect to the context) therefore a detailed 3D digital documentation of the rock paintings has been achieved. The multiple tests carried out on the BR07pic1 site by modifying the dataset and the processing parameters provide interesting results.

First of all the influence of the number of photos has been analyzed: by lowering the number of exploited images from the full set of 34 photos (100% of used images) to about a half, 20 photos (59% of used images), and to a third of them, 10 photos (29% of used images), the number of points of the dense point clouds slightly decrease (by using 59% or 29% of the total number of images, the resulting dense point clouds contain 88% and 68% of points respectively if compared to the full dataset - refer to dataset C35_34, C35_20, C35_10 in table 3). It is worth to conclude that the number of total point remains very high (tenths of millions for the dense cloud) and the mean resolution of the 3D models are really similar, less than 1 mm that represents an excellent result if one thinks to the rapid cost-effective way of collecting the data and the automation of the process.

Table 3. Results of the multiple tests: quality parameters of final 3D models obtained by varying the strategy of image processing to evaluate the influence of camera type, lens and dataset redundancy.

	BR07pic1					BR02pic1
Proc. ID	C35_34	C35_20	C35_10	C24_20	P4.5	C35_31
N. points sparse	145 185	101 468	48 742	104 465	190 540	141 268
N. points dense	16 625 786	14 696 760	11 409 307	14 950 825	14 352 837	16 193 554
Mean res. [mm]	0.9	0.9	0.9	0.6	0.8	0.9
N. GCP [a] / N. CP [a]	7/33	7/33	7/33	7/24	7/33	7/25
Mean [mm] [b]	3	3	3	3	3	2
Std.dev. 2σ [mm] [b]	4	4	4	3	4	2.1
Std.dev. 2σ [mm] [c]	--	0.5	0.5	0.7	1.1	--

[a] Number of measured distances used as known input for scaling (GCP) and number of measured distances used to validate the model distances (CP).
[b] Refers to the scaling error.
[c] Differences, computed as distances between meshes, with respect to the reference 3D model obtained by the dataset C35_34.

Moreover, the influence of the camera type has been addressed: the Panasonic dataset shows a comparable resolution with respect to the reference dataset (refer to P4.5 versus C35_34 in table 3), proving the success of exploiting mass market devices. The resolution about 1 mm, indeed, guarantees details in the documentation and performances that are unreachable by traditional manual drawings. The influence of the focal length has been tested with the Canon SLR camera type (refer to C35_20 and C24_20 in table 3): the comparison highlights that the performance of the final 3D model are quite similar, resulting again in great resolution (again about 1 mm) with the only disadvantage that it was not possible to properly represent the whole investigated area due to the lack of redundancy in the boundaries. Indeed, the shorter acquisition distance (1.23 m versus 2.63 m) and the different focal length (24 mm and 35 mm) did not allow a comprehensive detection of the scene unless a higher amount of images focusing on a larger area is accomplished, thus requiring more time.

In general, the comparison of all the tested scenarios for obtaining the 3D model suggests that the datasets provide 3D models quite similar and no significant differences are highlighted, as shown in figure 6; therefore the basic idea to use a low-cost and largely reachable camera to collect a redundant set of photos from an average distance to provide a good resolution (that can be also checked in the field by looking the first pictures on the screen) and from multiple perspectives allows to perform a powerful and successful digital documentation of the findings. Such images have to be coupled to a redundant set of distance measurements. At this point the reference 3D model (anyone else among the obtained 3D model could be used) is used to perform the unrolling of the multiple faces of the caves in order to provide the most reliable and accurate orthophoto of each rock painting (figure 6).

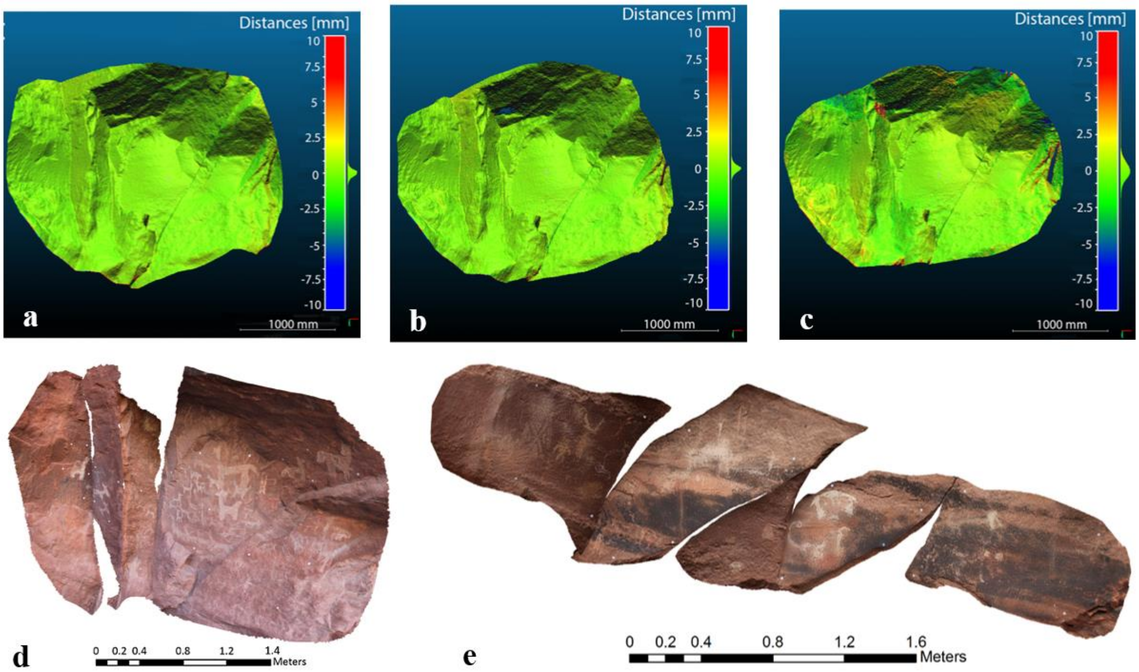

Figure 6. Comparison of the 3D models of BR07pic1 test site as obtained by modifying the image processing strategy: the reference solution is provided by the full dataset (C35_34) and is then compared to C35_20 (a),C35_10 (b), h_P4.5 (c). No significant differences exist within ± 10 mm. Then, final orthophotos have been computed with the reference 3D model and the unrolling procedure: from left to right, BR07pic1 and BR02pic1 rock paintings.

5. Conclusions

The creation of reliable 3D models with a metric content and a photorealistic appearance as well as 2D orthophotos allow the digital documentation of ancient rock paintings, thus providing archaeologists or scientists with technical data to be studied after the field mission and tourists or citizens with virtual reconstructions capable of enabling a remote visit. The photorealistic appearance combined to the geometric information allow to improve the knowledge and to monitor the evolution of rock paintings in an innovative way by exploiting the power of the third dimension. The use of modern photogrammetry based on image processing and SfM algorithm certainly simplifies both data collection and processing methods, but in spite of the simplicity it is still necessary to plan properly the image acquisitions and the ground measurements in order to provide the expected results in terms of accuracy, reliability and completeness.

Image matching is a cutting-edge research topic right now and new developments are being implemented. Ordinary image processing techniques, such as the classic photogrammetric approach, are not well suited for unknown archaeological findings located in wild areas, therefore the idea to develop, implement and test an innovative method for rapidly map new findings during archaeological prospections was pursued. The approach is evidently based on user friendly portable devices, such as a simple camera and a measuring tape; then more skills are required to process the data and be able to obtain a 3D virtual model and a suitable orthophoto but this step is leisurely carried out in office after the field mission is concluded. What is really of concern is to supply archaeologists with everything they need in the field, both devices and procedures, to be sure to be then able to fully document what they have been found. Then, on the basis of these preliminary data, future works can be planned. The present paper has shown the methodology and the results of several tests that allow to demonstrate the success of the methods and to give rules about the choice of devices, the way to collect the data and the way to process them for final helpful results. Moreover, these products enable the enhancements and the remote fruition of unmovable archaeological heritage, offering a modern way to attract tourists and the attention of the international community.

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References
[1] Wiseman J R and El-Baz F 2007 *Remote sensing in archaeology* (Springer Science & Business Media) p 552.
[2] Yastikli N 2007 Documentation of cultural heritage using digital photogrammetry and laser scanning. *J. Cult. Herit.* **8(4)**, pp 423–427. doi: 10.1016/j.culher.2007.06.003.
[3] Capra A, Bertacchini E, Castagnetti C, Rivola R and Dubbini M 2015 Recent approaches in geodesy and geomatics for structures monitoring *Rendiconti Lincei* **26(1)** pp 53-61. doi:10.1007/s12210-015-0436-z.
[4] Toschi I, Rivola R, Bertacchini E, Castagnetti C, Dubbini M and Capra A 2013 Validation tests of open-source procedures for digital camera calibration and 3D image-based modeling. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **XL-5/W2**, pp 647-652. doi:10.5194/isprsarchives-XL-5-W2-647-2013.
[5] Farenzena M, Fusiello A and Gherardi R 2009 Structure and Motion pipeline on a hierchical cluster tree. *Proc. of Computer Vision Workshops (ICCV Workshops) 2009 IEEE 12th International Conference (Kyoto, Japan)* p. 1489-1496. doi:10.1109/ICCVW.2009.5457435.
[6] Fonstad M A, Dietrich J T, Courville B C, Jensen J L and Carbonneau P E 2013 Topographic structure from motion: a new development in photogrammetric measurement. *Eearth Surf. Proc. Land.* **38** pp 421–430. doi:10.1002/esp.3366.
[7] Castagnetti C, Giannini M and Rivola R 2017 Image-based virtual tours and 3d modeling of past and current ages for the enhancement of archaeological parks: The visualversilia 3d project. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **XLII- 5/W1** pp 639-645. doi:10.5194/isprs-Archives-XLII-5-W1-639-2017.
[8] Gherardini F and Leali F 2016 A Framework for 3D Pattern Analysis and Reconstruction of Persian Architectural Elements. *Nexus Netw. J.* **18(1)** pp 133–167. doi:10.1007/s00004-015-0287-z.
[9] Remondino F, Spera M G, Nocerino E, Menna F and Nex F 2014 State of the art in high density image matching. *Photogramm. Rec.* **29** pp 144–166. doi:10.1111/phor.12063.
[10] Capra A, Dubbini M, Bertacchini E, Castagnetti C and Mancini F 2015 3D Reconstruction of an underwater archaeological site: comparison between low cost cameras. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **XL-5/W5** pp 67-72. doi:10.5194/isprsarchives-XL-5-W5-67-2015.
[11] Williams V I, Orsini C, Benozzi E and Castellanos M C 2014 Preliminary investigations in Brealito and Luracatao area: firsts results (dpt. Molinos, Salta). *Relaciones de la Sociedad Argentina de Antropologìa* **XXXIX(2)** pp 539-549. ISSN 1852-1479 (online version).