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The integration of 3D technology for the conservation and restoration of ruined archaeological artifacts

Abstract. *The restoration and conservation of monuments and archaeological sites is a delicate operation. It requires fidelity, delicacy, precision and archaeological authenticity. The aim is to reveal, recreate as accurately as possible the characteristics of an archaeological site or part of it. Research during the last two decades has proved that 3D modeling, or the digital documentation and visualization of archaeological objects in 3D, is valuable for archaeological research. As well, as for conservation and presentation to a wide audience, as it allows the creation of realistic and accurate digital copies of archaeological objects. In the past, 3D modeling technologies were prohibitively expensive and too technologically specialized to be integrated into most historical heritage projects. However, advancements in computing and digital photography over the past decade have resulted in several low-cost, user-friendly options for 3D modeling, using photogrammetry. The latter has been used successfully for documentation of historic cultural. In recent years, this technology has become increasingly more popular for archiving, which provide the 3D model and digital ortho-image using high accuracy dense 3D points. The study has opted for the technique of terrestrial and aerial photogrammetry by 3D surveys of architectural* *elements, to develop an archetype of the deteriorated Islamic Marinid site (a dynasty between the 13th and 15th centuries), and the Roman site (25 BC), located at the Chellah archaeological site in Rabat and Salé cities. However, the recognition of the importance of these Islamic sites, in terms of the evolution of Moroccan Islamic art, requires the combination of large-scale scanning capability of unmanned terrestrial, aerial photogrammetry and the photorealistic rendering of 3D, as well as exhaustive research on the history of this cultural site. The data acquired build an architectural database to archive and retrieve the entire existing architecture of monuments. This study has been completed by photogrammetrists, architects, and restorers.*

Keywords: *cultural heritage; photogrammetry; survey; architectural archiving; 3D reconstruction ; museology*

Introduction and research aims.

Unfortunately, Moroccan cultural heritage, despite its high potentials, such as many monuments, archaeological sites and valuable scientific data, has hardly benefited from the use of digital and new technologies. Therefore, the implementation of Photogrammetry for documentation, analysis and dissemination of archaeological findings to archaeologists is essential to make cultural heritage in Morocco accessible to the human community more easily and scientifically through these techniques. It enables us to produce accurate information on objects. Providing a 3D model of these monuments and sites can be a good way to document and record these works as they provide geometric measurements and extract quantitative information with good accuracy, which can be used to prepare restoration plans.

These methods are able to provide digital documentation and 3D modelling of historic monuments (Martin, Meynard, Pierrot-Deseilligny, Souchon, & Thom, 2017). Also, to generate 3D and 2D models, and, tips for virtual recovery of cultural heritage. Nowadays the world loses its heritage identity faster than they can be documented (Thomas, 2017). There is a particular need for technical guidance on recommended workflows, from data capture through to archiving based, if possible, on free software. This will greatly reduce the cost in terms of research and expense in the commercial sector and will ultimately lead to an enhanced record and understanding of our archaeological heritage (McCarthy, 2014).

In the last years, Photogrammetry was used for aerial and terrestrial applications largely motivated for the conservation of cultural heritage monuments (Hill, 2019). Terrestrial laser scanning technology allows fast and efficient collection of 3D coordinates of cultural heritage object automatically (Yastikli, 2007). The terrestrial Photogrammetry by camera photo is generally the most used technologies to virtually reconstruct the entity geometry of the monuments (Thomas, 2017). Using low-cost equipment like digital camera proved to be adequate to promote cultural heritage over the web such as virtual reality (Koutsoudis, Arnaoutoglou, & Chamzas, 2007).

Historical documentation using UAV-based images a significant time-saving compared with traditional measurement techniques (Colomina & Molina, 2014). The cost of UAV systems is major factors that determine the budgets of cultural heritage documentation projects (Bakirman et al., 2020). Loaiza Carvajal and al. (Loaiza Carvajal, Morita, & Bilmes, 2020) recommended that close range objects reconstructed by digital Photogrammetry allow an exact reconstruction, with micrometric resolution and a high-quality texture, used in the case of institutions that require the digitization of objects of heritage value. Also, Himasari Hanan and al. recommended that close range Photogrammetry techniques provide flexibility in data acquisition as the non-metric camera can be operated by almost anyone and more affordable (Hanan, Suwardhi, Nurhasanah, & Bukit, 2015). Compared to other 3D modelling techniques, they deliver a variety of data, from 2D images of photographs, dense point clouds, the geometry of the object and solid 3D model.

The choice of the appropriate method for 3D modelling is very important in the documentation, because the product model must also have the desired detail, in addition to being accurate(Alby & Grussenmeyer, 2012). This paper presents, an approach combining digital camera, UAV and image data, to model and reconstruct architectural features; in order to provide sufficient and comprehensive data regarding the documentation and evaluation of Abu AlHassan's Madrasa, and the Roman remains located at the archaeological site of Chellah. Also, the Madrasa Al-Marinia in sale city (13^{th} century). This will allow us, through the documentation and archiving of these historical data, to determine the physical damage in order to provide the necessary intervention and conservation methods.

Study sites.

Our chosen study sites (Figure 1) located in Salé city (Morocco) and, on the Chellah archaeological site in Rabat city (capital of Morocco); this site offers conditions conducive to human occupation from the earliest antiquity (7th-6th c. BC) (Terrisse, 2011). In 2012 it was added to the United Nations Educational, Scientific, and Cultural Organization (UNESCO) world heritage list (https://whc.unesco.org/fr/list/1401) (Salih & Amrani, 2012). The first site is the Marinid Madrasa of Abu Al-Hassan which is a Quranic school serving as a college and a student residence (Boukous, 2011; Shatzmiller, 2011). The second site is Madrasa Al-Marinia; it was built in the first half of the 14th century under the reign of the Marinid Sultan Abu al-Hassan ben Uthman, in the city of Sale near of the city of Rabat (Pennell, 2003). These Madrasas served a cultural, educational and political role (Belhaj, Bahi, & Akhssas, 2017), they were erected to deserve the favors of Allah, to do religious and God-pleasing work, to restore religious teaching and science, and to strengthen the political power of the rulers (Belhaj et al., 2017; Daniotti, Gianinetto, & Della Torre, 2020). The Marinid dynasty that ruled Morocco and the whole of the Maghreb for nearly two centuries, from the second half of the 13th century to the first half of the 15th century (Nagy, 2020; Shatzmiller, 2011).

The third site is the Romain settlements (in 25 B.C.). According to the excavations and the archaeological studies we can establish the portrait of Sala during the period of reign of Juba II. The city was laid out in terraces like some other great centers of the Hellenic East. On these narrow terraces were discovered many pre-Roman buildings, some of which were later integrated into the buildings of the Roman period and thus survived the stratification of the successive periods. It is to this Hellenic period that belong three temples and public buildings with isodomic wall structure or Moretan style with alternating blocks, warehouses built with mud bricks and paving of the streets in local sandstone (Boube, 1999).

Figure 1. Study area, a) Madrasa of Abu-Al-Hassan, b) The Roman site, c) AlMadrasa Al-Marinia. (Source: Google earth pro).

Material features and methodology.

Photogrammetry as any measurement technique that allows the generation of 2D or 3D digital models of the object as an end product (Daniotti et al., 2020; Obradović et al., 2020). Of course, this is the case when using photographic images, but it is still the case when any other type of 2D acquisition is used, for example, radar, or a scanning device: the photogrammetry process is basically independent of the type of image (Alberti, Ferretti, Leoni, Margottini, & Spizzichino, 2017; El-Din Fawzy, 2019). In this case, we used a digital camera that allows measurement of a large number of points placed on the object monitored without the need for them to be accessible but only visible (Cucci, Picollo, & Vervat, 2012). And a series of overlapped images were collected using UAS based digital and multispectral cameras Table 1.

a. Digital Camera.

Many architectural features (the columns, door arches, Fountain, and Mihrab) were photographed using a digital camera: Canon EOS 700D.

Table 1. Camera specifications

	Camera specifications
Brand of camera	Canon
Camera model	Canon EOS 700D
Type	22.3 x 14.9mm CMOS
ISO sensitivity	ISO-160
Focal length	F/4
Total pixels	Approx. 18.5 megapixels
Sensor cleaning	EOS integrated cleaning system

Table 2. Technical specifications of devices used

	Camera specifications
Brand of camera	Canon
Camera model	Canon EOS 700D
Type	22.3 x 14.9mm CMOS
ISO sensitivity	ISO-160
Focal length	F/4
Total pixels	Approx. 18.5 megapixels
Sensor cleaning	EOS integrated cleaning system

b. UAV-drone.

In recent years, UAVs or drones have been used in various archaeological areas, including site identification, mapping, and site modelling (Liang, Li, , Lai, Zhu, Jiang, & Zhang, 2018; Rocheleau, 2005). Given the limitations of drone availability for photography, cloud cover and satellite orbital characteristics that do not allow us to capture a specific location at a given time, UAVs have advantages such as cost reduction, low-level shooting capacity, high resolution images and high time flexibility (Rocheleau, 2005; Singhal, Bansod, & Mathew, 2018). For images acquisition, a 1-inch camera sensor camera is mounted on the DJI Phantom 4 Pro. This camera offers a multi-format sensor, which leads to a 20megapixel resolution. The Phantom 4 Pro also features DJI's Flight Autonomy system, providing you with five directions of obstacle sensing. The camera specifications are listed in Table 2.

Figure 2. Example of 75% recovery on two consecutive images (source: Authors).

The different architectural structures have established that the measurement must be carried out at different angles (Obradović et al., 2020). In order to have sufficient quality and accuracy, we will strive to achieve a minimum image to the image recovery rate of 75% (Figure 2) (Lee, 2018, Bedford, 2017). For the image in the Figure 3 representing a length of 1m, the digitized surface of 25% of this length, or 0.25m, is shifted parallel to the digitized surface to produce the following image (Ginzler & Hobi, 2015).

Figure 3. A series of corresponding images to digitize a surface (source: Authors).

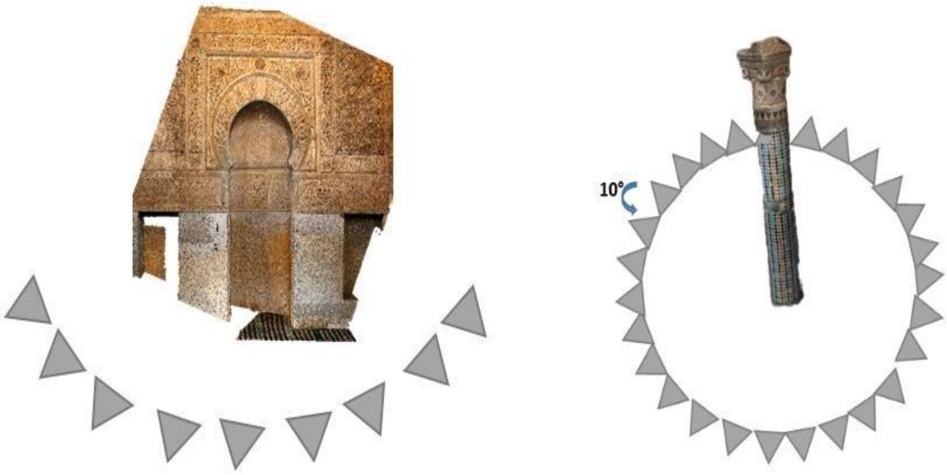


Figure 4. Positions of the device for angle scanning (source: Authors).

In the Figure 4, the grey triangle represents the location of the camera at the time of acquisition. Particular care must be taken to ensure that the edges of the object are present in several images so that only the central elements are covered (Bedford, 2017). To do this, the images were made beyond the desired object to have a recovery in the corners and edges of the object. For that, a point of the object must be visible at least on two images in order to be reconstructed (Pollefeys, 2000).

In the image (Figure 4), the surface to be digitized has an angle, so a movement around the angle has been initiated to connect the two surfaces, as shown in the diagram. This movement must always respect a minimum overlapping of 75%, and generally includes at least six photographs on an angle (New Jersey Department of Transportation, 2009; Bedford, 2017). For the columns, we need a 360° scanning around the object, to obtain the desired recovery (Rosin et al., 2018), since the object is highly textured; we have made 36 steps of 10° each.

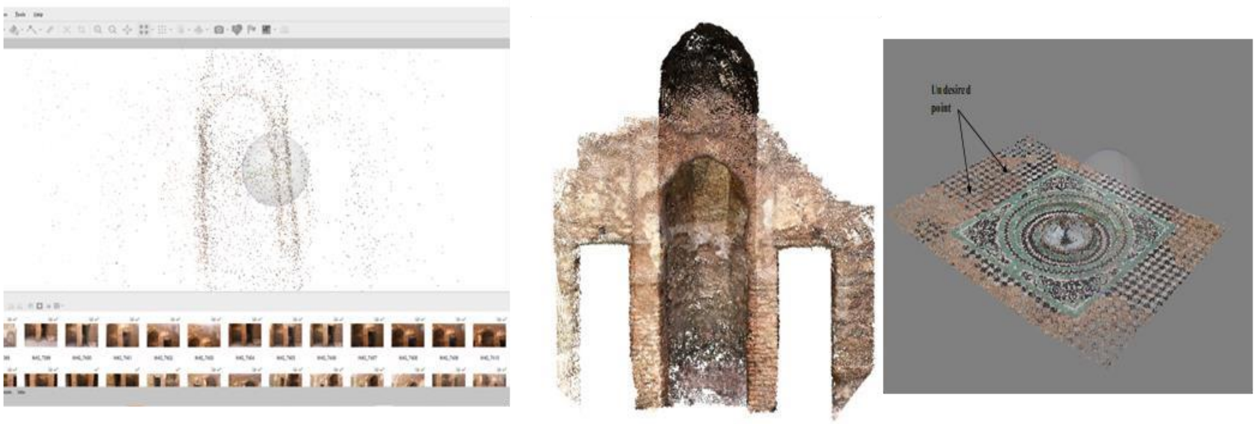


Figure 5. Pretreatment of a point cloud: undesirable points in the scene (source: Authors).

A total of 385 were taken using a DJI Phantom 4 Pro (DJI). Its price range is around 0.2% that of professional UAVs. The altitude was 5–30 m. The side lap and along-track overlapping were 85%.

Agisoft Metashape software was used for photogrammetric processing of digital images and 3D spatial data generation. This software based on structure from motion (SfM) method (Shervais, Dietrich, & Lauer, 2019), which is a photogrammetric method for creating three-dimensional models of a feature or topography from overlapping two-dimensional photographs taken from many locations and orientations to reconstruct the photographed scene (Bedford, 2017; Shervais, Dietrich, & Lauer, 2019). And has been implemented in many applications such as archeology (Chiabrando, Donadio, & Rinaudo, 2015), DEM creation (*Agisoft Metashape*, 2019), geodesy (Cook & DeSanto, 2019), geomorphology (Micheletti, Chandler, & Lane, 2015), and structural geology (Saputra, Rahardianto, & Gomez, 2017). It uses Scale Invariant feature transform (SIFT) algorithm (Napolitano & Glisic, 2018), which included four steps; scale–space extrema detection, key point localisation, orientation assignment, and key point descriptor (Bakirman et al., 2020; Peña-Villasenín, Gil-Docampo, & Ortiz-Sanz, 2019). In the first stage, it uses the difference of Gaussian function *(1)* to identify potential points of interest; naturally according to the algorithm these points are invariant to scale and orientation (Bakirman et al., 2020; Lee, 2018):

$$L(x, y, \sigma) = G(x, y, \sigma) * I(x, y) \quad (1)$$

Where * is the convolution operator, $G(x, y, \sigma)$ is a variable-scale Gaussian and $I(x, y)$ is the input image.

To determine the key-point localisation in the scale-space, difference of Gaussians is one such technique, locating scale-space extrema, $D(x, y, \sigma)$ by computing the difference between two images, one with scale k times the other. $D(x, y, \sigma)$ is then given by (Bakirman et al., 2020) *(2)*.

$$D(x, y, \sigma) = L(x, y, k\sigma) - L(x, y, \sigma) \quad (2)$$

The key-point descriptor *(3)*, described below, can then be represented relative to this orientation, achieving invariance to rotation. The approach taken to find an orientation is (Bakirman et al., 2020):

$$M(x, y) = \sqrt{\left(L(x+1, y) - L(x-1, y)\right)^2 + \left(L(x, y+1) - L(x, y-1)\right)^2} \quad (3)$$

$$\varphi(x,y) = \tan^{-1}\left(\frac{L(x,y+1) - L(x,y-1)}{L(x+1,y) - L(x-1,y)}\right)$$

Where L (x, y) is an image sample, m (x, y) is the gradient magnitude, and (x, y) is orientation. Finally, unique descriptors for each key point are computed to conclude the SIFT process.

Photogrametric results and disscussion.

The Photogrammetry process used in this study is less expensive compared to other techniques such as laser scanning. Digital Photogrammetry applied to historical heritage has great potential as a mechanism and a tool for documentation, dissemination and enhancement, and even restoration and monitoring (Calin, 2015; Wei et al., 2019).

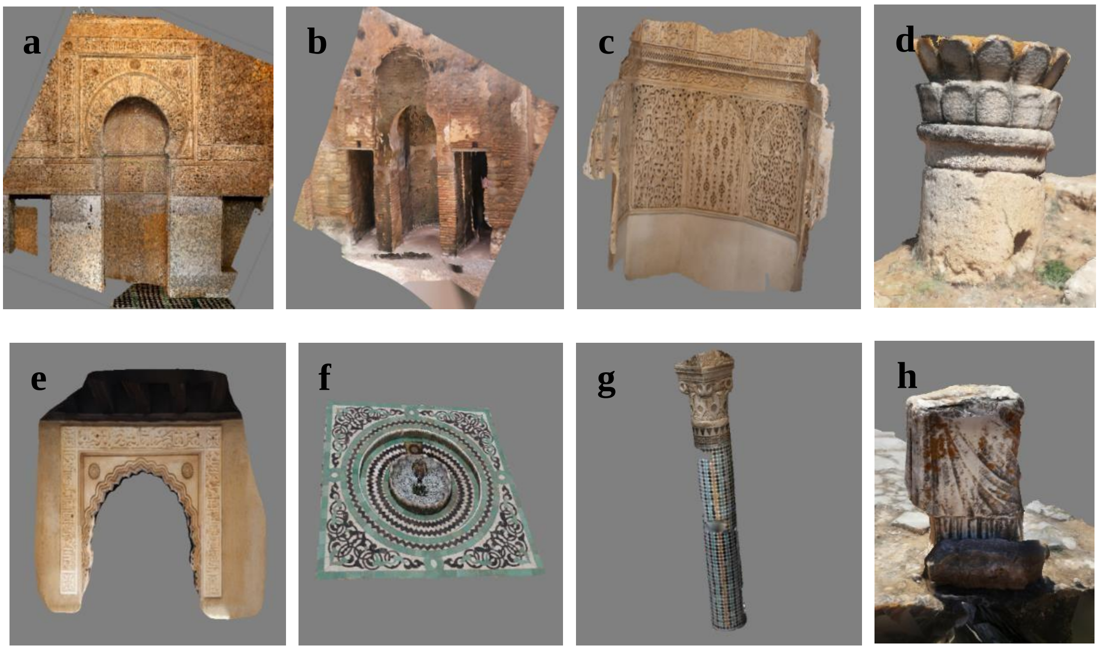
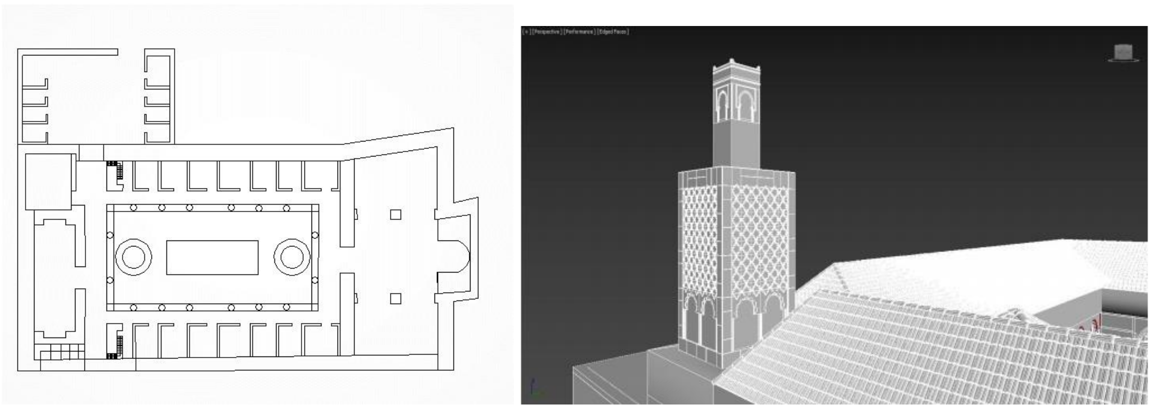


Figure 6. 3D modelling of architectural features, a-c) Mihrab Al-Marinia, b) Mihrab remain of Madrasa of Abu Al-Hassan, d) The Romain Fountain e) door of Madrasa Al-Marinia, e) The Marinid Fountain, g) The Marinid column, h) The Romain statue, (source: Authors).

In order to obtain consistent data (Figure 6), the pretreatment phase (Figure 5) is necessary to reduce undesired scenes and noise in the point cloud, and to keep that the points of interest for the model. The digital models resulting from the point cloud modelling are simple models, made from data from the field. These products can be used for video and animation creation. And also, can create measurement supports (Loaiza Carvajal et al., 2020) (Figure 7), as well as generate 2D plans, and cross-sections (Figure 9), and create profiles (Yilmaz, Yakar, Gulec, & Dulgerler, 2007; Galantucci & Fatiguso, 2019).

Figure 7. Point cloud as a support for measuring (source: Authors).

Figure 8. Aerial view of the current state of the study area (DJI Phantom pro4) (source: Authors)



a b

Figure 9. The Medersa Marinid, (a) 2D plan, and (b) 3D model (non-textured view) , (source: Authors).

The acquired images by drone are used to generate and integrate 3D models, generate orthophotographs, with precision, and perform visual inspections of the site in its current state (Figure 8).

These models can serve as a reference for future studies and even for public diffusion based on better production proposals that produce more accurate documentation, dissemination and interpretation (Grussenmeyer, 2003; Martin, Meynard, Pierrot-Deseilligny, Souchon, & Thom, 2017). Despite the advantages of the method and sub-processes, it also faces practical complications that are generally related to climatic conditions (wind, rain, other), as well as the availability of disparate technological means, such as the current situation itself, or the environmental sphere, lighting conditions, solar radiation and others (Aparicio, Espinoza-Figueroa, Aguirre, Mejía, & Matovelle, 2018).

The 2D data and models generated from terrestrial photogrammetry are exported to the 3Ds Max platform which allows, through the use of advanced modelling techniques, the construction of a three-dimensional digital model that can be visualized, manipulated and modified at any time, being able to develop different versions of the same model (Figure 10).

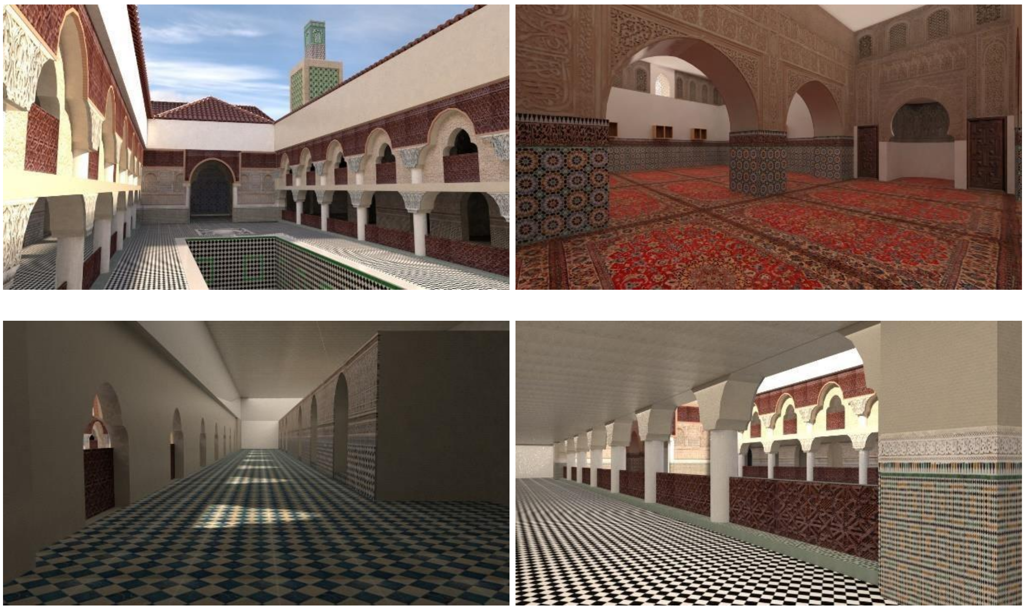


Figure 10. Multiple view of 3D photorealistic model of Marinid architectural features, (source: Authors).

A question was posed during the modelling of the Medersa that was not very clear in the books on the history of the site: how many floors did this site have? Some hypotheses take into consideration, due to the traces of the stairs that are still visible. The first hypothesis is that the site is constituted by the ground floor and two floors, it is based on similar Medersa built in the same period and by the same Marinid dynasty, and especially that of Abu Al-Hassan located in the Sale city, and El Attarine in Fez. The second hypothesis, it has been proposed that the site consists of the ground floor and a single floor, based on a comparison between the supporting structures; the square and circular columns of the Medersa Marinid in Chellah and other similar sites. The square columns of the study site are (50×50) cm, and the circular columns (25×25) cm in size, while those of Medersa Abu Al-Hassan and El Attarine are twice as large. Indeed, the first hypothesis was eliminated and the second was used as a model (Simou, Baba, Nounah, & Aarab, 2020).

Conclusions.

Betting on technologies applied in everyday life shows the improvement of heritage conservation processes, also shown by this study, through the effective restoration, for example, of the damaged Mihrab of Madrasa Marinid, whose immediate value has slowed the loss of individual value of the object and of course of the architectural complex. In general, the demand for 3D technologies to digitize heritage is increasing rapidly and efficiently (Alshawabkeh, El-Khalili, Almasri, Bala'awi, & Al-Massarweh 2020; Xie & Matusiak, 2016). This is a promising option for the future, and current efforts are focused on cost-effectiveness, speed, efficiency and accessibility to capture and compute large-scale 3D virtual models from archaeological discoveries (Erenoglu, R. C., Akcay, & Erenoglu, O., 2017). Although photogrammetry helps to digitally record historical remains with a high level of detail (Yang et al., 2020), this will facilitate the rehabilitation and effective analysis of cultural sites by cultural centers. This study provides a three-dimensional documentation of the Medersa Marinid site located at the Chellah Archaeological Site, combining different methods after their examination, starting with aerial photogrammetry by drone which allowed us to carry out a survey of the site in order to have an overview of the current state of the site, and terrestrial photogrammetry with a digital camera, which is one of the most economical and rapid ways to digitize archaeological objects, this methods has allowed us to generate three-dimensional models of some architectural models that are still durable in the site, with high quality and with the ability to display all parts of these objects as a 3D file and orthophotographs, which have been a valuable addition to this documentation. Then, to use the data retained by photogrammetry methods to modelling software, to reconstruct and record the studies of the Medersa Marinid Monument through graphic documentation. The selected 3D virtual models are reactive and allow to quickly analyzing the construction elements and associated data. These technologies open up new opportunities for the management and conservation of this cultural heritage, and even for the tourism and educational processes that attempt to bring this heritage closer to the new generations.

Unfortunately, Moroccan archaeology, despite its high potential, such as many archaeological sites and valuable scientific data, has hardly benefited from the use of digitization and new technologies. Therefore, the introduction of digital methods of documentation, analysis and dissemination of archaeological findings to archaeologists is essential to make archaeology in Morocco accessible to the human community more easily and scientifically through these techniques.

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Conflicts of interest.

The authors declare no conflict of interest.

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Інтеграція 3D-технологій для консервації та реставрації зруйнованих археологічних артефактів

Анотація. *Реставрація та консервація пам'ятників та археологічних об'єктів – справа тонка. Вона вимагає делікатності, точності та археологічної достовірності. Ціль полягає в тому, щоб максимально точно виявити, відтворити характеристики археологічного пам'ятника або його частини. Дослідження останніх двох десятиліть довели, що 3D-моделювання, або цифрова документація та візуалізація археологічних об'єктів у 3D цінні для археологічних досліджень, а також для консервації та представлення широкій аудиторії, оскільки дозволяє створювати реалістичні та точні цифрові копії археологічних об'єктів. У минулому технології 3D-моделювання були надмірно дорогими та надто технологічно спеціалізованими, щоб їх можна було інтегрувати у більшість проектів історичної спадщини. Однак досягнення в розвитку обчислювальної техніки та цифрової фотографії за останнє десятиліття призвели до появи кількох недорогих та зручних варіантів 3D-моделювання з використанням фотограмметрії. Останній був успішно використаний для документування історико-культурної спадщини. В останні роки ця технологія стає все більш популярною для архівації. Вона забезпечує* *отримання 3D-моделі та цифрового ортозображення з використанням високоточних щільних 3D-крапок. У дослідженні був обраний метод наземної та аерофотограмметрії за допомогою тривимірних зйомок архітектурних елементів, щоб розробити архетип занепаду поселення ісламських маринідів (династія між 13 і 15 століттями) і римського поселення (25 р. до н. е.), розташованого на археологічних розкопках Челлах у містах Рабат та Сале. Проте визнання важливості цих ісламських пам'яток з погляду еволюції марокканського ісламського мистецтва потребує поєднання великомасштабного сканування безпілотними наземними засобами, аерофотограмметрії та фотореалістичного 3D-рендерингу, а також вичерпних досліджень з історії цього культурного об'єкту. Отримані дані створюють архітектурну базу даних для архівування та відновлення існуючої архітектури пам'ятників. Це дослідження виконано фотограметристами, архітекторами та реставраторами.*

Ключові слова: *культурна спадщина; фотограмметрія; обстеження; архітектурне архівування; 3D реконструкція; музеологія*

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