Archeologia e Calcolatori
31.2, 2020, 33-45
doi 10.19282/ac.31.2.2020.04

SfM-PHOTOGRAMMETRY FOR FAST RECORDING OF ARCHAEOLOGICAL FEATURES IN REMOTE AREAS

1. Introduction

In the last twenty years, digital heritage methodologies supporting the identification and documentation of archaeological sites have become a crucial tool for the study, protection, management, and promotion of archaeological landscapes, sites and monuments (e.g. Daly, Evans 2005; Richardson 2013; Law, Morgan 2014). Archaeological features are a fragile category of cultural heritage, threatened by urbanization, industrialization, natural and human-induced erosion, intensive agriculture, social instability, and warfare (Harmanşah 2015; Pierdicca *et al.* 2016; Howland *et al.* 2018; Shahab, Isakhan 2018; Carvajal-Ramírez *et al.* 2019; Mariani *et al.* 2019; Zerboni *et al.* 2020a). For this reason, the fast acquisition of digital details is becoming a global priority in heritage science.

Digital recording practices are at the basis of modern archaeological research, but in many cases these methods are expensive and require instrumentations often not easily transportable to remote areas. To mitigate these issues (Perez-Garcia *et al.* 2019) remote sensing techniques such as satellite or aerial imagery provide useful tools to acquire high detailed information and perform assessments of the archaeological landscape (e.g. Bewley 2017). On the other hand, when surveying remote regions of the Earth field-based archaeological inspection is limited by several factors:
– the possibility of repeating surveys in a single place,
– the amount of time available for each archaeological site/feature,
– the availability of professional equipment (for instance: total stations, RTK GPS, LiDAR, TLS),
– the specific environmental settings (e.g. light and meteorological conditions).

Recently, the improvement of photogrammetric commercial software and hardware offered an invaluable tool in archaeological survey. The optimization of Image Based Modeling techniques with Structure from Motion (SfM) approaches (Szeliski 2010) paved the way for comprehensive photogrammetry software and made recording of 3D data with budget cameras possible. SfM-photogrammetry has been widely applied to cultural heritage studies in different ways such as digitisation of historical documents (Ballarin *et al.* 2015; Brandolini, Patrucco 2019), 3D modelling of archaeological artefacts (Sapirstein 2018; Zangrossi *et al.* 2019), surveys of cultural and geo-heritage (Brandolini *et al.* 2019), monitoring of buildings (Galantucci, Fatiguso 2019), digital reconstruction of lost monuments (Beltrami *et al.* 2019)

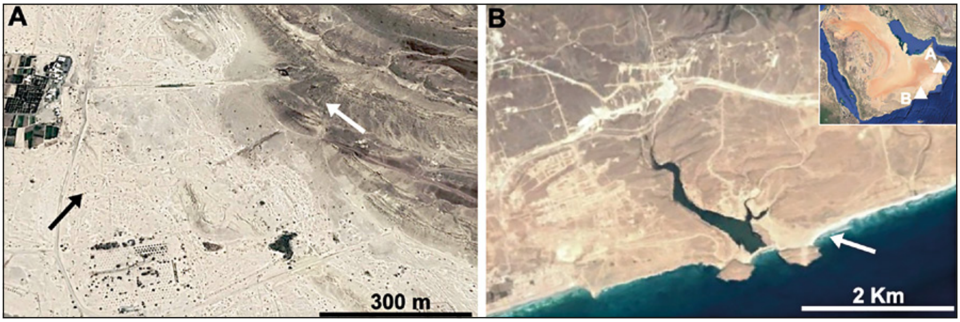

Fig. 1 – A) Aerial view of Salut-ST1 tower. B) Location of the KR-N1 necropolis at Khor Rori (white arrow).

and damaged archaeological sites (Carvajal-Ramírez *et al.* 2019), and as an instrument for communication and valorisation of cultural heritage (Guidi *et al.* 2014).

Improvements in the technology of cameras and methods for the calibration of non-metric cameras have expanded the use of photogrammetric modelling (Westoby *et al.* 2012) to non-professional and semi-professional users. Nowadays, high-performance Digital Single-Lens Reflex (DLSR) cameras are relatively affordable and the technological improvements of mobile devices (i.e. smartphones) cameras allow the use of devices for the acquisition of digital images with an acceptable quality (Barbero-García *et al.* 2017). Photogrammetry thus has become a cost-effective and versatile technique (Campana 2017) that is currently widely applied for three-dimensional documentation of archaeological heritage sites (Peña-Villasenín *et al.* 2019; Waagen 2019). The potential of both terrestrial and aerial SfM-photogrammetry is constrained by the need for Ground Control Points (GCPs) and CheckPoint (CP) acquired with expensive (and often cumbersome) professional topographic equipment often not available during archaeological survey. In fact, GCPs are required in order to georeference the topographic models, refine the camera calibration parameters, and remove artefacts of optical distortion. However, recent research in geomorphological survey tested the possibility to produce 3D models with acceptable topographical precision using only consumer-grade drones along with low-cost SfM-photogrammetry packages (Carbonneau, Dietrich 2017) in "sub-optimal survey conditions" (Jaud *et al.* 2016), where GCPs are limited or not available at all.

In this paper, we illustrate the application of SfM-photogrammetry to document archaeological features detected during surveys in two regions of the Sultanate of Oman (Fig. 1). Case studies include features quite common in remote arid and semi-arid regions, thus representing a good test to apply a fast, low-cost, and highly flexible SfM-based approach (Jalandoni *et al.* 2018) to create 3D models in order to reduce the time and equipment needed in the field. We observe that the centimetric accuracy of the elaborated 3D models is acceptable in the perspective of a fast and reliable recording of archaeological features in remote areas, barely accessible with topographic instruments.

2. Case studies

The case studies here described belong to two major archaeological contexts from the northern and southern Sultanate of Oman (Fig. 1). The first explored area corresponds to the ancient oasis of Salut (Avanzini, Degli Esposti 2018), including the low bedrock heights bordering it to the E/NE (Jabal Hammah). The area is characterised by an extremely rich archaeological landscape that bears witness to a long history of Holocene local human occupation (Degli Esposti 2015). In particular, the Early Bronze Age (mid-3rd millennium BC) saw the establishment of typical tower sites, equipped with substantial water-management systems. One of the towers – Salut-ST1 – was extensively excavated between 2010 and 2015 (Degli Esposti 2016). In the second half of the 2nd millennium BC, after the abandonment of Salut-ST1, the prominent Iron Age site of Salut was established atop and around a small limestone hill (Degli Esposti, Condoluci 2018). The whole area hosts coeval smaller dwellings, probable field relics and hydraulic structures (Cremaschi *et al.* 2018). Later features are present, telling about a human occupation lasting until the early centuries AD and then re-starting in the early Islamic period (Degli Esposti *et al.* 2018, 2019). Over this long period, numerous engravings were carved on rocks outcropping in the area. SfM-photogrammetry was applied to a large boulder bearing engravings and to the Salut-ST1 tower.

The second area corresponds to a site along the shorelines of the Arabian Sea in the region of Dhofar, near the border with eastern Yemen (Zerboni *et al.* 2020b). The area has been characterized by human presence since ancient times, but it is only since the Iron Age that permanent settlements were established. In the 4th century BC, the settlement HAS1 (Lischi 2019) on the promontory of Inqitat dominated the area until the arrival of the South Arabian people a few centuries later and the subsequent building of the city of Sumhuram (Avanzini 2014). In this context many necropolises rise, including KR-N1 necropolis. The latter was tentatively dated to the Iron Age given the architectural features and archaeological findings. In this context, SfM-photogrammetry has been employed to record an Iron Age grave of the necropolis.

3. Method: hardware and software

Pictures were acquired with a Canon EOS 100D DLSR digital camera, and with a OnePlus 3T mobile device equipped with Snapdragon 821 Mobile Platform hardware and an optical sensor Sony IMX 298. During the acquisition phase, different scale-bars were placed in different positions on the scene following the method proposed by Cultural Heritage Imaging Company. Images were processed through the photogrammetric commercial software Agisoft PhotoScan (version 1.4) to elaborate the 3D model of archaeological features. The scale-bars allowed rescaling the 3D model during the photogrammetric process. Image acquisition was processed following the procedure reported in the Agisoft 1.4.4 guidelines. Pictures were acquired with both devices and elaborated in the laboratory. The photogrammetric elaboration of 3D models was performed through a high-performance workstation Dell – Alienware Aurora R5[1]. Desk processing of images followed the procedure described in the Agisoft 1.4.4 manual and consisted of 5 operations:

– aligning photos,
– building the dense cloud,
– building the mesh,
– building the model texture.

In the case of the Salut-ST1 tower, the mesh of the model was refined through Refine Mesh tool (see details in cap. 4. Results) to obtain a more detailed final model.

4. Results

Case sites cover different types of archaeological features: a rock art gallery, a large building (the tower), and a stone monument. Each one has specific issues to consider during collection and elaboration of pictures.

4.1 *Early Bronze Age Salut-ST1 tower*

Stone or mudbrick towers constitute the distinctive monument for the Early Bronze Age (3100-2000 years BCE) of South East Arabia, scattered over the territory going from the Musandam Peninsula to the island of Masirah. Three such monuments stand in the lower reaches of the valley of wadi Sayfam,

[1] For technical aspects, see respectively: https://www.canon.it/for_home/product_finder/cameras/digital_slr/eos_100d/specification.html; https://www.oneplus.com/it/support/spec/oneplus-3t; https://www.agisoft.com/pdf/tips_and_tricks/CHI_Calibrated_Scale_Bar_Placement_and_Processing.pdf; https://www.agisoft.com/pdf/photoscan-pro_1_4_en.pdf; https://www.dell.com/support/manuals/it/it/itbsdt1/alienware-aurora-r5-desktop/alienware-aurora-r5-setupandspecifications/set-up-your-computer?guid=guid-02a836d6-932b-4f7c-8bfa-0643923149d0&lang=en-us (sites accessed on 20th December 2019).

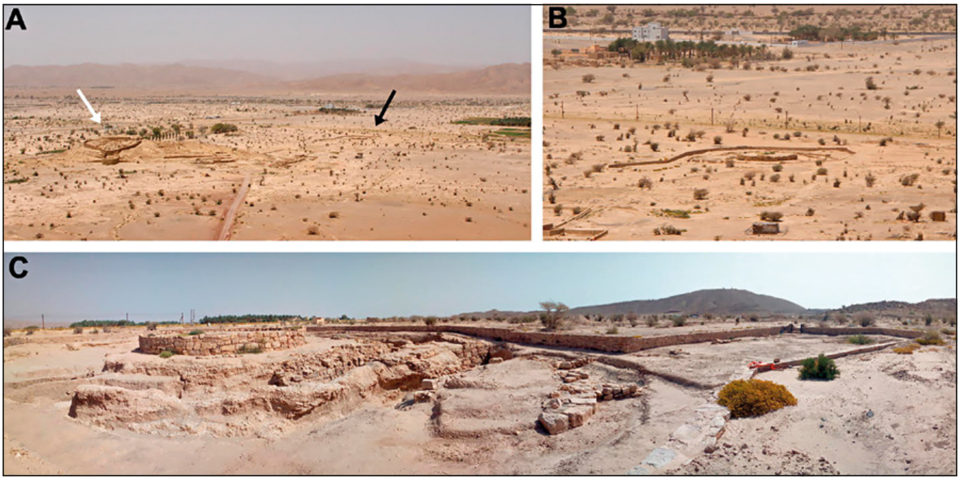

Fig. 2 – A) Location of the Salut citadel (white arrow) and the Salut-ST1 tower (black arrow). B) The Salut-ST1 tower in distance. C) An inside-detail of the tower.

where the site of Salut is located. The Salut-ST1 (Fig. 2) tower was excavated by the Italian Mission to Oman, revealing the complete layout of the central stone tower with its central well and the surrounding ditch (Degli Esposti 2016). The latter is part of a complex system of water management that testify to the relevant project lying behind the construction of the site. The site can be dated to the second half of the 3rd millennium BC, after which it was abandoned to be re-occupied during the Early Iron Age, when the central well was re-excavated (Degli Esposti 2011, 2016). Salut-ST1 was selected for its size, as the number of pictures required to perform SfM-photogrammetry is very high. The innermost tower is 2 m high and has a diameter of 22 m; whereas the diameter of the whole structure including the tower and the moat is 58 m. Using a commercial mobile device (Tab. 1), 820 pictures were taken to cover the whole surface of the Salut-ST1 tower.

The terrestrial acquisition phase was performed in 3 concentric paths by one operator and took ~1 hour in order to acquire all images. Details in wells and trenches required the acquisition of further pictures covering the surface with a uniform and high-detailed overlapping (Fig. 3A).

The photogrammetric elaboration required ~9 hours to be completed (Tab. 1). The alignment process was set to High Accuracy and took ~3 hours to be completed to enable the perfect alignment of all the images acquired on the field. Dense Cloud and Mesh were elaborated in Medium Quality and then refined with the Refine Mesh tool. The whole elaboration of the Salut-ST1 tower 3D model was conducted in Batch Process mode, by which the workstation performed automatically all the photogrammetric phases assigned by the operator.

Device: ONEPLUS A3003			
Number of pictures	820	Camera stations	787
Altitude	8.30 m	Tie points	677,421
Ground resolution	2.26 mm/pix	Projections	2,218,084
Coverage area	1.16e+03 m^2	Reprojection error	1.91 pix
Images Acquisition time	≈ 1 hour		
Images Processing time	≈ 8 hours and 54 minutes		

Tab. 1 – Camera location parameters used to generate the 3D model of the Salut-ST1 tower.

The textured 3D model obtained was then scaled with known metric measures thanks to the scale-bars positioned in the Salut-ST1 tower before the image acquisition phase. The obtained model (Fig. 3B) consists of a 3D digital reproduction of the archaeological monument with a centimetric precision.

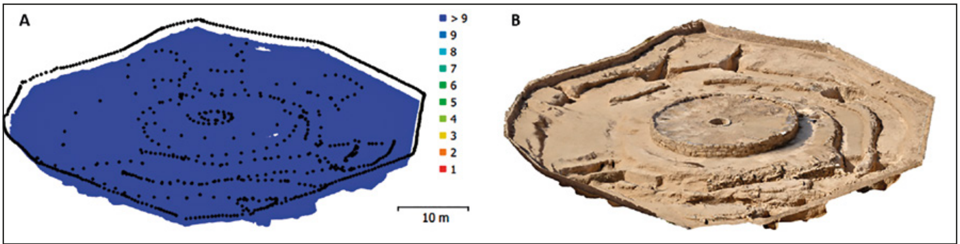

Fig. 3 – A) Camera locations (black dots) and image overlap of Salut-ST1 tower. The whole surface was homogeneously covered by more than 9 images. B) The 3D model of the Salut-ST1 tower.

4.2 *Rock Art boulder on the Jabal Hammah (Salut)*

Rock art is abundant in the area of the ancient oasis of Salut, with petroglyphs depicting a range of themes that find numerous parallels in the corpus of Arabian and South East Arabian rock art. Despite the difficulties in dating rock engravings, one of the petroglyphs on a boulder along the Jabal Hammah (Fig. 4A-D) was dated investigating the formation of the rock varnish that covers part of petroglyphs (Zerboni *et al.* in press), which provides a *terminus ante quem* for the realization of the engraving. The dated engravings depict standing stick-men holding a halberd for which no fitting parallel was found attributed to the Early Iron Age at the lates (Zerboni *et al.* in press).

The boulder with rock art was selected as a test to record such type of archaeological feature through SfM-photogrammetry. This technique has been tested in rock art studies (Robert *et al.* 2016; Bea, Angás 2017), being the most appropriate solution for macroscopic 3D recording in the field and representing a valuable, cost-effective alternative to Terrestrial Laser Scanner (TLS) (Johnson, Solis 2016; Jalandoni *et al.* 2018). In this case, we acquired 156 pictures with a Canon EOS 100D with ~60% overlap; markers of known length were placed near the boulder. The camera location parameters used in the elaboration of the 3D model are indicated in Tab. 2. The image acquisition phase of the Salut rock art boulder took ~15 minutes.

Device: Canon EOS 100D			
Number of pictures	156	Camera stations	156
Altitude	2.67 m	Tie points	128,354
Ground resolution	0.647 mm/pix	Projections	400,483
Coverage area	13 m^2	Reprojection error	1.48 pix
Images Acquisition time	≈ 15 minutes		
Images Processing time	≈ 17 hours and 4 minutes		

Tab. 2 – Camera location parameters used to generate the 3D model of the boulder with rock art.

The workflow followed to create the 3D model of the boulder was the same that was applied to the Salut-ST1 tower, but Highest Accuracy was preferred in this case. The photogrammetric process took ~17 hours to be completed, and resulted in a very high-resolution digital reproduction of the boulder with rock art, where petroglyphs appear very clearly (Fig. 4E). The goal of this 3D recording involved especially the digital recording of the petroglyphs with a fast, low cost, and high flexible tool.

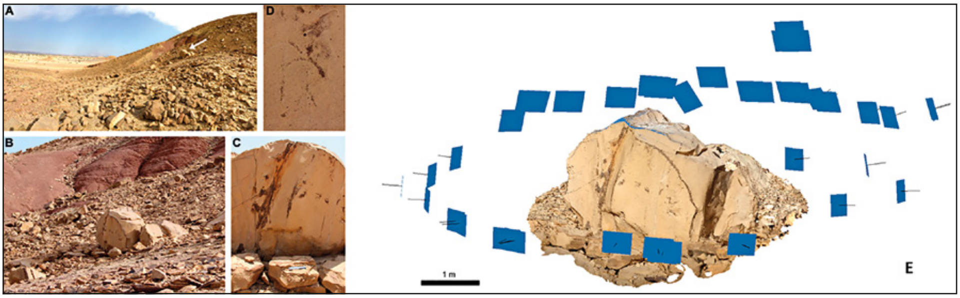

Fig. 4 – A-B) Location of the engraved boulder in the study area (Jabal Hammah, Salut). C-D) Details of the petroglyphs. E) 3D model of the boulder with rock art in the Agisoft project; camera locations are highlighted.

4.3 *Megalithic grave in the KR-N1 necropolis (Khor Rori)*

The necropolis KR-N1 is located in the Archaeological Park of Khor Rori, ~2 km from the ancient city of Sumhuram. Cremaschi, Perego (2008) surveyed the area and identified a huge amount of stone structures interpreted as graves. The importance of this site has increased since the discovery of HAS1, the Iron Age-Classical settlement found on the top of the Inqitat promontory (Lischi 2019). In the area of the necropolis (Fig. 5A), funerary structures are composed of megalithic stones arranged vertically around the burial chamber, with small and medium-sized stones filling gaps. The roof of each stone structure consists of two or more large stone slabs, and is finished with small and medium-sized stones that fill the gaps between architectural elements. An opening of variable dimensions, located immediately under the roof, is visible in all the well-preserved stone structures. SfM-photogrammetry was performed on grave D2 before archaeological excavation, because in the region – and elsewhere in arid and semi-arid regions – small to medium size stone structures are one of the best preserved and most commonly found archaeological features, and deserve recording before excavation or destruction.

To create the 3D model of the stone tomb (Fig. 5B), 156 images have been acquired in ~20 minutes (Tab. 3). In this case, the main purpose in using SfM-photogrammetry consisted in documenting the archaeological monument before the archaeological excavation. The workflow was set to Medium Accuracy enabling to obtain a scaled 3D model with centrimetric precision in only ~65 minutes (Tab. 3).

Device: ONEPLUS A3003			
Number of pictures	156	Camera stations	156
Altitude	2.67 m	Tie points	128,354
Ground resolution	0.647 mm/pix	Projections	400,483
Coverage area	13 m^2	Reprojection error	1.48 pix
Images Acquisition time	≈ 20 minutes		
Images Processing time	≈ 1 hour and 5 minutes		

Tab. 3 – Camera location parameters used to generate the 3D model of the Iron Age grave.

All elaborated 3D models have a very high accuracy, especially if compared to the time required to gather field pictures and their desk elaborations. Our 3D models not only are valuable tools for extracting precise (numeric) data on structures' layout, but also represent a robust tool to preserve the cultural significance of archaeological heritage. Finally, they provide a fast and wide-public friendly way of exhibiting archaeological features (for instance on-line), with a level of fruition and readability higher than accurate archaeological maps or even simple pictures.

5. Final remarks

The three examples here discussed confirm the great potentiality of a low-cost SfM-photogrammetry approach in recording archaeological

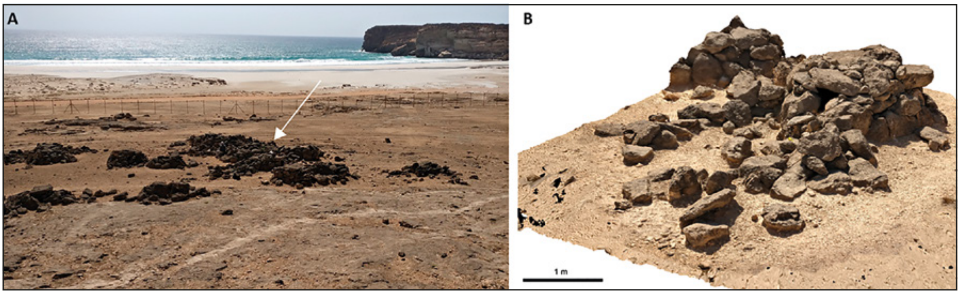

Fig. 5 – A) Location of the Iron Age megalithic grave at the KR-N1 necropolis in the Khor Rori area. B) 3D model of the D2 Iron Age megalithic grave in the Agisoft project.

features of different dimensions. Case studies well represent the many categories of archaeological features that can be identified in remote regions, thus confirming the robustness and reliability of the method in such fragile landscapes. The obtained centimetric accuracy is acceptable in such situations, when the only alternative for recording topographic data is handmade sketches and field pictures. Our approach adopted low-cost equipment consisting of a digital camera (and/or a smartphone) and portable scale-bars; the latter represent an affordable tool to rescale models during the in-lab photogrammetric process. During the acquisition phase, the combination of different types of terrestrial acquisition allows minimizing problems due to site accessibility and light condition. While the use of a DLSR digital camera allows a higher manual control of light and exposure parameters in order to maximise the visual rendition of the resulted image, a smartphone device can automatically correct image setting through software algorithms with no manual interference, thus representing a common and valuable tool for non-expert photographers.

3D models obtained after the elaboration of field pictures allow extracting a great amount of data from archaeological features and provide a high-potential tool for communication and valorisation of cultural heritage. SfM-photogrammetric recording is usually claimed to need considerable financial resources or trained staff. As highlighted from our study, this is true if the research goal is to obtain models with sub-millimetric precision, a task technically feasible only in specific contexts. In many cases, archaeological features recorded and modelled with centimetric errors (as the ones presented here) represent a valuable alternative to high-cost TLS or low-detail, time-consuming handmade drawings.

This is especially true during initial, fast surveys of vast and remote areas. Obtaining metric products in inaccessible areas represents an important basis for documentation and the workflow presented here demonstrates how low-cost equipment allows to elaborate 3D models of sufficiently high quality to record archaeological features during fast surveys. This is a crucial issue since the main task of each archaeological survey in remote regions is to collect as much information as possible, in order to increase the knowledge on the culture heritage of fragile territories.

Acknowledgments

We would like to thank the Office of the Adviser to His Majesty the Sultan for Cultural Affairs, Muscat, whose help made the geoarchaeological research in the region possible. We would also to thank A. Avanzini, Director of the Italian Mission to Oman (IMTO). This research was supported by the Italian Ministry of Education, University, and Research (MIUR) through the project "Dipartimenti di Eccellenza 2018-2022" (WP4 – Risorse del Patrimonio Culturale) awarded to the Dipartimento di Scienze della Terra "A. Desio" of the Università degli Studi di Milano. Further financial support is from Università degli Studi di Milano, Progetto Linea 2 (2017) entrusted to A. Zerboni.

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ABSTRACT

Digital documenting of archaeological evidence represents a crucial tool in the study, preservation, management, and promotion of archaeological sites in remote regions and in fragile landscapes. In fact, in marginal environment, the knowledge related to archaeological heritage can quickly disappear, especially when policies to protect cultural heritage are unreliable or lacking. In the last few decades, archaeological fieldwork has seen the increasing use of Structure-from-Motion (SfM) photogrammetric technique as a tool for mapping and recording archaeological evidence. This technique allows the creation of highly detailed 3D models of archaeological sites, monuments, and artefacts from sets of simple but accurately taken pictures, thus preserving the data for further research or (digital) cultural valorisation. Nowadays, low-cost/commercial off-the-shelf sensors (professional and semi-professional digital cameras and smartphones as well) are widely available and accessible by most of the users operating in cultural heritage documentation. This has made the acquisition of field pictures in archaeological research much more flexible and cost-effective. 3D models obtained from these pictures through photogrammetric commercial software can be scaled with a known-measure providing highly detailed models for archaeological purposes. This enhances the ability of archaeologists to record archaeological features during field surveys and rapidly obtain 3D models. This is especially useful in the case of archaeological surveys carried out in remote and barely accessible areas. In this paper, we present the results of the application of the above-mentioned methods during archaeological surveys in the Sultanate of Oman, where several archaeological features have been recorded through SfM photogrammetry using commercial devices and portable scale-bars. We demonstrate that this is a highly-flexible and fast process to record archaeological heritage in low-accessible or fragile contexts, where a 3D model (with centimetric precision) represents a valuable dataset for further in-lab analysis and cultural dissemination.