Heritage Science

RESEARCH

Open Access

Use of 3D models as a didactic resource in archaeology. A case study analysis

Francisco Arias[1] , Carlos Enríquez[2] , Juan Manuel Jurado[3] , Lidia Ortega[4] ,
Antonio Romero-Manchado[2] and Juan José Cubillas[5*]

Abstract

The generation of 3D models through Terrestrial Laser Scanning has proved to be valuable tools for the study, documentation and recreation of archaeological remains. In this context, it is described how to generate a physical model to provide not only to researchers, but also as teaching material for teachers for university students, facilitating their access and study. As a practical case, this article describes the acquisition, processing and management of archaeological data in the archaeological site of Cástulo, Jaén, in South Spain. We expound how to get the 3D-printed model of the Muslim tower, showing how it is possible to generate a scale and very reliable reproduction of the structure, being also an useful and tangible material in the teaching of cultural heritage.

Keywords: Teaching archaeology, 3D-model, 3D-printing, Tangible resources

Introduction

In education there are many environments where three-dimensional elements are used for learning content. Tangible objects are common tools in fields such as engineering and architecture, in geography or even in anatomy classes, where models, relief maps or organ replicas are used. In fact, several studies show that content is learned more quickly through the manipulation of tangible objects [1]. This is due to the fact that, traditionally, study and teaching have been limited to the one-sidedness of information and the two-dimensionality of paper or the screen, forgetting that a large part of the subjects dealt with are representations of events and elements that belong to a 3D (three-dimensional) universe. In this sense, there are students and teachers who, although they have mastered their subjects, do not manage to form a mental image of the subject because they do not know the physical elements to relate them to, making it difficult to receive and retain the message, causing a provisional

memory of the content dealt with. Therefore, it is important to have didactic material to offer students real problems and situations with which they interact and have to analyse and provide answers [2].

If tangible objects are important in education, virtual learning environments are a digital solution with similar didactic characteristics for students in different fields of science. Such is the case, for example, of the use of artificial intelligence as an educational resource [3].

In the field of archaeology, the incorporation of new virtual environment technologies is particularly interesting. Consider that the traditional techniques used to preserve and document this information are drawing, an inherently subjective process, and photography. However, these data collection procedures are tedious and its degree of detail and accuracy are not enough for today's researchers and conservators needs. If metric measurements are needed, photogrammetric techniques and a 3D realistic model are needed in order to document, manage and analyse the shape and dimension of the represented objects with a high degree of accuracy and resolution for each archaeological record [4] and [5]. 3D models can also be obtained from other techniques such as laser technology [6]. In this sense, although 3D

*Correspondence: juanjose.cubillas@unir.net

[5] Dept Tecnologías de La Información Y Comunicación Aplicadas a La Educación, Universidad Internacional de La Rioja, Logroño, Spain
Full list of author information is available at the end of the article

Arias *et al. Heritage Science* (2022) 10:112

Page 2 of 15

laser technology was developed during the last half of the twentieth century, it was not until the mid-nineties when they become available to general researches [7]. Ten years ago and due to different reasons, among them the high cost of 3D equipment [8], its systematic use for documentation or surveying archaeological sites was not established.

Terrestrial Laser Scanners (TLS) has been benefited from the development of technology. Its irruption has meant a new revolution in the generation of 3D models, since the model is obtained at real scale, while the model generated with photogrammetric techniques needs to be scaled to get real dimensions. Therefore, TLS can be used to get a detailed record of complete or portions of a site, which may be lost or changed, such as an archaeological excavation or a site at risk. In addition, as an active sensor, it does not require environmental light to generate the model, being very practical in environments with little or no lighting: caves, galleries, etc.

Both techniques are non-invasive and not only they do not damage the archaeological artefacts but provide metric information and its 3D visualization as well. These geomatic techniques have been used in a complementary way, and their integration have been applied at the process of study, planning and execution of the restoration [9]. Nevertheless, while digital photogrammetry is a passive method, based on recording light reflected from illuminated surfaces by natural or artificial light, laser scanning is an active method, which records its own transmitted light reflected back from its target. The selection of the method depends on several factors as the user's previous experience, the investigated object or area, and the available budget and time [8]. In this sense, the advantages and disadvantages of using TLS or SfM photogrammetry, it is worth mentioning the study carried out in 2012 in which TLS was compared with terrestrial photogrammetry in archaeological applications [10]. However, in recent building structure modelling applications [11], a comparison between the two techniques finally favours TLS for reasons such as the need for fewer GCP (Ground Control Points) than SfM photogrammetry, and with reference to the accuracy of measurements on the object geometry, work such as [12] favour TLS over photogrammetry. More recently, these two geomatics techniques have been compared for the study of a Roman mosaic, in this case although both technologies offer very good results the porosity of the material produced a slight delay in the reflection of the signal emitted by the scanner [6].

In short, in the field of archaeology and cultural heritage, these techniques and instrumentation allow massive captures of 3D data of the environment through a TLS, capable of generating a textured three-dimensional metric model at very high resolution. With the help of a RTK-GNSS, it is possible to georeference the data to establish a spatial correlation between the different findings belonging to the same archaeological site, and their localization within the appropriate spatial framework. This allows researchers to share and analyse, almost in real time, the current and previous state of the archaeological records.

Considering that 3D models can be used to generate educational resources, either in the classroom or even for presentations in visitor centres, museums and through the media to improve accessibility, engagement and understanding [13]. Thus, and in favour of further dissemination and value of these findings, the model is 3D printed. In the field of archaeology and cultural heritage, this provides a more holistic appreciation of objects, although it makes it necessary to develop basic guidelines for 3D printed models. Thus, 3D printing is not only vital in the field of object reconstruction, but also for research, documentation, preservation and educational purposes, and has the potential to serve these purposes in an accessible and inclusive way [14]. The use of 3D printing in different fields of science is becoming more and more widespread, in fact there is already a specific regulation to regulate the whole process of additive manufacturing [15].

The main aim of this paper is to demonstrate the 3D model as an educational resource in archaeology, for this purpose a description of how is it generated a scaled and very reliable reproduction of any structure, regardless of its original size, can be generated in a simple and inexpensive way. For this case study, TLS technology has been selected instead of photogrammetric SfM. The main reason was that, following the literature review above, TLS gives very good results in terms of the metric quality of the products generated. This reason, together with the availability of this instrumentation, led us to choose this technology. In this work, we describe the process of acquisition, processing, management of archaeological data and the generation of a tower of a Muslim castle in the archaeological site of Cástulo (Jaén).

Cástulo was an Ibero-Roman city in Baetica, near Linares (Jaén), in southern Spain. It was inhabited from the end of the Neolithic period until the end of the fourteenth century, and with more than four thousand years behind it, it is a good example of one of the most common problems archaeologists face in their work: excavation is a destructive process and there is no way to achieve its archaeological record without destroying later records. Consequently, the availability of 3D virtual environments of the different scenes at each moment of the excavation is a suitable teaching tool for monitoring the excavation

Arias *et al. Heritage Science*   (2022) 10:112

Page 3 of 15

process of this site, without losing any descriptive or geometric detail.

The paper is structured to provide a full vision of the whole process: from the data acquisition until the 3D printed process. Firstly, and once the research aims are presented, we present a basic review of the technology and material resources that were available for the project. We also describe the techniques that have been used. Secondly, we describe the archaeological place of Cástulo and detail the data acquisition procedure as well as how to tackle with data processing. Thirdly, we explain how to get the 3D-printed model of the Muslim tower obtained by TLS techniques. Finally, we discuss the results and the perspectives of these techniques as educational tools.

Research aims

Having a Muslim tower of the thirteenth century in our hands was something unthinkable until a few years ago, but today the development of new technologies has made

it possible. Nowadays, there are massive data collection systems, which allow you to obtain 3D models with a high degree of accuracy and 3D printers that can materialize these models at low cost. Figure 1 shows the flow diagram of the whole process.

The objective of this work is to show in detail these phases: data collection, generation of the model, and the 3D printing.

Review of technology

In this part, we will give a brief overview of the technics and instruments used in our work. A deep analysis in the employment of close range photogrammetry and TLS can be found in [16], where the workflow phases for different case studies are described: From the aspects to be considered in survey planning, field operation, data acquisition, preparation, processing to quality control of the results. The topic of georeferencing terrestrial laser scanning or photogrammetric data is widely exposed in
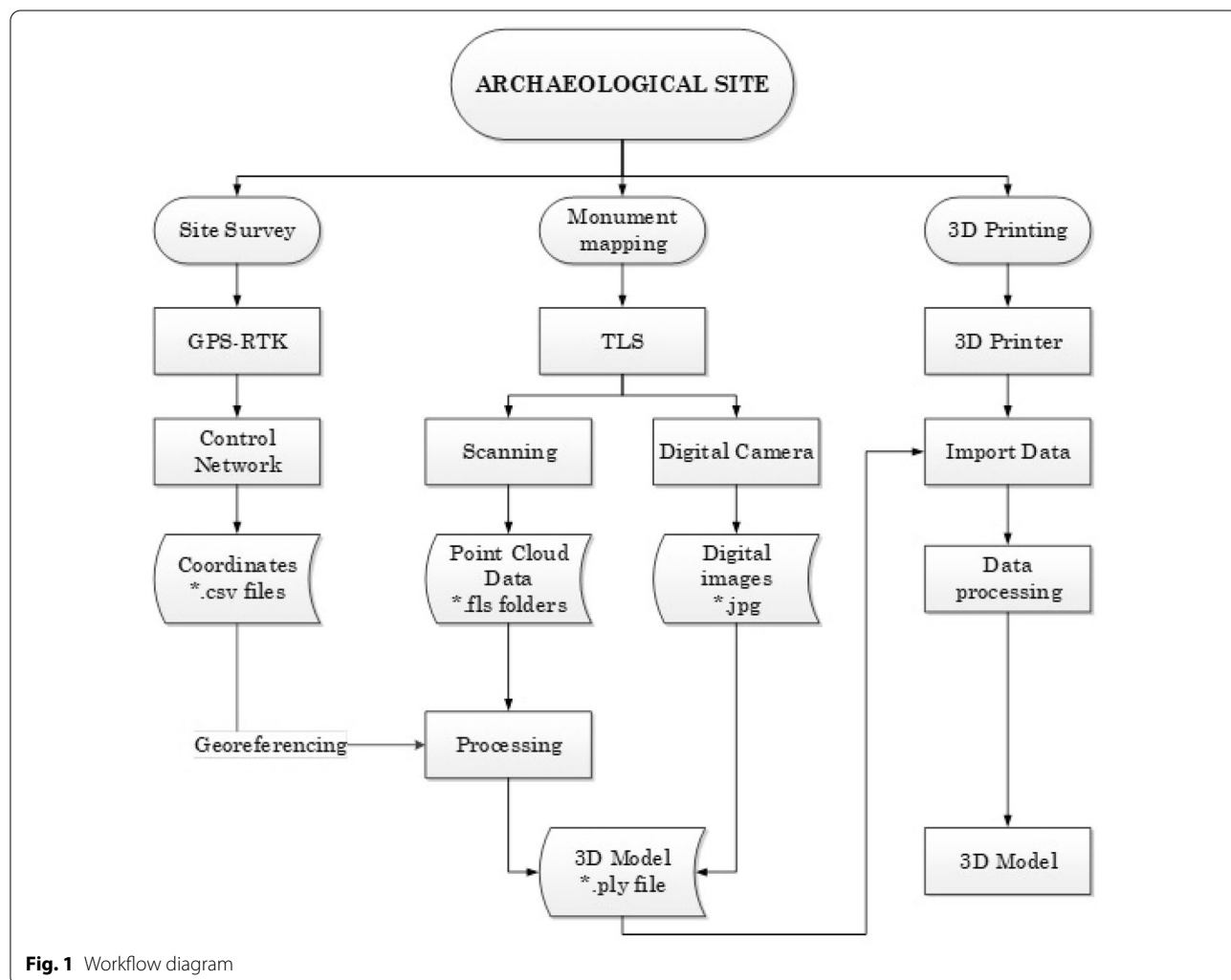

Fig. 1 Workflow diagram

Arias *et al. Heritage Science*   (2022) 10:112

Page 4 of 15

[17], here different georeferencing methods are described concluding topographic instrumentation is the most accurate compared to other methods based on virtual models with tie points or the use of low-cost GPS. Finally, how the technologies are used for solid printing in Cultural Heritage are described in [18], which concludes that in 3D models printed, the metric characteristics of precision and accuracy must be evaluated in relation to the precision of the instrumentation used in the data acquisition of the object.

Terrestrial laser scanning (TLS)

The Terrestrial Laser Scanning is the name that LIDAR technology receives when the sensor is placed on the Earth's surface. It uses light in the form of a pulse radar to measure ranges. The 3-D point clouds acquired is matched with digital images taken of the scanned area to create geometric 3-D models. This is a non-contact, non-destructive and active technology, which allows taking a huge amount of data in absence of external light.

The TLS might be classified according to its range of measurements or its principle of operation: triangulation, time-of-flight or phase-based. The description of

the two first types can be found in [4]. We focus our attention in the latter one, for describing the operating scheme of our TLS.

In this method, the TLS emits continuously a periodical signal of moderate intensity and compares the phase of the laser source with the same when radiation comes back. As only the phase-shifting is measured, the number of full wavelengths between the transmitter and the receiver at the instant of the measurement is an unknown value, known as *ambiguity*, Fig. 2. The problem is that there is no way to fix it if we only use a single frequency length because, as we can see in Fig. 2, all the red lines, separated by the wavelenght L_1, represent possible solutions. However, adding another one L_2 reduces the number of solutions to five and adding a third one, L_3, reduces it just to one (A).

This is why several frequencies are used (multi-frequency-ranging or MF), being the higher used to calculate range and the lower used to eliminate ambiguity [19]. Another capability of some scanners is capturing the colour of measured points. In consequence, point clouds are much more representative of the scanned objects.
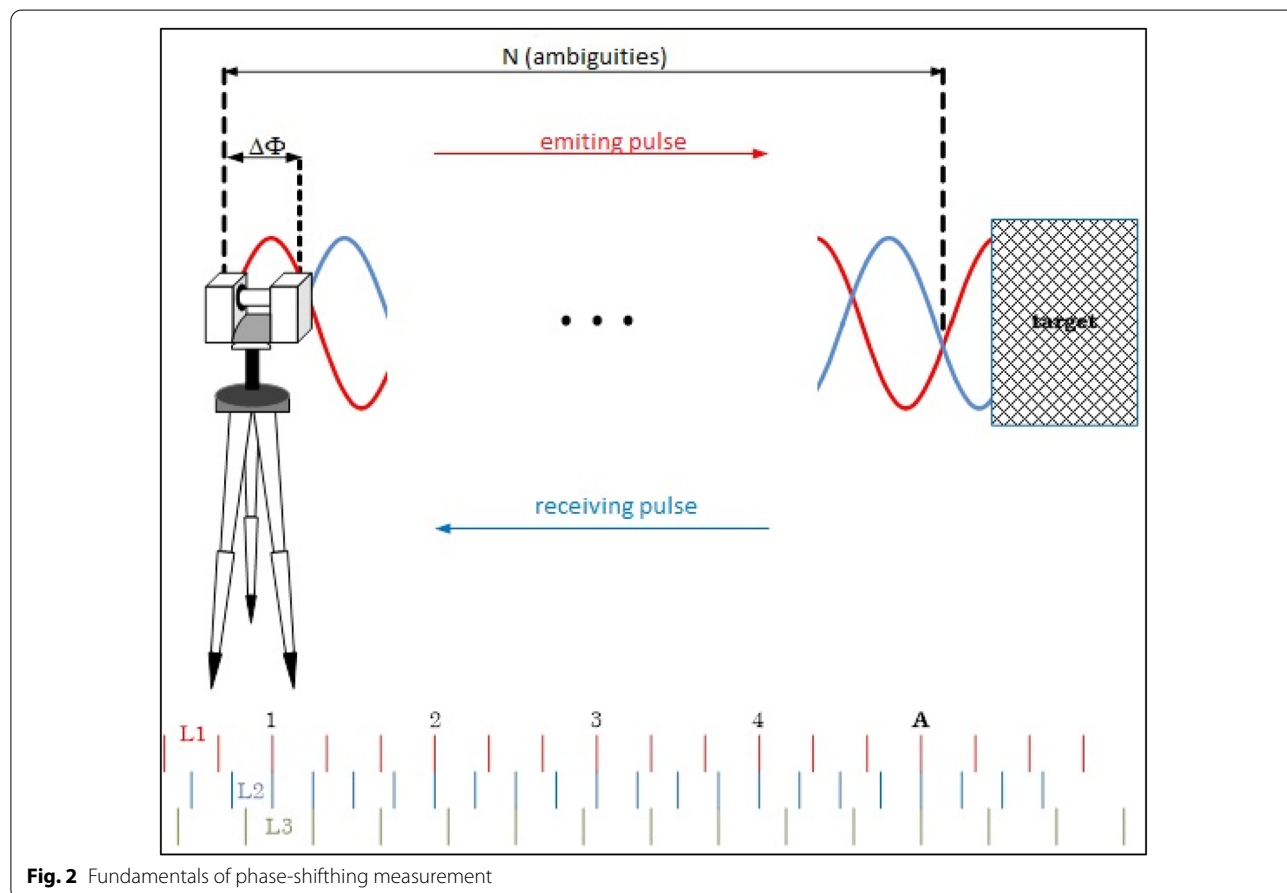

Fig. 2 Fundamentals of phase-shifthing measurement

Arias *et al. Heritage Science*   (2022) 10:112

Page 5 of 15

When comparing TLS and close range photogrammetry, we found that a TLS is less versatile than a camera. Scanning might take a minimum of 15 min or over an hour for each scan if higher resolutions and qualities are required, while a camera records a scene in a few seconds. There is still more issues: cost, a TLS weights much more than a camera, transportation problems, and the complexity of post-processing. In brief, TLS are not as versatile or flexible as cameras with regard to capturing data and it might be unnecessary for the level of deliverable output required. However, equipments are improving in performance and portability, the 12 kg of weight of the Leica HDS3000 have become the 5.2 kg of the Faro Focus, and a handheld mobile scanner is even lighter.

A complete guide of TLS theory and practice can be found in [4] and a description of the services and standards required for the supply of various types of metric survey in cultural heritage, including a study of laser scanner accuracies in [20].

Both TLS technology and digital photogrammetry are techniques used and equally valid for cultural heritage conservation. However, there are differences between them that make one or the other more appropriate depending on the main objective of the work. In this sense there are some research which specifically focuses on the need for geometrically accurate documents of cultural heritage sites rather than generating 3D models for visualization. In these cases, a comparison between the results obtain from TLS & digital photogrammetry result in better performance of the TLS by obtaining better accuracy in systematic errors in the position of the control points [21]. Our TLS is a Focus 3D X 130 HDR (High Dynamic Range), which uses phase shift technology. Its range varies from 0.6 m up to 130 m, and it can capture millions of 3D measurements at up to 976,000 points/second, with a ranging error of ± 2 mm. In addition, it has a built-in 8 mega-pixel, HDR-colour camera which captures detailed imagery easily while providing a natural colour overlay, up to 165 megapixel colour, to the scan data in extreme lighting conditions. The point cloud was referenced in the topographic reference system by using the set of the 145 mm diameter spheres supplied by the manufacturer. We used target-based registration with spheres because in planar views a circle is always visible, no matter the angle of view.

Data was processed with the software Scene 7.0 and Cloud Compare was used to display some models.

Georeferencing

An important aspect of the data collection process is determining a control network which georeferences the whole area to a national grid and height datum. On archaeological excavations, it provides the basis for long-term monitoring or structural analysis and the georeferencing of found artefacts, barrows and structures that can lead to studies of their spatial relationship and more extensive archaeological analysis [13].

It also provides, when working with TLS, a network of accurate points so that the point clouds can be successfully unified into a common coordinate system and gives certainty and, with some redundancy in the network, an estimate of the overall accuracy. Finally, it can provide the basis for long-term monitoring or structural analysis [13].

The control network was built by widening a previously existing one, with a series of stakes driven onto the earth. Once the stakes were driven, a metal washer of 18 mm in diameter was screwed into them, so that the spheres could be fixed thanks to the magnetic support that it bears, Fig. 3.

To get the coordinates of the control network, we use a single Topcon GR5 RTK-GNSS, with centimetre accuracy linked to the Andalusian Positioning Network (Red Andaluza de Posicionamiento, RAP), an active geodetic reference frame materialized by 22 permanent reference stations. RAP-NRTK solution provides a precision between 0.004 m and 0.030 m in the East component, between 0.004 m and 0.059 m in the North component and between 0.007 m and 0.094 m in the Up component [22]. The coordinates are in ETRS89, the map projection used is UTM, zone 30, and the heights are referred to the mean sea level at Alicante (Spain), that is they are orthometric heights, Table 1. Therefore, we get coordinates of the centre of the spheres with a centimetre accuracy.

Printed 3D-model

3D printing has become a highlighted technology in the archaeological area in order to generate three-dimensional models for multiple purposes. Traditionally, the
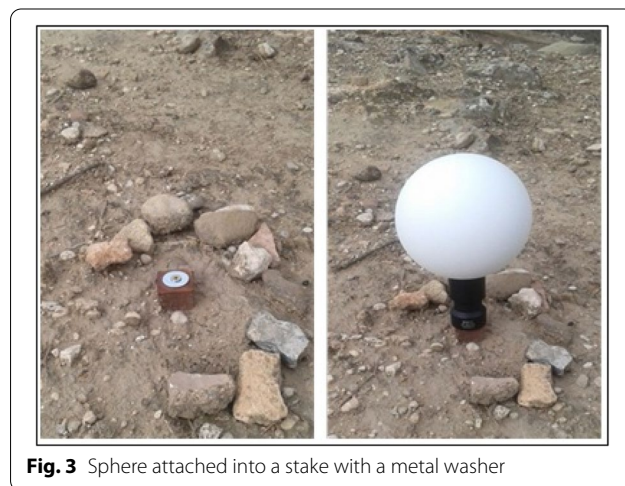

Fig. 3 Sphere attached into a stake with a metal washer

Arias *et al. Heritage Science*   (2022) 10:112

Page 6 of 15

Table 1 Coordinates of the spheres - Reference System: UTM zone 30 (ETRS89)

ID_Point	X (m)	Y (m)	H (m)
P_01	445,231.567	4,209,561.140	304.751
P_02	445,252.984	4,209,569.550	305.033
P_03	445,271.503	4,209,560.821	304.598
P_04	445,267.313	4,209,538.216	304.157
P_05	445,240.459	4,209,530.924	302.830
P_06	445,251.575	4,209,557.726	306.164
P_07	445,215.497	4,209,571.763	299.135
P_08	445,240.741	4,209,590.468	298.958
P_09	445,273.549	4,209,592.124	296.452

Fig. 4 Overview of process for 3D printing

difficult access to artefacts in the archaeological sites has supposed a negative impact on research. Likewise, handling original artefacts may be risky, as many items are easily damaged. The use of 3D printing in archaeology may be a support for a wide range of research activities involving that archaeological discoveries become more accessible to educators and the researchers worldwide. However, scanned models are not usually water light so they have many holes in its geometry and non-manifold edges. Consequently, apart from the capturing method such as LIDAR or photogrammetry, the resulting models need to be repaired, and therefore printed.

Pre-processing techniques commonly focus on error correction, decimation of surfaces, cutting the model, and scaling and positioning on the (virtual) printer ground plane. In this work, a 3D printer based on FDM (Fused Deposited Modeling) technology generates printing models. Thereby, according to the limits of this 3D printing technology, we have determined two main goals: (1) the removal of holes in the geometry and (2) the minimization of support material. The workflow is shown in Fig. 4.

The resulting geometry which has been captured from a scanned method usually presents complex triangular meshes with many errors and lack the flat base for 3D printing. Therefore, the input model needs to be repaired and this task is carried out in the remeshing stage. Firstly, we are going to eliminate non-manifold geometry. Non-manifold geometry is defined as any edge shared by more than two faces. It ends up confusing for 3D printing software. The next task is checking surface normal. The normal vector has to be perpendicular to the surface and facing outward. If the surface normal is reversed, the model is not correctly loaded for the slicing. Finally, the 3D model must be a hollow model. According to the normal vectors, every hole is detected and fixed in the geometry.
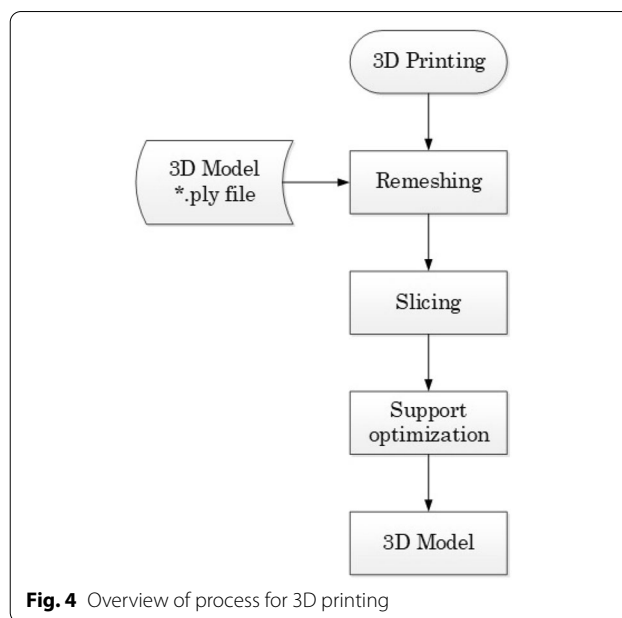
Once the 3D model is prepared to be printed, we have used an open-source printing software for the slicing process (Fig. 5). In this stage, all printing settings are defined to generate the G-code file that contains commands to move the extruder and all parts within the 3D printer. In this regard, the correct configuration of the printing properties influences the quality of the resulting 3D model. These are always depending on the input model so there is not a single valid setting for printing artefacts.

Other relevant issue for 3D printing is the distribution of the support area. In this case, we try to preserve as much as possible the details of the artefact surfaces. For this purpose, the option to insert the support material everywhere has to be disabled. It is just allowed from the build plate to the model. According to this constraint, we try to minimize the required support quantity. Our method is capable of testing automatically the input model with multiple poses. Thus, a transformation matrix is computed to estimate the most adequate orientation and translation of the 3D model. Finally, after all these stages are concluded, the output G-code file is generated for the 3D printing.

To get the printed model we used a Prusa MK3 3D printer, based on FDM technology, able to build a model with a resolution of up to one millimetre of thickness per layer. This family of 3D printers is very versatile and frequently used for the generation of prototypes in many professional sectors. In archaeology, 3D printing is a significant advance since it makes possible the rapid fabrication of a faithful replica from the previously digitized archaeological finding.
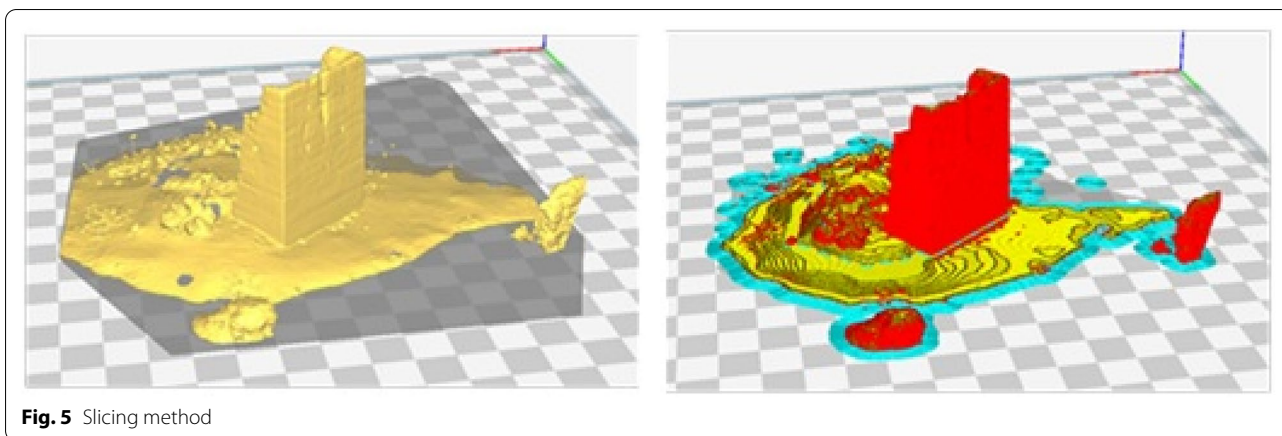
Fig. 5 Slicing method

Methodology

The archaeological place of Cástulo.

The *oppidum*, or fortified city, of Cástulo, was the most important population hub of the Iberian Oretania. Its archaeological site covers about 70 ha and is placed about 5 km south of Linares (Jaén), on one of the terraces on the right bank of the River Guadalimar (Fig. 6). This complex stratigraphic and temporary sequence stars in the Cooper Age, and it is possible to identify different periods of occupation between the 3rd millennium BCE until the fourteenth century. Vestiges of the settlement are found both on the slopes and on a walled plateau located in the hills of Plaza de Armas and La Muela, at about 300 m above sea level, being an important junction, controlling an extensive visual field that dominates the fertile plain of the river and the entrance to the mines of Sierra Morena.

During the Second Punic War, Cástulo was allied to the Carthaginian cause, in fact, Himilice, Hannibal's wife, was from Cástulo, but as the tide of the war changed Cástulo finally allied with Rome, avoiding its destruction. After the fall of the Roman Empire, begun its decline and,
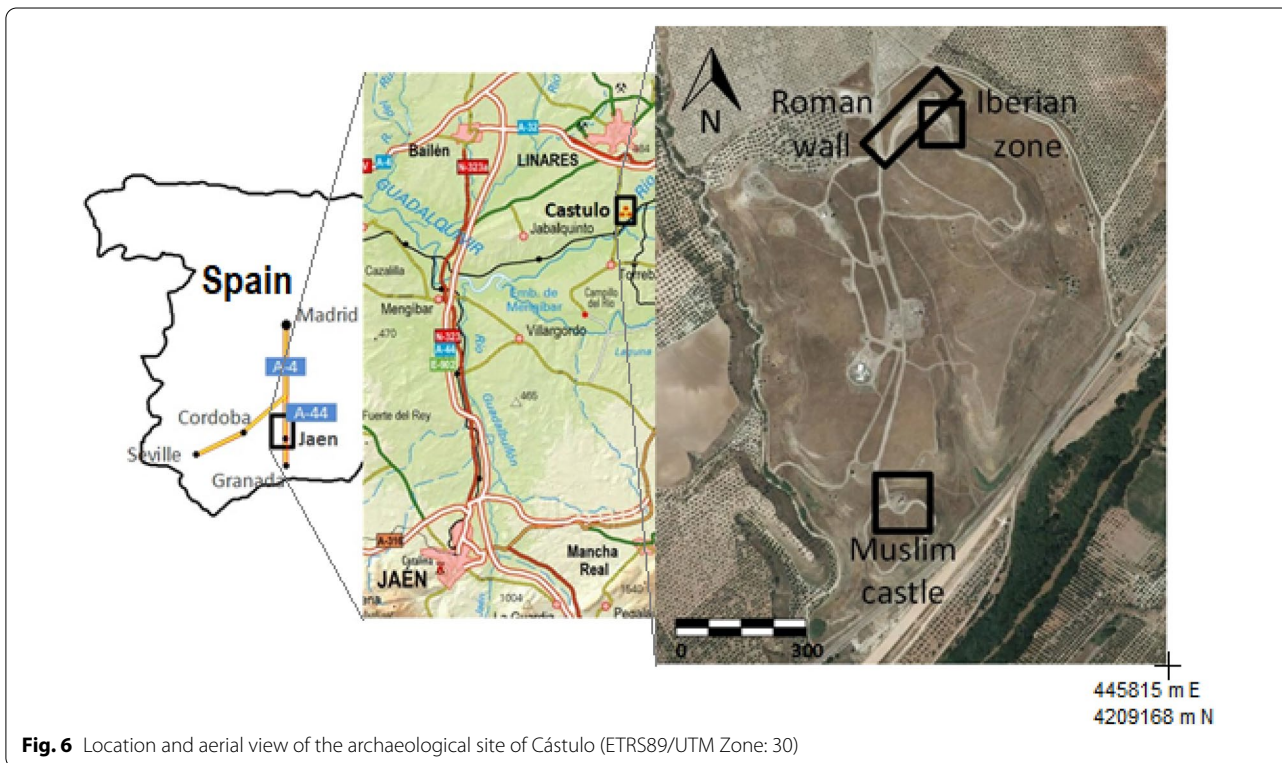

Fig. 6 Location and aerial view of the archaeological site of Cástulo (ETRS89/UTM Zone: 30)

Arias *et al. Heritage Science*   (2022) 10:112

Page 8 of 15

at the beginning of the thirteenth century, under Islamic rule, its walls were destroyed, and the town was depopulated shortly afterwards. Therefore, it is possible to find remains from at least eight cultures: Copper Age, Bronze Age, Iberian, Carthaginian, Roman, Visigoth, Jews, and Islamic.

The tower is the only vestige that remains of the Muslim castle of Santa Eufemia, and is located in a small watchtower at the southern end of the Archaeological Site of Cástulo, being a construction isolated from the rest of the archaeological site. It emerged as a remote facility in the south of the city, dominating the River Guadalimar enclosed the most recent remains of the Cástulo history.

Planning and data acquisition

Our first goal was to ensure the full coverage of the zone. Our prerequisites were that the first set of scans should include a good distribution of control points while the second set may be matched sufficiently by cloud-to-cloud registration. In addition, it was desirable a significant amount of overlap among scans, and to get an orthogonal view of the subject to be scanned. Finally, our last condition was that, as long as possible, the last scan should overlap the first one.

Under these assumptions, we made a first selection of suitable TLS setup points and the five spheres were located with these conditions:

- At least, there must be three common spheres between each surveying.
- These spheres must not be aligned.
- Their disposition must be regular around the TLS setup point.
- The maximum distance between the TLS and the spheres should be less than 30 m (Europe Laserscaning).

Data were taken with a quarter of the maximum resolution and a quality of 4x, so each point is measured four times, to reduce the noise of the measurement, looking for a compromise of accuracy and time of scanning, so that it took about 20 min to perform a complete 360º scan with HDR colour. With this resolution and at working distance of 30 m, the expected accuracy is about 2 mm.

In the design phase, it is necessary to specify the sensor, TLS or camera, its characteristics as well as to define the optimal zones to place the sensor, to get a good geometry of the shot. That implies that the incidence angle between the ray and the surface must be greater than 30º. This geometrical restrain establishes a restricted area around the target where you cannot place the sensor.

However, it is possible to get additional shots to capture hidden zones, but always observing the fore mentioned restrictions. For example, in Fig. 7 (right), we find the places where the scanner was situated and, in blue color, the zones where the scanner should not be placed due to the geometrical restriction. However, we can see that the position TLS_08 is located in a restricted are. It had to be done like that, due to the complexity of the zone that is delimited by remains of walls about half metre in height. At the right, we can see the possible positions for the photographic shots divided into four rings: a general one, to give a view of the whole, and three around the structures, to capture the details.
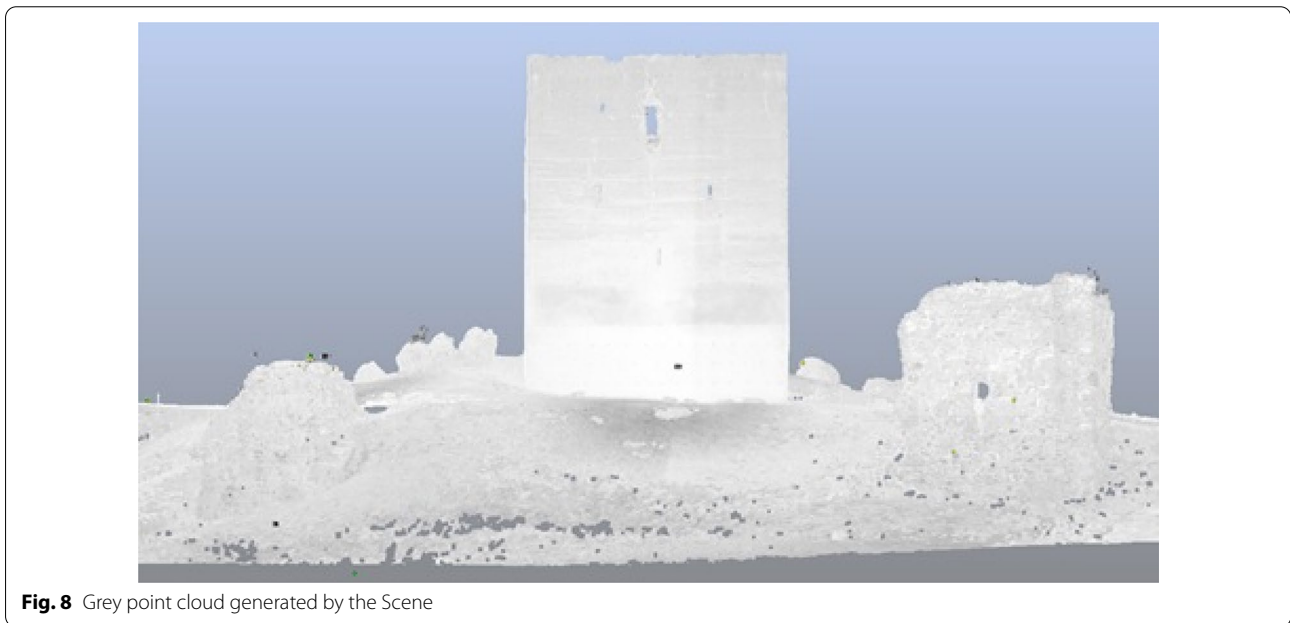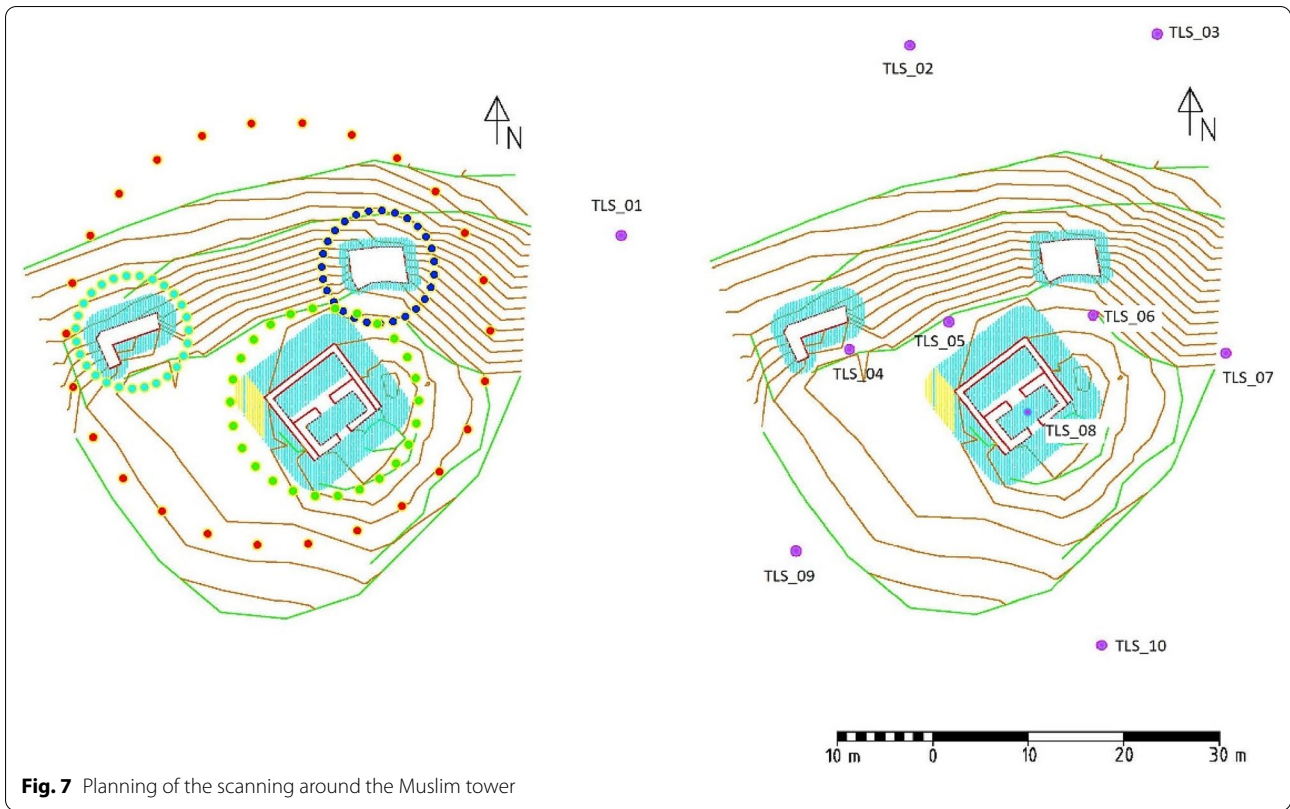
Point cloud processing

The result of the scanner is an unprocessed point cloud, which can provide useful information by displaying the project through static scenes or cross sections. This raw file can be used to extract information in a Computer-Aided Design (CAD) or Geographic Information System (GIS) system. Nonetheless, in most cases, as we want to get as much information as possible, the scan data must be processed.

Figure 8 shows the point cloud resulting from the scan in grey levels, whose value depends on the value of the reflectance obtained when the laser pulse reaches the object. To colour the point cloud, we use the images taken with the scanner camera and the use of the HDR to improve the quality of the images obtained.

Point clouds are recorded and saved in a local coordinate system whose origin is the position where the laser meets the mirror. Therefore, if you have two or more scans taken at different places, as each one is relative to the scanner, each scan will only know its own coordinate system. Hence, it is necessary to determine the spatial relationship between them, to express all the scanners in the same coordinate system. This process is called *Registering the Scan* and the step from the scan coordinate system into the overall coordinate system is called *transformation*. Subsequent processing steps to provide deliverable products include: cleaning, filtering, segmentation, classification, sectioning, meshing, rendering (texturing), tracing CAD or Building Information Modeling (BIM) detail (vectorisation), image-based output, animation, and visualisation [13].

To remove undesired scan data, like people or vegetation, data must be cleaned and filtered. Besides, these processes reduce the size of the dataset and should make registration more efficient. Even more, spurious data can be removed after registration, if they may prove useful for registration in the absence of good overlaps, or if there is little ground control. Also filtering is used to remove the

Arias *et al. Heritage Science*   (2022) 10:112

Page 9 of 15

Fig. 7 Planning of the scanning around the Muslim tower

Fig. 8 Grey point cloud generated by the Scene

noise generated by poor signal return or to select only the first return obtained when the laser dot strikes an edge.

Data was processed using SCENE 7.0, the software provided by the manufacturer. Table 2 lists the values of the filters that we have applied to remove or correct inaccurate points. Filters can be applied simultaneously or after the point cloud generation. The workflow process is shown in Fig. 9.

Arias *et al. Heritage Science*   (2022) 10:112

Page 10 of 15

Table 2 Applied filters

Filter	Definition	
Dark Scan Point	It removes points based on a reflectance valuve It is used to remove scan points with too much noise	Reflectance threshold 200
Distance	It removes all scan points which are outside of a certain distance range	Maximum distance: 30 m
Stray Point	It checks if the 2D grid cell of a scan point contains a sufficient percentage of points with a distance similar to the scan point itself	Grid size: 3px Distance threshold: 0.02 m Allocation threshold 50%
Edge Artifact	It is especially useful to remove artefacts at the edges of obejcts	Yes
Smooth	It is used to minimize noise on surfaces	No

We applied the filters simultaneously to the point cloud generation to obtain it as clean as possible. The *Stray Point Filter* is useful to remove scan points resulting from hitting two objects with the laser spot or by hitting no object at all, for example the sky. We do not use the *Smooth Filter* to assure that important characteristics were not deleted and the *Distance Filter* was set to 30 m.

Prior to *Registering the Scan*, it is convenient enter the UTM coordinates of each of the spheres. To do this we create a text file with **.csv* format in which each line contains: the sphere name, its UTM coordinates, and the height; with all the fields separated by commas. Next, in *Import Objects*, we import the file and a new folder called *References* with the uploaded points is created. Now, when registering, we check the option of '*Forcing Correspondences by names of objectives*' to make sure we are taking into account all the common references, in our case the spheres. Although registering makes all scans form a single model, it has the disadvantage that errors in the transformation must be added to measurement errors. Finally, the point cloud is generated and the final file is exported.

An aerial view of the Castle scanning generated by the software is shown in Fig. 10. In this image, it is possible to appreciate, in form of white spots, the places where the TLS was placed.
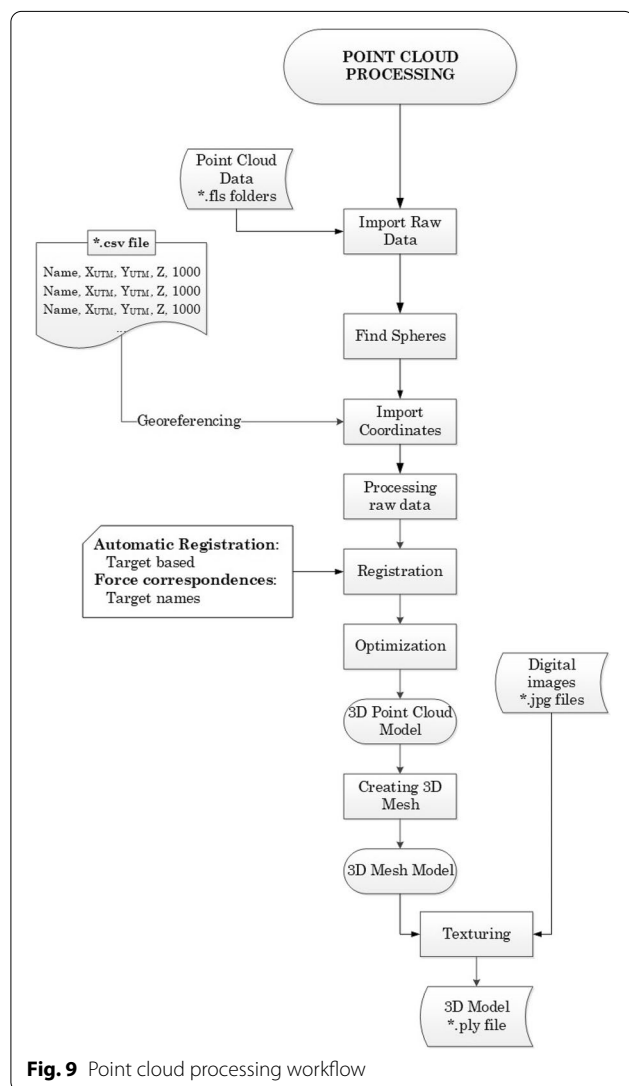

Fig. 9 Point cloud processing workflow

Generation of the 3D model

In this section, we describe the 3D printing process, once the 3D point cloud has been generated from the 3D reconstruction software. The printer used is based on the FDM technology and it is able to build strong, durable and dimensionally stable models with a high accuracy and repeatability. The use of 3D printing in Archaeology is an enhancement for many applications. One of the key issues is the access to archaeological remains which are located some distance away and the direct view becomes costly and time-consuming to travel and view in-situ. Likewise, the use of 3D printing for a faithful replication of the target piece provides many advantages such as the risk decreasing by not handling original artefacts, which may be easily damaged, a full 3D observation and manipulation, and an accurate and detailed measurement.
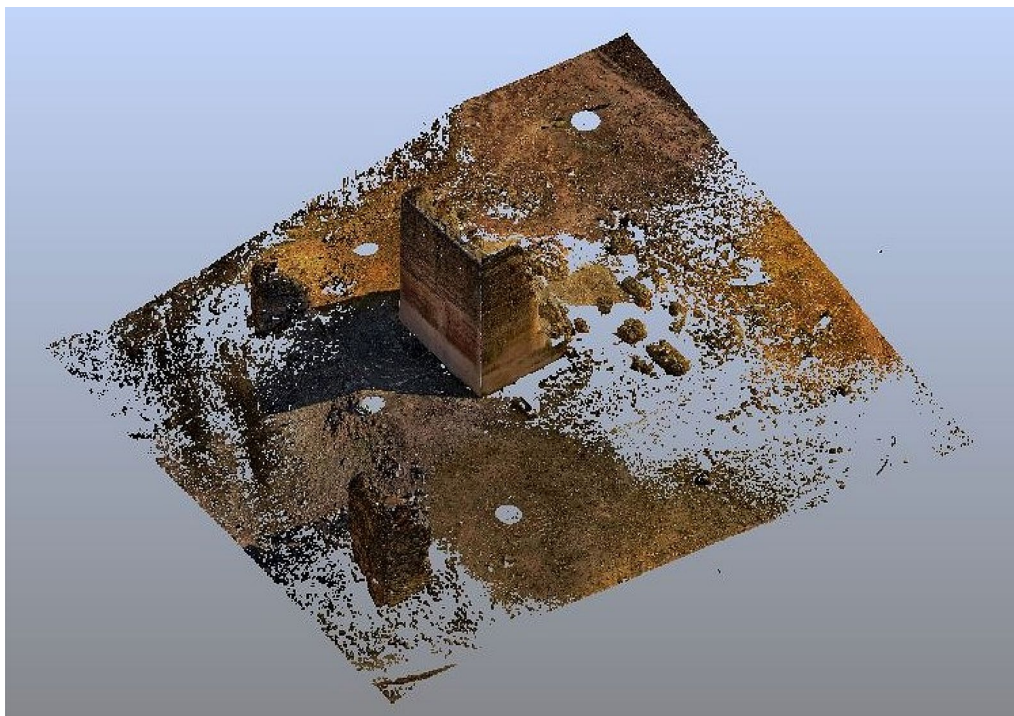
Arias *et al. Heritage Science* (2022) 10:112

Page 11 of 15

Fig. 10 Scanning of the Castle. Observe the white spots, where the TLS was placed to summarize the obtained results, in Table 3 we show the number of scans and the size of the point cloud generated

Table 3 Summary of the obtained results

View points	Maximum error (mm)	Recording points/million	Scanning time (days)
14	18.1	179	2

The output point cloud from the LIDAR scanning is triangulated for the mesh generation by applying the Poisson surface reconstruction method [23]. However, the resulting mesh presents noise and many holes, which need to be repaired in order to be properly printed. For this purpose, the geometry of this model is edited with Blender, an open source 3D creation suite. Several custom tools are applied for filling holes, smoothing surface and making planar faces. As a result, the mesh is now without holes and the lower part of the model is removed to make one side flat, so it can be adhered to a research poster or exhibition panel.

The next stage is the selection of the most adequate printing material. A detailed survey is out of the scope of this paper, and we briefly review some key materials in this section. In general, the reconstruction of archaeological objects produces 3D models with many concave and convex surfaces. Consequently, the distribution of support areas is a requirement for every printing. It supposes a worse quality in the object surface, which is below the support material and a tedious work to support removing. We propose two multi-material solutions with very similar results to overcome the previous problem. The first one is the use of polylactic acid (PLA) for model printing and polyvinyl alcohol (PVA) for printing support. Both materials share the same melting point 200º so the same extruder may deposit them. The second solution is based on the fusion of acrylonitrile butadiene styrene (ABS) and high impact polystyrene (HIPS) for printing model and support respectively. In this last solution, the melting point of both materials is a little higher in the range from 210º to 249º. These multi-material printing provide us the capability of using a specific solvent to remove the support material as the water for PVA and limonene for HIPS.

Finally, we must just set the printing parameters in order to achieve the expected quality. In this sense, our model was printed with a high resolution so the thickness of each layer is one millimetre. In addition, to ensure a greater resistance in the borders, the wall width has been increased 0.5 cm. The infill density is reduced until 30% to add less plastic on the inside of the print and thus cut the time printing.

Arias *et al. Heritage Science*   (2022) 10:112

Page 12 of 15

Results

The Muslim castle

The model obtained from the Muslim tower, Fig. 10, is highly detailed and shows, not only the constructive characteristics with absolute fidelity but also the remains of another two small towers. Having very sharp edges, you can see the edge effect on the point cloud, which is not a problem when obtaining a 3D printed model.

The below image, Fig. 11, shows the resulting 3D printing which has an optimal appearance and a detailed model of the scanned environment.

Printing of 3D models

The availability of a scale model of the castle thanks to 3D printing is a resource available to any educational centre, Fig. 12. From a didactic point of view, it allows the student to appreciate more directly general aspects

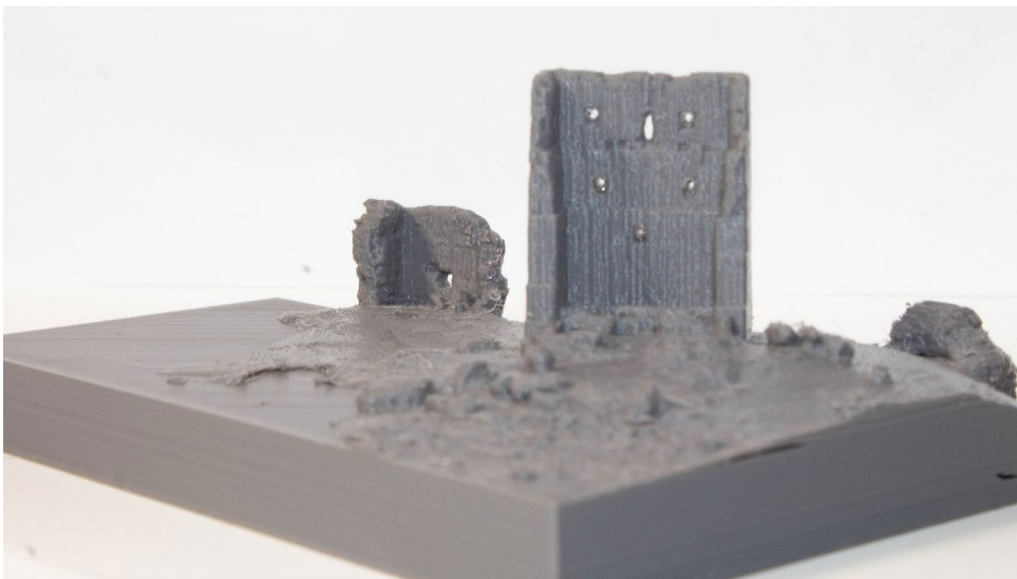**Fig. 11** The Muslim castle generated by the Scene

Fig. 12. 3D printed model

Arias *et al. Heritage Science*   (2022) 10:112

Page 13 of 15

of geometry and more concretely information about the proportions of the castle. Comparing this model with other scenarios printed at the same scale facilitates, for example, a comparative analysis of the sizes and dimensions of specific parts. This kind of analysis is more difficult to perform on a projected image on a screen, especially for students with poor spatial vision.

3D printing also aids in the dissemination of the site under study for audiences with different levels of expertise. In this case it is an archaeological model, which contributes to the better preservation of the remains found and even, for a specialised public, to test reconstructive hypotheses based on the construction of the model itself. The model helps to provide an overview, spatial references and sometimes conjecture about the form, location and relationship of the original buildings. The quality of the techniques used in the generation of the 3D model means that the print faithfully reflects aspects to be identified by a specialised public without losing the attraction for a public with a lower level of archaeological knowledge. As discussed in the introduction section, numerous studies highlight the importance of technology in archaeological education [24, 25] among others already mentioned. However, although some research has been conducted [26, 27], the integration of 3D visualisation systems with successful pedagogical theories that promote deep learning approaches in field archaeology courses is lacking.

In the case of the Tower of Castulo, the use of the 3D model brings the students, in a very realistic way, closer to the current state of the Tower. In this way, with the use of specific 3D model processing software, such as 3D Builder, Blender or others [28], a virtual reintegration can be generated and a visual reconstruction can be obtained in which the decoration and texture and even the continuity of the Tower are reproduced using non-invasive techniques.

From the didactic point of view, the student can directly analyse the exploded view of the element by studying separately the elevation, the ground plan, etc.… even in inaccessible areas, such as the highest part of the Tower.

In short, 3D models are offered as an attractive and motivating tool for students by approaching the studied scenario in a different way. Not only does it allow for visualisation and manipulation but, being a product with metric characteristics, it facilitates the assimilation of proportions, volumes and other geometric characteristics.

Conclusion

As the castle was in an isolated place, we had the advantages that there were not many visitors and the survey can be done at different seasons. As a drawback, there were a large amount of rocks and debris in the ground causing many shaded areas.

Neither can we ignore that to handle the huge amount of data generated by a TLS, it is necessary to have a state-of-the-art computer. Still, the times of processing and generation of the point cloud are high so that it is convenient to arm yourself with a good dose of patience. However, this one is the minor problems, since it is foreseeable that in a few years the development of the hardware will facilitate computers with higher performances that facilitate us even more the work.

Despite all these issues, it was clear that the possibilities of the TLS from the point of view of research, education and dissemination of heritage are enormous, although its high price plays against it. However, this point should be qualified, since on the equipment is becoming more affordable and there is the possibility of renting the equipment.

Another advantage of the TLS techniques is once the scanners are done, the excavation site can be protected through covering with soil, and the zones can be analysed subsequently without direct access to the surfaces. Even more, when the 3D model is generated, it can be upload to a public domain repository, allowing anyone to download and to reproduce it, in its own home. As the generation of 3D models has become more affordable, its applications will boost in the next few years. Although we have only applied our results to a printed model, with a little effort it can be also used for virtual reality applications. For those applications that does not require millimetre accuracy, low cost close range photogrammetry should be an interesting option.

To sum up, 3D printing is begging to show its capabilities to reproduce in a quite accurate way any structure, no matter its original size was. This opens up a set of very interesting applications that can range from documentation to allow enable visually impaired the recognition of any monument. It is pretty obvious its potential as a tool for educational purpose at any level, from primary to university levels.

Finally, the 3D models ensure the integrity and reliability of the heritage documentation, as the information recorded is timely, relevant and accurate. It provides a clear understanding of the condition and materials of the studied environment, as well as the chronology of modifications and alterations to the property throughout its excavation. Therefore, documenting and recording these aspects, and being able to use and display them in such an accessible and easy to manipulate way. In this sense 3D models are an essential teaching tool in the field of archaeology, being an attractive and motivating tool for students as they approach the scenario under study in a different way. Not only does it allow visualisation and

Arias *et al. Heritage Science*   (2022) 10:112

Page 14 of 15

manipulation, but also, as it is a product with metric characteristics, it facilitates the assimilation of proportions, volumes and other geometric characteristics.

Abbreviations

ABS: Acrylonitrile butadiene styrene; BCE: Before Current Era; BIM: Building Information Modeling; CAD: Computer-aided design; ETRS89: Earth Terrestrial Reference System 1989.; FDM: Fused Deposited Modeling; GIS: Geographic Information System; Ha: Hectare; HDR: High Dynamic Range; HIPS: High impact polystyrene; LIDAR: Light Detection and Ranging; M: Meters; MF: Multi-frequency-ranging; Mm: Milimeters; NRTK: Network Real Time Kinematic; PLA: Polylactic acid; PVA: Polyvinyl alcohol; RAP: Red Andaluza de Posicionamiento; RTK-GNSS: Real Time Kinematic – Global Navigation Satellite System; TLS: Terrestrial Laser Scanners; UTM: Universal Transverse Mercator.

Author contributions

FA contributed to the archaeological investigations, conceptualisation of the study area, the interpretation and analysis of results and conclusions. CE contributed to the planning of the fieldwork. The design of the flight parameters in order to obtained and the desired photogrammetric products. JMJ has supervised the planning of the flight and has also contributed with the execution of the drone flights. LO has contributed in the supervision of the analysis of the products resulting from the processing of the images. AR has contributed to the quality analysis of the cartographic products generated. JJC has contributed to the general supervision of the paper giving it a didactic approach, to the writing of the manuscript and layout of the manuscript as well as to the mailing and exchange of mailings with the journal. All authors have read and agreed to the published version of the manuscript. All authors read and approved the final manuscript.

Availability of data and materials

Not applicable.

Declarations

Competing interests

The authors declare no competing interests.

Author details

[1]Conjunto Arqueológico Monumental de Cástulo Crta. Linares-Torresblascopedro Km. 3,3, 23700 Linares, Spain. [2]Dept. Ingeniería Cartográfica, Geodésica y Fotogrametría, Universidad de Jaén, Jaén, Spain. [3]Dept. Ingeniería del Software, Universidad de Granada, Granada, Spain. [4]Dept. Informática, Universidad de Jaén, Jaén, Spain. [5]Dept Tecnologías de La Información Y Comunicación Aplicadas a La Educación, Universidad Internacional de La Rioja, Logroño, Spain.

References

1. Andrade Lotero LA, Gó E. Tocar o Mirar: Comparación de Procesos Cognitivos en el Aprendizaje con o sin Manipulación Física. Psicol Educ. 2012;18:29–40. https://doi.org/10.5093/ed2012a3.

2. Ramirez EBR, Diaz FJ, Arias GAG, Villamizar NI. Impresión 3D como Herramienta Didáctica para la Enseñanza de Algunos Conceptos de Ingeniería y Diseño. Ingeniería. 2018;23:70–83. https://doi.org/10.14483/23448393.12248.

3. Zawacki-Richter O, Marín VI, Bond M, Gouverneur F. Systematic review of research on artificial intelligence applications in higher education—where are the educators? Int J Educ Technol High Educ. 2019;16:39. https://doi.org/10.1186/s41239-019-0171-0.

4. Lerma JL, Navarro S, Cabrelles M, Villaverde V. Terrestrial laser scanning and close range photogrammetry for 3D archaeological documentation: the upper palaeolithic cave of Parralló as a case study. J Archaeol Sci. 2010;37:499–507. https://doi.org/10.1016/j.jas.2009.10.011.

5. Marín-Buzón C, Pérez-Romero A, López-Castro JL, Ben Jerbania I, Manzano-Agugliaro F. Photogrammetry as a new scientific tool in archaeology: worldwide research trends. Sustainability. 2021;13:5319. https://doi.org/10.3390/su13095319.

6. Marín-Buzón C, Pérez-Romero AM, León-Bonillo MJ, Martínez-Álvarez R, Mejías-García JC, Manzano-Agugliaro F. Photogrammetry (SfM) vs. terrestrial laser scanning (tls) for archaeological excavations: mosaic of cantillana (Spain) as a case study. Appl Sci. 2021. https://doi.org/10.3390/app112411994.

7. Ebrahim M. 3D laser scanners: history, applications, and future. Saarbrücken: Lambert Academic Publishing; 2014.

8. Lambers K, Remondino F. Optical 3D Measurement techniques in archaeology recent developments and applications. Layers of perception: proceedings of the 35th international conference on computer applications and quantitative methods in archaeology (CAA). Berlin: Heidelberg Propylaeum; 2007. p. 27–35.

9. Vacca G, Dessi A. Geomatics supporting knowledge of cultural heritage aimed at recovery and restoration. 2020. Int Arch Photogramm Remote Sens Spatial Inf Sci. https://doi.org/10.5194/isprs-archives-XLIII-B2-2022-909-2022.

10. Fabris M, Achilli V, Artese G, Bragagnolo D, Menin A. High resolution survey of Phaistos palace (Crete) by tls and terrestrial photogrammetry. 2012. Int Arch Photogramm Remote Sens Spatial Inf Sci. https://doi.org/10.5194/isprsarchives-XXXIX-B5-81-2012.

11. Lewińska P, Róg M, Żądło A, Szombara S. To save from oblivion: comparative analysis of remote sensing means of documenting forgotten architectural treasures – Zagórz monastery complex. Pol Meas. 2022;189: 110447. https://doi.org/10.1016/j.measurement.2021.110447.

12. Moyano J, Nieto-Julián JE, Bienvenido-Huertas D, Marín-García D. Validation of close-range photogrammetry for architectural and archaeological heritage: analysis of point density and 3D mesh geometry. Remote Sens. 2020;12:3571. https://doi.org/10.3390/rs12213571.

13. Boardman C, Bryan P. 3D laser scanning for heritage: advice and guidance on the use of laser scanning in archaeology and architecture. London: Historic England; 2018.

14. Neumüller M, Reichinger A, Rist F, Kern C. 3D Printing for Cultural Heritage: Preservation, Accessibility, Research and Education. In: Ioannides M, Quak E, editors. 3D research challenges in cultural heritage: a roadmap in digital heritage preservation. Berlin, Heidelberg: Lecture Notes in Computer Science; Springer; 2014. p. 119–34.

15. ISO - ISO/TC 261 - Additive manufacturing. https://www.iso.org/committee/629086/x/catalogue/ Accessed 19 May 2022.

16. Lerma García, J.L Theory and practice on terrestrial laser scanning. http://jllerma.webs.upv.es/pdfs/Leonardo_Tutorial_Final_vers5_SPANISH.pdf Accessed 7 Apr 2021.

17. Schuhmacher S, Böhm J. Georeferencing of terrestrial laserscanner data for applications in architectural modeling. Stuttgart: Stuttgart Universitätsbibliothek der Universität Stuttgart; 2005. https://doi.org/10.18419/opus-3749.

18. Balletti C, Ballarin M, Guerra F. 3D printing: state of the art and future perspectives. J Cult Herit. 2017;26:172–82. https://doi.org/10.1016/j.culher.2017.02.010.

19. Alonso JISJ, Rubio JM, Martín JJF, Fernández JG. Comparing time-of and phase-shift the survey of the royal pantheon in the Basilica of San Isidoro (LEÓN). ISPRS - Int Arch Photogramm Remote Sens Spatial Inform Sci. 2011;3816:377–85. https://doi.org/10.5194/isprsarchives-XXXVIII-5-W16-377-2011.

20. Andrews, D.; Bedford, J.; Bryan, P. Metric survey specifications for cultural heritage (3rd Edn) | Historic England http://historicengland.org.uk/

Arias *et al. Heritage Science*   (2022) 10:112

Page 15 of 15

images-books/publications/metric-survey-specifications-cultural-herit age/. Accessed 7 Apr 2022.

21. Nuttens, T.; De Maeyer, P.; Wulf, A.; Goossens, R.; Stal, C. 2011 Terrestrial laser scanning and digital photogrammetry for cultural heritage: an accuracy assessment. ISBN 978–87–90907–92–1.

22. Garrido MS, Giménez E, de Lacy MC, Gil AJ. Quality analysis of NRTK positioning on boundary regions and under unfavorable topographic conditions in the Southern Iberian Peninsula. IEEE J Sel Top Appl Earth Observations Remote Sens. 2013;6:2364–74.

23. Kazhdan, M.; Bolitho, M.; Hoppe, H. 2006 Poisson surface reconstruction. In Proceedings of the Proceedings of the fourth Eurographics symposium on Geometry processing; Eurographics Association: Goslar, DEU. 61–70 June 26 2006.

24. Agbe-Davies AS, Galle JE, Hauser MW, Neiman FD. Teaching with digital archaeological data: a research archive in the university classroom. J Archaeol Method Theory. 2014;21:837–61. https://doi.org/10.1007/s10816-013-9178-3.

25. Dell'Unto N. 3D Models and Knowledge Production. Routledge: In Archaeology and Archaeological Information in the Digital Society; 2018.

26. Garstki KJ, Larkee C, LaDisa J. A role for immersive visualization experiences in teaching archaeology. Studies in Digital Heritage. 2019;3:46–59. https://doi.org/10.14434/sdh.v3i1.25145.

27. Peuramaki-Brown MM, Morton SG, Seitsonen O, Sims C, Blaine D. Grand Challenge No. 3: digital archaeology technology-enabled learning in Archaeol. J Archaeol Educ. 2020;4(3):4.

28. Davis A, Belton D, Helmholz P, Bourke P, McDonald J. Pilbara rock art: laser scanning, photogrammetry and 3D photographic reconstruction as heritage management tools. Herit Sci. 2017;5:25. https://doi.org/10.1186/s40494-017-0140-7.

Publisher's Note