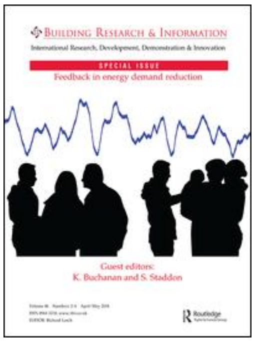

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Combination of nadiral and oblique UAV photogrammetry and HBIM for the virtual reconstruction of cultural heritage. Case study of Cortijo del Fraile in Níjar, Almería (Spain)

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ABSTRACT

Historic Building Information Modelling (HBIM) is the most effective method of rebuilding virtual 3D models of heritage buildings, and constitutes a new information management system in the field of cultural heritage interventions. In this study, photogrammetry based on Unmanned Aerial Vehicles (UAV photogrammetry) was applied as an alternative to Terrestrial Laser Scanning (TLS) for the development of HBIM for historical buildings in a ruinous state, analysing as a case study the Cortijo del Fraile, in Níjar, Almería (Spain). Based on the analysis of the historical information of the building, a photogrammetric survey was carried out with UAV by means of a combination of nadiral and oblique photographs. In this way, a precise characterization of the object was obtained, avoiding the grey areas that are characteristic of TLS. The generated 3D point cloud served as the basis for the virtual reconstruction of an HBIM model focused on both the exterior and interior. In order to ensure reasonable agreement between the parametric model and the ground truth, a validation procedure has been established that restricts the deviations between the two. Finally, a texturizing process is applied to the HBIM model to achieve a photorealistic finish for purposes of visualization, archiving, and recording.

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UAV photogrammetry; HBIM; cultural heritage; virtual reconstruction; 3D modelling

Introduction

In recent years, the three-dimensional (3D) models obtained through tools and computer media have become a good source of data for the preservation, reconstruction, and exhibition in museums of emblematic buildings of cultural heritage (El-Hakim, Beraldin, Picard, & Godin, 2004; Galeazzi, 2017; Remondino, 2011). Indeed, virtual reconstruction was one of the procedures added to the UNESCO World Heritage list in 1985 for the conservation and preservation of buildings of cultural interest. Likewise, in 2006 the London Charter (Denard, 2016; INITIATIVE, 2006) established the principles of 3D visualization in the field of cultural heritage research and dissemination.

Technological advances have led to important changes in the field of 3D modelling, specifically those related to Terrestrial Laser Scanning (TLS) (Lemmens, 2007; Rüther et al., 2009) and digital photogrammetry (Alshawabkeh & Haala, 2004; Boehler & Marbs, 2004; McCarthy, 2014; Rasztovits, Dorninger, & Scanning, 2013; Yastikli, 2007; Yilmaz, Yakar, Gulec, & Dulgerler, 2007), which today is fully automated using Structure from Motion (SfM) algorithms (Fonstad, Dietrich, Courville, Jensen, & Carbonneau, 2013; Javernick, Brasington, & Caruso, 2014; Westoby, Brasington, Glasser, Hambrey, & Reynolds, 2012) and Multi-View Stereopsis (MVS) (Furukawa & Ponce, 2010) through processes derived from computer vision.

The literature shows that improvements in SfM photogrammetry technology allow it to be used as a reliable system in the field of 3D acquisition, with results comparable to those obtained with TLS (Chatzistamatis et al., 2018; Chiabrando, Spanò, Sammartano, & Teppati Losè, 2017; Fryskowska & Stachelek, 2018; Kadobayashi, Kochi, & Furukawa, 2004; Liang et al., 2018; Valenti & Paternò, 2019; Zhihua et al., 2014). The choice of one or another technique depends on the morphology and accessibility of the study zone but also on the assumed costs of carrying out the 3D modelling. In effect, in many cases there are zones that are not accessible or visible through TLS. In this context, Unmanned Aerial Vehicles (UAVs) represent an emerging and economic technology which can be equipped with high-resolution cameras to carry out SfM-based photogrammetry for

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application to the monitoring and management of historical heritage (Achille et al., 2015; De Reu et al., 2013; Chiabrando, Nex, Piatti, & Rinaudo, 2011; Verhoeven, 2009; Hendrickx et al., 2011; Mesas-Carrascosa, García, De Larriva, & García-Ferrer, 2016; Mozas-Calvache, Pérez-García, Cardenal-Escarcena, Mata-Castro, & Delgado-García, 2012; Ortiz, Gil, Martínez, Rego, & Meijide, 2013; Sauerbier & Eisenbeiss, 2010), especially when there are access restrictions. Another possibility is the integration of the laser scanning on board the UAV, which is called Aerial Laser Scanning (ALS) (Lin, Hyyppä, & Jaakkola, 2011; Roca, Armesto, Lagüela, & Díaz-Vilariño, 2014). However, UAVs also have limitations such as access to the interior of buildings, cavities, hollows or inner parts of arcades. The challenge of autonomous drones flying in an interior space, with no access to GPS is one that is currently being researched by a few research groups (Dupont, Chua, Tashrif, & Abbott, 2017). In turn, the use of oblique photographs improves the results obtained through SfM photogrammetry by allowing visualization of details hidden from the nadiral views (Aicardi et al., 2016; Lin, Jiang, Yao, Zhang, & Lin, 2015; Vetrivel, Gerke, Kerle, & Vosselman, 2015), thus avoiding the use of terrestrial photographs.

In all cases, the result obtained is a point cloud or a 3D mesh model that can be used as a basis for the creation of a Building Information Model (BIM), whose mission is to cover the design, construction, and administration processes of a building's data throughout its life cycle (Merchán, Salamanca, Merchán, Pérez, & Moreno, 2018; Vacanas, Themistocleous, Agapiou, & Hadjimitsis, 2015). This process is known as 'scan-to-BIM' or 'cloud-to-BIM' and allows one to get a true view of the locations (Angelini, Baiocchi, Costantino, & Garzia, 2017; Rodríguez-Moreno et al., 2018). Although BIM has its main application in the construction sector (Eastman, 2011), in recent years it has been used successfully in the management of information on architectural heritage and its representation (Biagini, Capone, Donato, & Facchini, 2016; Oreni, Karimi, & Barazzetti, 2017; Quattrini, Malinverni, Clini, Nespeca, & Orlietti, 2015; Quattrini, Clini, Nespeca, & Ruggeri, 2016). In the case of digitizing existing data with artistic and historical significance, this method is referred to as Historic Building Information Modelling (HBIM) (Karachaliou, Georgiou, Psaltis, & Stylianidis, 2019; León-Robles, Reinoso-Gordo, & González-Quiñones, 2019; Saygi, Agugiaro, Hamamcıoğlu-Turan, & Remondino, 2013). However, its implementation in the field of architectural heritage depends on the peculiarities of each building, due to the irregularities they present in terms of morphology and the elements that make it up. Because of this, parametric objects created on BIM platforms cannot be used and new objects and libraries have to be developed. Indeed, it is necessary to develop an HBIM library of prototypes of parametric architectural objects, built from historical data and remote collection of survey data, using TLS or photogrammetry in order to digitally model historical buildings (Capone & Lanzara, 2019; Dore & Murphy, 2012). The main problem of this reverse engineering process is the amount of time required to parametrize the geometric elements, regardless of the operator's experience, the manual modelling work, or even the recent developments of automated semantic recognition processes (Armeni et al., 2016). The quality of the model is related to the 'level of approximation' or the 'level of simplification' applied during the modelling phase. In the case of heritage elements that are in ruinous state, this 'level of approximation' depends on the quantity and quality of the historical information collected on the original geometry.

New challenges are currently being posed in 3D digital modelling, relating to the simulation of the structural analysis of the building using a finite element model (FEM), known as Cloud-to-BIM-to-FEM (Barazzetti et al., 2015; Bassier, Hadjidemetriou, Vergauwen, Van Roy, & Verstrynge, 2016).

The main goal of the present study is to develop an HBIM model of a singular building of Spanish cultural heritage to carry out its virtual reconstruction, specifically the Cortijo del Fraile in Níjar, Almería, which is in a state of partial collapse.

Due to the impossibility of accessing the interior of the building as it is fenced for security, the point cloud used as a basis for the HBIM modelling has been obtained only by UAV photogrammetry, as an alternative to the use of TLS or any other method. The research is also intended to highlight the importance of combining nadiral and oblique photographs to avoid the grey areas typical of TLS.

Materials and methods

The methods used to carry out this research are summarized in Figure 1. A historical study of the building was carried out to provide us with information on its original state. It was also necessary to know exactly the current state of the building, which was obtained through UAV photogrammetry. From both analyses it was possible to create a BIM that allows the virtual reconstruction of the original state of the building, which can be used for purposes of archiving and visualization.

Study site

The Cortijo del Fraile is a building located southeast of Níjar, Almería (Figure 2), within the Natural Park of

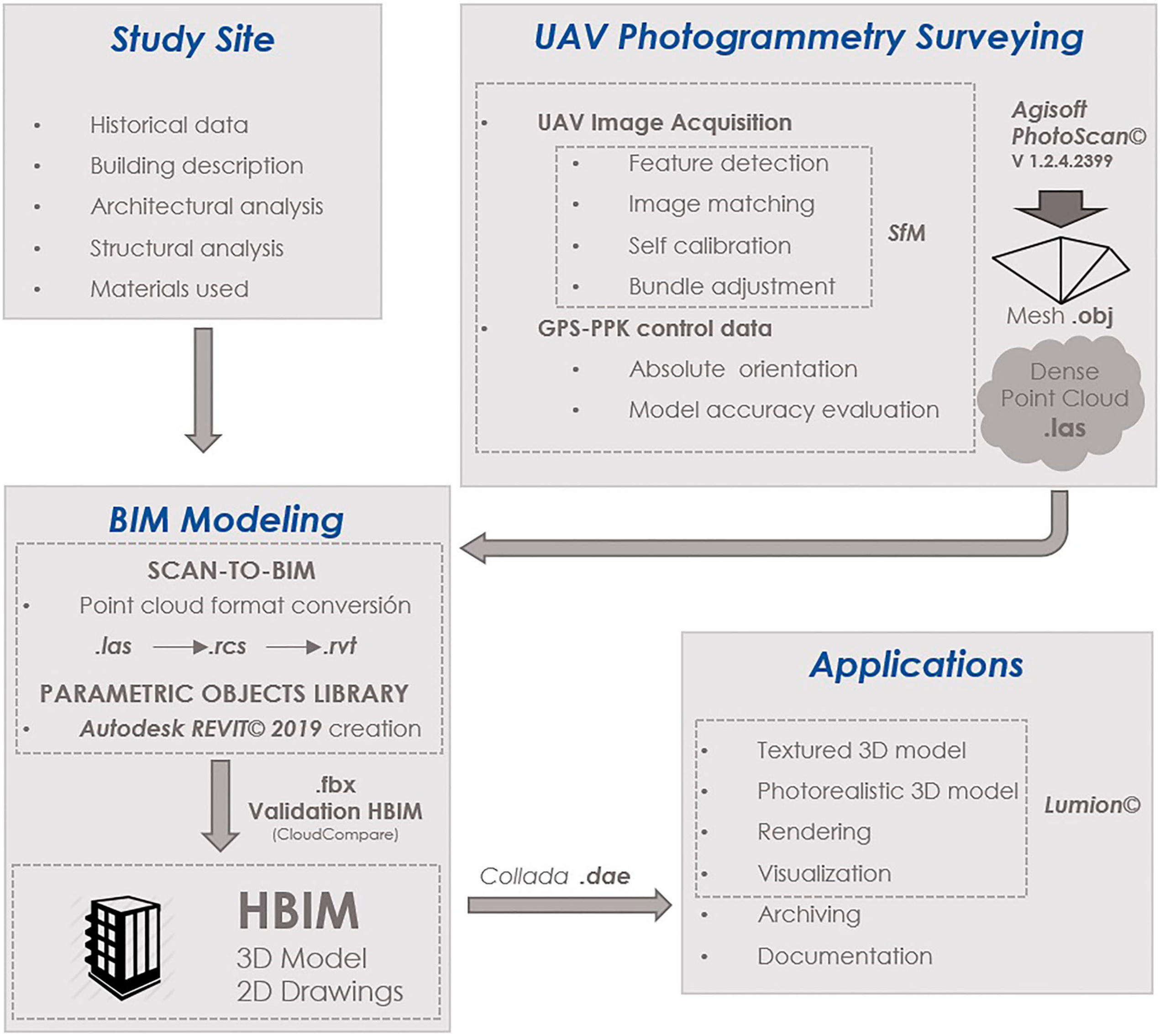


Figure 1. Flowchart of the methodology of this research.

Cabo de Gata-Níjar, about 6.5 km from the coast of the Mediterranean Sea. It is located in a farm of 730 hectares and surrounded by other smaller farmhouses in the vicinity. The southwest and northeast UTM coordinates (Zone 30, ETRS89) of the study area are (582385, 4080340) and (582515, 4080470), respectively.

Historic information

The farmhouse was built in the 18th century by the friars of the Convent of Santo Domingo de Almería as an important centre of agricultural exploitation with olive trees and vines. Originally it was known as the 'Cortijo del Hornillo' because it had a large oven for bread making in the central courtyard.

This property was probably formed following the process of confiscation of communal lands, which in Níjar gave rise to the consolidation of vast agropastoral complexes that marked the rural economy of the area until the mid-20th century. Originally it belonged to the Acosta family. However, in 1836 the farmhouse passed to the state patrimony, as part of the process of confiscation of, properties of the religious orders, and was later sold at auction.

The Cortijo del Fraile is known for a crime that occurred in its vicinity, the so-called 'crime of Níjar' (Cerezuela, 2018; Torres Flores & Roldán Molina, 2018), which took place on 22 July 1928 and whose protagonist, Francisca Cañadas, lived in the vicinity all his life. The facts were the real events that inspired the plot of Federico García Lorca's dramatic piece *Bodas de Sangre* (1935) and were also a source of inspiration for

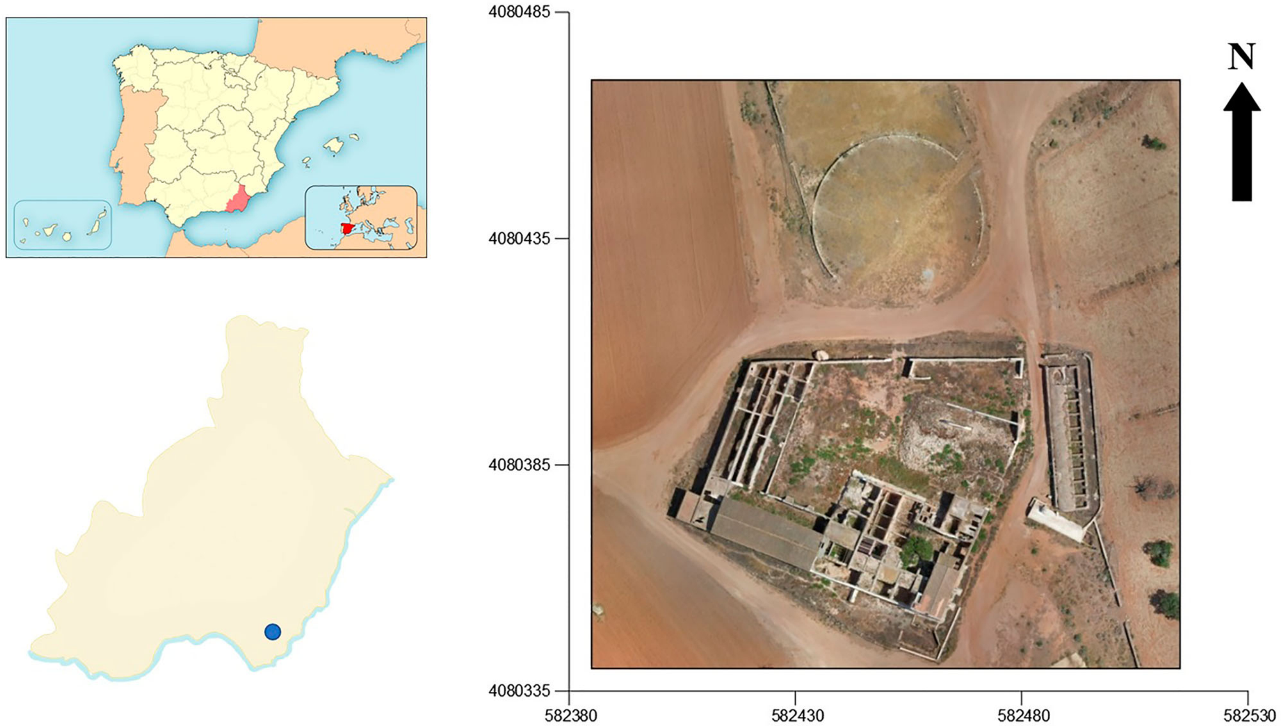


Figure 2. Location of the study area. Coordinates are referred to UTM Zone 30N (European Terrestrial Reference System 1989, ETRS89).

the work *Dagger of Carnations* (1931) by the Almeria writer Carmen de Burgos. It has also been related to cinema, being the scene of numerous films, highlighting those directed by Sergio Leone in the 1960s, which, due to the peculiarity of its climatology and landscape, pretend that the building was located in the American West.

Nowadays there is little documentary information and few photographs about the original image of the farmhouse ('Cortijo del Fraile', 2019; 'Cortijo del Fraile – Lista Roja del Patrimonio', 2012; Jiménez López, 2012; Olmedo Granados, 1999; Pérez-Millán, Yáñez-Pacios, Contreras-García, & Socorro-Picó, 2016). However, there are a large number of films that show images of the original architecture. As an example, the following films stand out: *The Good, the Bad and the Ugly* and *For a Few Dollars More* by Sergio Leone in 1966, *A Bullet for the General* by Damiano Damiani in 1967, *Last of the Badmen* by Nando Cicero in 1967, and *Silbersattel* by Lucio Fulci in 1978.

After its abandonment in the 1980s the building has deteriorated and is now in ruins, having spent more than 40 years in constant danger of collapse. On 23 March 2010, a resolution by which the Cortijo del Fraile was declared a 'Property of Cultural Interest' was published in the Official Gazette of the Junta of Andalucía, and the building was enrolled in the General Catalogue of the Andalusian Historical Heritage, categorized as a 'historic site' ('Decreto 44/2011, de 22 de febrero, por el que se inscribe en el Catálogo General del Patrimonio Histórico Andaluz como Bien de Interés Cultural, con la tipología de Sitio Histórico, el Cortijo Fraile, en el término municipal de Níjar (Almería).', 2011).

In 2011 some walls suffered damage and collapsed and thus had to be rebuilt and stabilized. Today the farmhouse is privately owned by a company that exploits the farm and its water wells for ecological agricultural production. Figure 3 shows the current status of Cortijo del Fraile.

Architectural analysis and description of structures

Cortijo del Fraile is a building with diverse types of architectural constructions. It is trapezoidal in shape with a plot surface of 3013 m^2, of which the constructed surface is estimated to be 1835 m^2. The access road to the farmhouse is a dirt track and is delimited with rows of agaves.

Its spatial distribution is compact and irregular, formed by a main nucleus and several annexed constructions where almost all the rooms are developed around a large central courtyard. The nucleus consists of housing for the owners, public oratory, houses of the sharecroppers and shepherd, courtyard, corrals, and haystacks and has as annexed constructions two threshing floors, pigsty, wells, and cisterns. Figure 4 shows the architectural plan of the Cortijo del Fraile.

On the main façade, with large gaps and regular distribution, the chapel, the house of the owners, and the houses of the sharecroppers are aligned. Just in front of

Figure 3. Actual image of the Cortijo del Fraile.

the main façade, and following the position of the atrium entrance to the chapel (with wrought iron handrails), it can be recognized that there were several benches separated by walls, which could have been a meeting point. The owner's house has a large window in the façade, and is the only one built with metallic carpentry. It stands out for its superiority with respect to the other houses. The sharecropper's house is a modest dwelling and was directly linked to some work areas; it has access to the courtyards and a big stable, of rectangular plan, with its interior split with diaphragm arches and gabled roof with beams, reeds, mud mortar, and curved tiles.

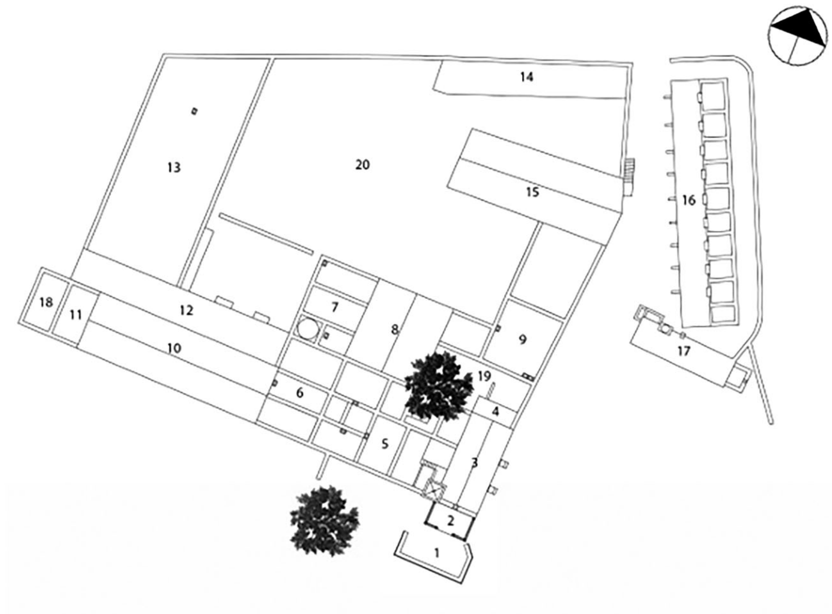
The housing of the priest located to the East has a different typology, with a single room, compartmentalized into four smaller spaces by vertical walls that do not reach the ceiling at several points in the house. It has a flat cover made with beams, reeds, palm leaves, and lime. It also has access to rooms that correspond with stables and masonry haystacks, which have been practically destroyed.

The chapel or oratory stands out for its volume throughout the whole, with a rectangular plant and gable roof of ordinary masonry with lime mixture and plaster. On the outside it is reinforced with two side stirrups and a small bell tower with a square brick base, as shown in Figure 5. The main facade of the chapel, being a religious construction, has characteristic elements such as the rosette with stained glass windows and whose panes are generally built in radial form.

Next to the public access road, two wells with masonry rims are preserved. On the eastern flank of the farmhouse is the pigsty, which is very close to one of the two cisterns.

The vertical structure is made up of load-bearing walls of irregular stone masonry with mud, plaster, or lime as agglomerates, garrisoned and bleached externally. In the interior of the load-bearing walls, there is an important concentration of semi-circular arches, something which is not usual in the constructions in the fields of Níjar. These arches are present in the stables located to the west of the complex, whose interior walls are formed by arcades, as shown in Figure 6.

The roofs are mostly flat, resting on wood joists of varying dimensions that are embedded in the load-bearing walls. In the whole group there are three



1. Seating area	11. Workers dwelling
2. Entrance atrium to the chapel	12. Entrance of carriages
3. Chapel	13. Barns
4. Access to the crypt	14. Animal drinker
5. Main dwelling	15. Haystack
6. Sharecropper's dwelling	16. Pigsty
7. Stockyards	17. Cattle cistern
8. Stockyards	18. Electric transformer
9. Shepherd's dwelling	19. Inner court
10. Haystack and warehouse	20. Courtyard

Figure 4. Architectural plan of the Cortijo del Fraile.

units with gable roofs of two types: the flat tile that appears on the chapel and the curved or Arabic tile present in the other two dependencies, the corrals linked to the housing of the sharecropper and the haystack or warehouse located on the South façade. The top cover of the bell tower is a four-way roof with flat tiles.

The carpentry, of which only some examples are preserved, was made of wood, with ironwork being used only in certain places, such as in the atrium and the choir railing of the chapel, in the entrance door, and in the windows of the main house.

Survey of the current state of the building using UAV photogrammetry

Image acquisition

The images used in this work were taken from a rotatory wing DJI Matrice 600 Pro UAV with six rotors. The UAV was equipped with a DJI Zenmuse X5 motion-compensated three-axis gimbal mounting a digital camera with a lens with a fixed focal length of 15 mm and diagonal FOV of 72 degrees. The resolution of the camera sensor was 16 megapixels (4608×3456).

Two different flights were carried out to obtain the images. The first flight was carried out with an autopilot using the DJI GS Pro © application for the purpose of obtaining nadiral photographs. Figure 7 shows some of the parameters configured for the flight execution. Due to the low slope of the surrounding terrain of the building, the flight altitude was set at a constant distance of 50 m above ground level, which implies a surface of 64.7×48.5 m^2 covered by every photo and an equivalent ground sample distance of 1.1 cm, the reason why this flight height was selected. In accordance with the flight altitude, UAV speed, and light conditions at the time of flight, the shutter speed was adjusted to minimize the effect of blurring on the images taken. The flight plan consisted of 11 passes, and a total of 330 images

Figure 5. Detail of the bell tower.

were selected to carry out the photogrammetric project. The camera was triggered every two seconds and the flight speed was set to obtain forward and side overlaps of 80% and 65%, respectively.

The second flight was carried out in manual mode to obtain oblique photographs, with the aim of guaranteeing the photographic capture of the interior of the building and of the four façades of the enclosure. This flight was carried out at an approximate height of 15 m, and a total of 293 photographs were taken. This flight height was selected because the maximum height of the building was 12 m. In this way, the entire study area could be flown over without danger of collision. In addition, due to the FOV of the camera it was possible to cover the whole façade without having to move too far away from it. The angle of inclination of the camera was around 45° to avoid the appearance of the horizon in the photographs.

A total of 623 photographs with different points of view and scales were used to carry out the photogrammetric project. Figure 8 shows the camera locations and image overlap.

Survey campaign for georeferencing and evaluating the accuracy of the photogrammetric products

Prior to the image acquisition, eight targets were scattered on the studied surface for the purpose of georeferencing (ground control points, GCPs) and evaluating the accuracy of the photogrammetric project (checkpoints, CPs). Due to the impossibility of entering the interior of the enclosure, the targets were placed on the perimeter of the study zone, as shown in Figure 9a. As in (Martínez-Carricondo et al., 2018). This provision of targets ensured that the results were obtained with good accuracy in both planimetry and altimetry.

The targets consisted of A3 size (420 × 297 mm) red paper on which were two black squares. Figure 9(b) shows a detail of one of these targets. The three-dimensional coordinates of these points were measured with a Global Navigation Satellite System (GNSS) receiver working in Post Processed Kinematic (PPK) mode, with the base situated at a point near the main facade of the building (Figure 9c). The 3D coordinates of the base, corrected through the Trimble CenterPoint RTX Post-Processing

Figure 6. Perspective of the ensemble showing the semicircular arches in the stables of the Cortijo del Fraile.

Service, are 582481.520, 4080315.510, and 184.506 m, respectively. Horizontal coordinates are referred to UTM Zone 30N (European Terrestrial Reference System 1989, ETRS89) and the elevation is referred to the Mean Sea Level (MSL) using the EGM08 geoid model. Both rover and base GNSS receivers were Trimble R6 systems. For PPK measurements, these dual-frequency geodetic instruments have a manufacturer's stated accuracy specification of ±8 mm +1 ppm horizontal RMS and ±15 mm +1 ppm vertical RSM. As the distance between the base station and the study area was approximately 100 m, the horizontal and vertical errors were around 8 and 15 mm.

Photogrammetric processing

The photogrammetric process was carried out using the software package Agisoft PhotoScan Professional © version 1.2.4.2399. This kind of photogrammetric software based on the SfM algorithm was used because it has been proven to outperform other software applications in terms of accuracy (Sona, Pinto, Pagliari, Passoni, & Gini, 2014). The workflow is a three-step process (Verhoeven, 2011). The first step is the alignment of the images by feature identification and feature matching. While carrying out the image alignment, this software estimates both the internal and external camera orientation parameters, including nonlinear radial distortion. Only an approximate value of the focal length is required, which is extracted automatically from the EXIF metadata. This task was carried out with the PhotoScan accuracy set to high. The results of this step are the camera position corresponding to each picture, the internal calibration parameters, and the 3D coordinates of a sparse point cloud of the terrain. In the second step, the sparse point cloud is referenced to an absolute coordinate system (ETRS89 and frames in the UTM, in the case of this study) and densification of the point cloud is achieved with the quality set to medium, which is based on a pairwise depth map computation. This point cloud needs to be 'cleaned up' to eliminate all of the wild points that do not belong to the model. This process is performed manually. This resulted in a more detailed 3D model. Using the height field method, the mesh is obtained from the dense point cloud. The third step applies a texture to the mesh obtained in the previous step. Finally, the orthophoto is exported and a grid DSM can be generated from the point cloud. The

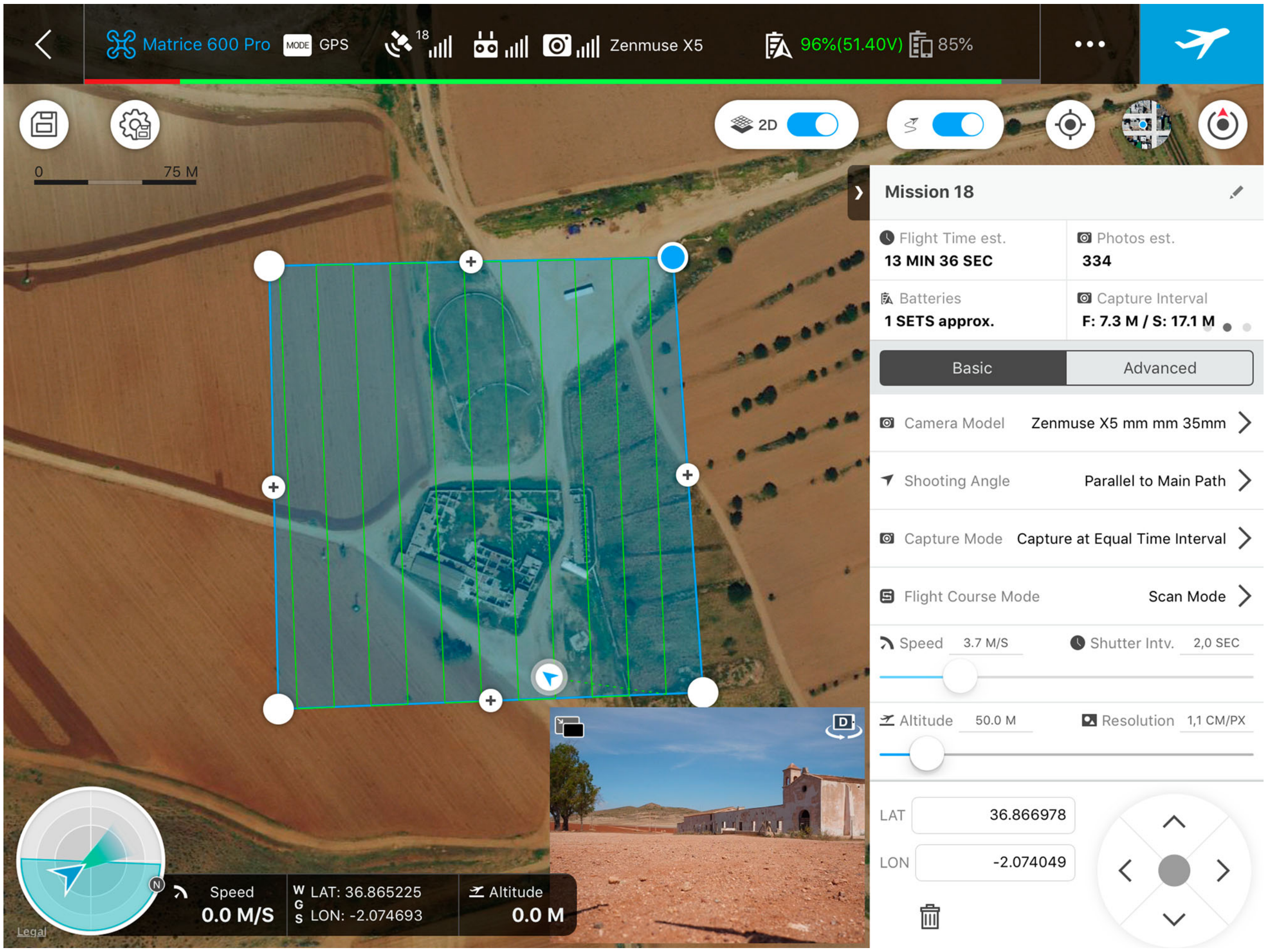


Figure 7. Flight path configuration with DJI GS Pro © software.

dense point cloud can also be exported in *.las format, as well as the mesh in *.obj, *.3ds or *.dxf format. The bundle adjustment can be carried out using at least three GCPs, but more accurate results are obtained if more GCPs are used, and it is recommended that more of them be used to obtain optimal accuracy (Agüera-Vega, Carvajal-Ramírez, & Martínez-Carricondo, 2017; Rosnell & Honkavaara, 2012). In this study, four targets placed in the field around the building were used as GCPs for the georeferencing of the project. The rest of the targets not used in the block adjustment were used as CPs to evaluate the accuracy of the photogrammetric project, according to the formulation of the root mean square error, described in (Agüera-Vega, Carvajal-Ramírez, & Martínez-Carricondo, 2016). The process was completed with about 15 h of cabinet work by a technician with high knowledge of UAV-SfM photogrammetry.

Virtual reconstruction using HBIM methodology

BIM is an intelligent 3D model-based process that involves the generation and management of digital representations of the physical and functional characteristics of places. BIM design tools allow extracting different views from a building model for drawing production and other uses. After the BIM model has been constructed, drawings of the plans, elevations, and sections of the building can be generated directly from the BIM model for purposes of documentation. Also, information such as the material, colour, height, thickness, and so on can be added to each component in the BIM database (Themistocleous, Agapiou, & Hadjimitsis, 2016). The BIM modelling was carried out using the software Autodesk Revit © 2019, one of the most used BIM software in the world, which includes a visual programming environment that allows designing with elements of modelling and parametric drawing. The great contribution of this software was to allow the introduction of several dimensions 4D (Time), 5D (Cost), 6D (Sustainability) and 7D (Management and Maintenance) in the building models, achieving interoperability through the use of different software and various disciplines (Tommasi & Achille, 2017), communicating with each other through compatible formats, with the Industrial Foundation Classes (IFC) data exchange format being the most widely used, as it is an open and neutral standard

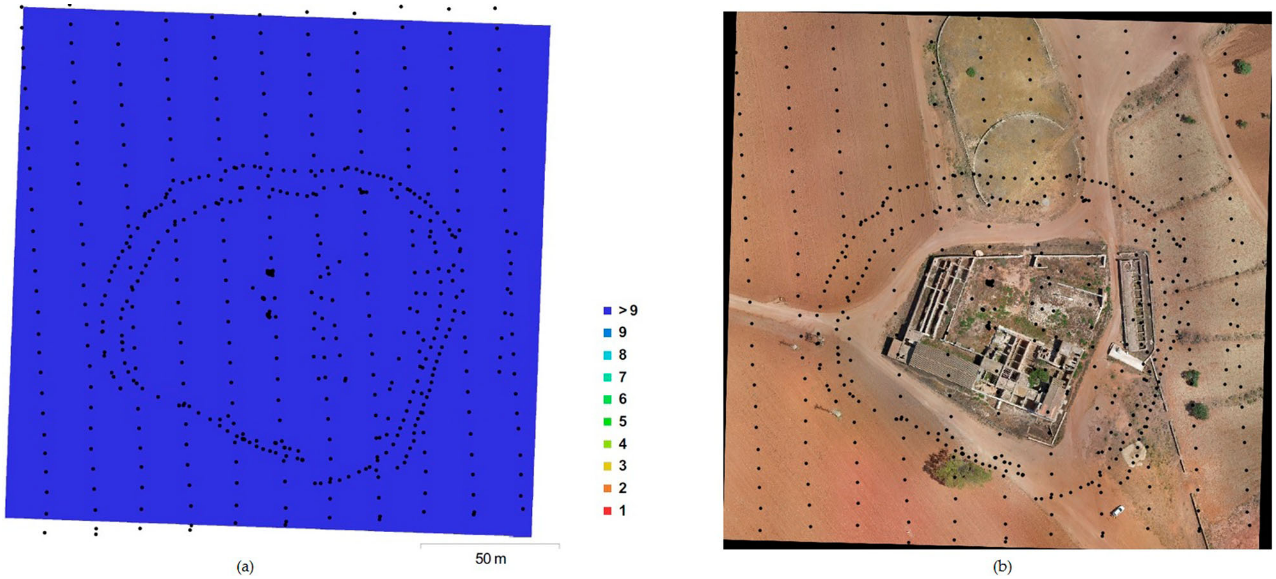


Figure 8. Camera locations and image overlap. Blue colour indicates that the terrain point appears in more than nine photographs.

maintained by BuildingSMART®. The Cloud-to-BIM process continues to import the dense point cloud in *.las format generated by UAV photogrammetry and converting it to Revit format *.rcp or by using Autodesk ReCap®. The information received from the dense cloud is thousands of colorimetric points of information that show the details of the current state of the building, for example, irregularities in a wall, different finishes, and even whether a wall has an inclination. In this way it is possible to visualize the dense point cloud for use as a guide to establish the levels in the section and the axes of the plan (Donato, Biagini, Bertini, & Marsugli, 2017; Chiabrando, Lo Turco, & Rinaudo, 2017; Chiabrando, Lo Turco, & Santagati, 2017; Oreni et al., 2017; Rodríguez-Moreno et al., 2018). It is also possible to import the mesh obtained from Agisoft using the plugin 'Mesh Import from OBJ Files' ('Mesh Import from OBJ Files – Revit App – truevis.com', 2019), which allows you to study the facial properties of every wall and roof. The modelling of all the walls, holes, windows, and doors as well as the roofs starts from the dense point cloud generated by UAV photogrammetry. All of this modelling is based on the historical information gathered in the previous phase as well as in the research work carried out in the field. To carry out this process it is necessary to create a library of parametric objects. Each of these objects is created manually as Revit does not have an automatic geometry recognition option. The most recent scientific literature shows that great efforts are being made to generate 3D geometries in automatic recognition, but this lacks the details that would be valid for application in the heritage area (Dore & Murphy, 2017). As an example, Figure 10 shows the Tuscan portico attached to the inside of the chapel, created from other objects (entablature, capital, shaft and base of Tuscan order) to modify its values and dimensions according to the scale, thus being able to obtain infinite combinations depending on the alphanumeric parameters. This process is applicable to all the historical parametric objects created that make up the model. Figure 10 also shows the objects created to develop the barrel vault inside the chapel. Metadata is entered for each component created. So, for example, if performing a structural calculation is wanted, entering the parameters that define the resistance of the materials used will be required.

In turn, from the point cloud it is possible to obtain a cartographic representation of the digital terrain model (DTM) on which to support the 3D model of the building.

Once the 3D model has been developed, it is necessary to add materials and textures to achieve a photorealistic finish. Revit is not a software designed for rendering, since working with different materials is complex, and external elements such as trees are not very sophisticated. On the other hand, Lumion© is a software based on the rendering engines of videogames that is revolutionizing the current panorama due to the speed with which it allows rendering videos, as well as images, being one of the most used nowadays. It has vegetation libraries, and standard natural environments, which allow giving greater realism to the model and creating images with very high resolution (De Kleijn, De Hond, & Martinez-Rubi, 2016; Meini, Felice, & Petrella, 2018).

The best way to export 3D models from Revit to Lumion is through 'Lumion Plug-in for Revit'. It includes two functionalities: as an exporter for LiveSync, which makes it possible to visualize the model in Lumion in real time, and to export it as a file type Collada (*.dae) of Revit and to load or recharge it constantly in Lumion.

Figure 9. GCPs used for the georeferencing of the photogrammetric project: (a) distribution of GCPs; (b) example of target; (c) GNSS used in this work.

Validation of the HBIM model

Each of the parametric objects created to develop the HBIM model must be validated by measuring the distances between the mesh of the photogrammetric model and the mesh of the created parametric object. In order to do this, the parametric object must be exported from Revit in *.fbx format and the photogrammetric model must be exported from Agisoft in *.obj format. Both files must be imported from CloudCompare (Girardeau-Montaut, 2017), where the 'Cloud to Mesh Distance' command can be used to compute the distance between the parametric object created in Revit and the model created in Agisoft.

In the absence of a criterion adopted by the scientific literature for the validation of a parametric object (Adami, Scala, & Spezzoni, 2017), in this research the criterion has consisted in obtaining an average difference around 0 (between −0.05 and 0.05 m) and a standard deviation of less than 0.10 m.

Results and discussion

Table 1 shows the accuracy obtained in the photogrammetric project. $RMSE_{XY}$ shows the error differences obtained between the X and Y coordinates measured by GNSS and those obtained in the orthophoto, and $RMSE_Z$ shows the error difference obtained between the Z coordinate measured by GNSS and that obtained in the Digital Surface Model (DSM). $RMSE_T$ shows the total error.

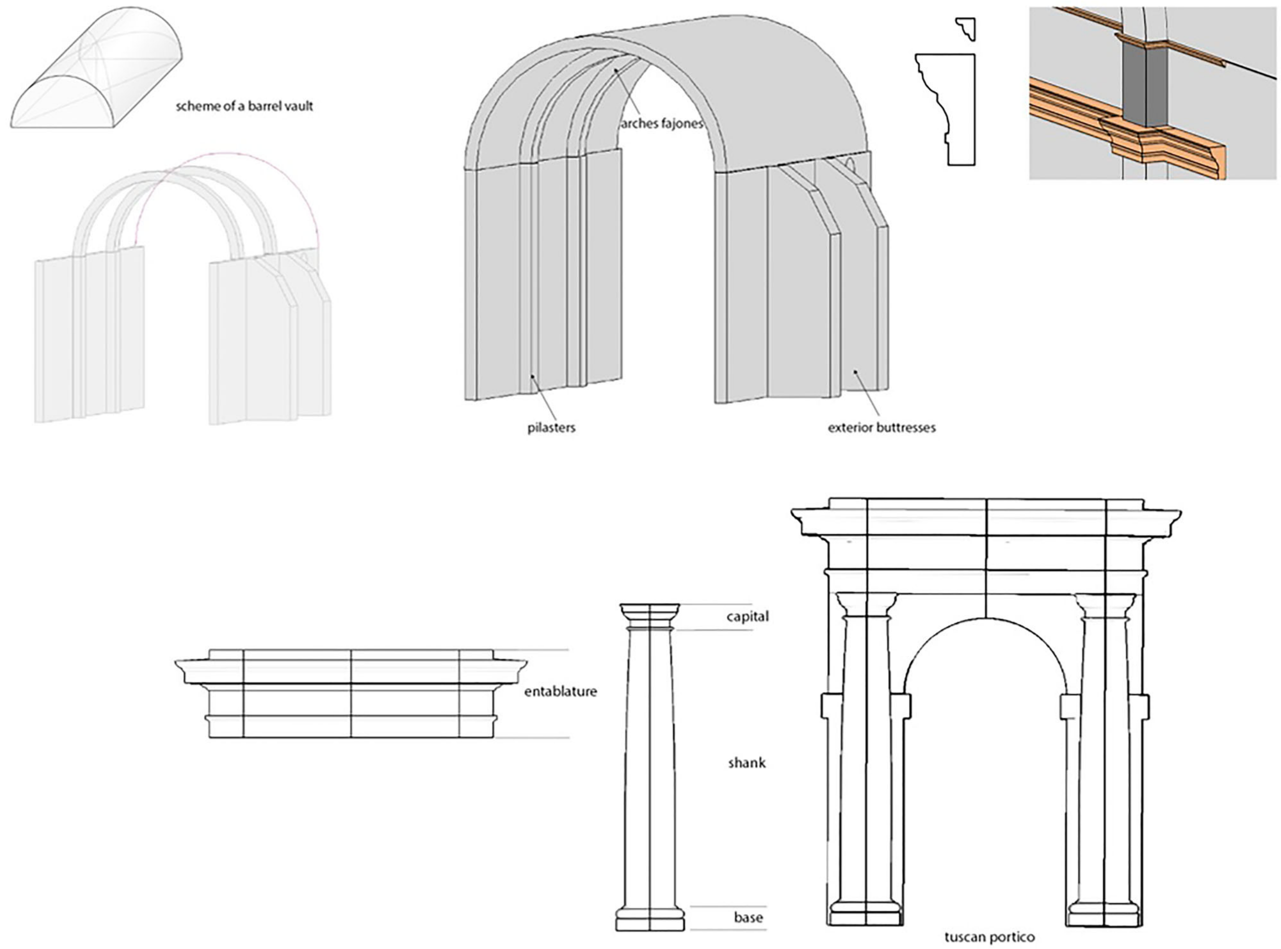


Figure 10. Some examples of parametric objects created to develop the HBIM model.

The results were $RMSE_{XY} = 0.133$ m, $RMSE_Z = 0.086$ m and the total error or vector sum of 0.159 m. Figure 11 shows the point cloud imported into Revit obtained by UAV photogrammetry using Agisoft PhotoScan, where the point cloud had a total of 27,046,199 points. The mesh obtained had a total of 1,801,780 faces and 901,504 vertices.

From this point cloud, the reconstruction of the original state of the building was carried out based on the historical information collected. Figure 12 shows the superimposition of high-precision 3D models based on the dense point cloud and the HBIM model made in Revit, matching its corresponding heights and each vertex of both models. There are

Figure 11. Point cloud imported from Autodesk Revit.

Table 1. Accuracy obtained in the CPs of the photogrammetric project

Label	RMSEXY (m)	RMSEZ (m)	RMSET (m)
P2	0.026	0.040	0.047
P5	0.101	0.158	0.189
P7	0.106	0.028	0.110
P8	0.222	−0.048	0.227
Total	0.133	0.086	0.159

also some details of the rosette of the main façade and the belfry.

Figure 13 shows an example of the validation carried out for the roof of the chapel, where the average differences between the created object and the photogrammetric model are around 0 with a standard deviation of less than 0.05 m. The results are represented by a false colour which describes the differences. Using Revit, plans were generated, including floor plans, elevation, and sections of the building. Different views were also generated in perspective of the built complex. Figure 14 shows some of the renderings obtained with Lumion © of the 3D model of the virtual reconstruction of the Cortijo del Fraile, with the aim of achieving a photorealistic finish and preservation for archival and documentation purposes.

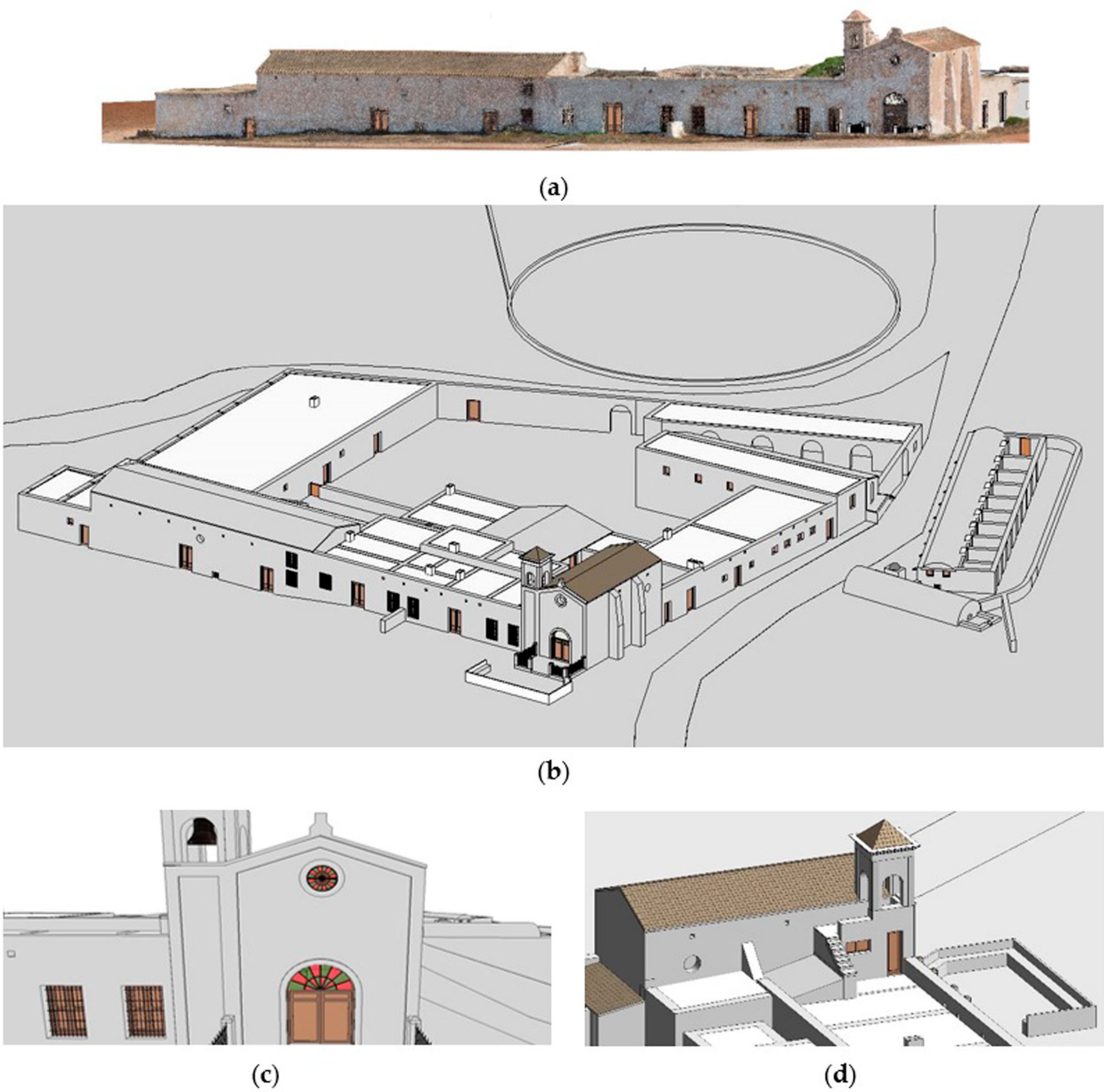


Figure 12. HBIM model of the building made in Revit: (a) detail of the superimposition between the point cloud and the HBIM model; (b) overall perspective; (c) detail of the rosette of the main facade; (d) detail of the bell tower.

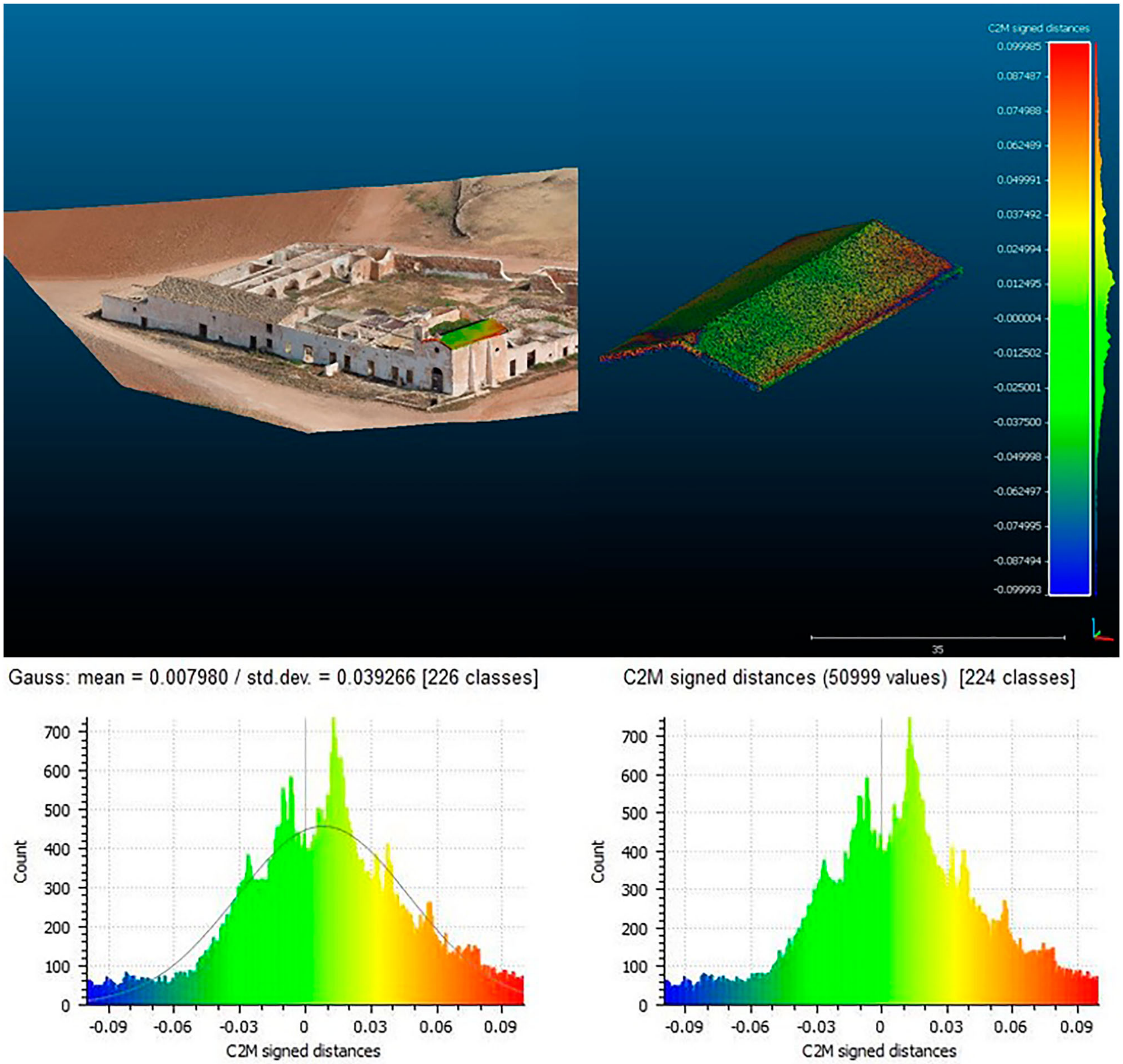


Figure 13. Example of the validation carried out for the roof of the chapel.

Accuracy of the photogrammetric project

The values obtained in the photogrammetric project are in accord with several applications studied by (Clapuyt, Vanacker, & Van Oost, 2016), who compared 10 cases of 3D topographic reconstructions based on the SfM algorithm with similar conditions to those in this archaeological site. In all the cases, the accuracy of measurements was on the order of centimetres. In this research, the total error obtained in the georeferencing of the model is 0.159 m, which is considered more than sufficient for this kind of intervention. Although this reference is not focused on the field of cultural heritage, the other studies consulted in this research do not evaluate the absolute precision of the photogrammetric model or the point cloud obtained by TLS, but are limited to making comparisons between the results obtained by different methods.

Comparison between TLS and UAV photogrammetry

Many authors have conducted studies performing comparisons between point clouds obtained by laser scanner and by UAV photogrammetry. Among them, (Koutsoudis et al., 2014) processed 183 nadiral and 469 terrestrial images using PhotoScan software for modelling the state of a building, in particular an Ottoman monument located in the region of Xanthi (Greece). The objective of that study was to compare the results with those generated by a laser scanner, and an average difference of 1.4 cm was obtained. They concluded that, although there are advantages and disadvantages regarding the use of laser scanners, it is possible to obtain models and high-quality digitalizations from software based on SfM photogrammetry. (Barrile, Bilotta, Lamari, & Meduri, 2015) obtained a point cloud to model a fifteenth to 16th-century masonry castle in southern Italy (Marina di Gioiosa Jonica, Reggio Calabria) called Torre Galea. This point cloud was obtained with different software applications and it was concluded that the point cloud obtained with PhotoScan showed smaller differences (2 cm) than that obtained by laser scanner. In this research it has been impossible to carry out a survey with a TLS, as there is a fence on the perimeter of the building that prevents access to the interior for security reasons.

Regardless of the accuracy obtained by each method (TLS or UAV photogrammetry), both are complementary and, in many cases, the only way to achieve a complete HBIM model, both interior and exterior faces of the building.

Height of the photogrammetric flight and use of oblique and terrestrial images

(Grenzdörffer, Naumann, Niemeyer, & Frank, 2015) carried out a survey of the Cathedral of St Nicholas in the City of Greifswald. For this, they combined the use of laser scanners and nadiral and oblique images obtained by means of UAV. Once the point clouds were obtained, they performed a comparison, obtaining differences between 2.5 and 8.8 cm. They concluded that UAVs are an excellent tool for those places that are not accessible to a laser scanner but that in some cases may require the use of terrestrial photographs for zones adjacent to the ground. In our study, it was not necessary to use terrestrial photographs, due to the use of low-altitude oblique aerial photographs (<15 m) with different pitch angles. This has been possible due to the peculiarities of the building studied, as there are no prominent projections along the façade, and the ability of the UAV to move along all elements of the building. The major limitation found for the use of the UAV in this study has been for the survey of the lower areas of the semi-circular arches. In this case, the only solution would have been to enter the interior of the building.

(Aicardi et al., 2016) carried out a survey of S. Maria's Chapel, which is part of the Novalesa Abbey, a Benedictine monastery in Val Susa (Piedmont, Italy) using oblique aerial photographs at short distance (20 m) and processed the model using software based on SfM, concluding that in all cases high precision point clouds were obtained, in accordance with the results obtained in this study.

(Karachaliou et al., 2019) developed an HBIM model of Averof's Museum of Neohellenic art located in

Figure 14. Renders obtained with Lumion © software.

Metsovo, Greece. In this case the flight was performed in three strips (two nadiral and one oblique), without the use of terrestrial images, as in our study. The main difference between the two pieces of research and ours is that they had the architectural designs of the exterior and interior in order to extract information regarding its dimensions. In our case most of the interior information was captured from the air because most of the rooms had a collapsed roof, and from other historical information sources.

Accuracy of the HBIM model

The 'level of accuracy' of information has to be chosen, related to the type of intervention and as homogenous as possible, in order to obtain a model that is easy to manage and understand (Biagini et al., 2016). For this reason, there are no quantitative records to establish the permitted precision limits. (Adami et al., 2017) makes a comparison between the objects created and the point cloud, but does not set the permissible limits of precision either. In this study, some limits have been used that may be indicative for other studies and which have given good results, as the whole parametric model has been adjusted in a reasonable time. In most of the cases of this study, the differences found are due to surface irregularities and deformations over time.

Conclusions

UAV photogrammetry has been shown to give results that are competitive with those obtained through surveys carried out by TLS. In this sense, both the increase in the number of photographs and the combination of nadiral and oblique photographs significantly improves the quality of the dense points cloud obtained through the photogrammetric process, as well as avoiding the emergence of potential grey areas. This dense point cloud is obtained with centimetre accuracy and is the best possible basis for modelling the existing architecture. It is therefore essential in the case of carrying out virtual reconstructions of buildings in a dilapidated state. During the modelling process, it is very important to adopt a validation procedure that ensures maximum compatibility between the parametric object and the ground truth. In this research, references have been established that can serve as a basis for other authors who carry out similar projects. In addition, in order to successfully complete an HBIM model, it is necessary to complement this technology with a thorough and exhaustive study of existing historical documentation that provides information on the original geometry and architecture. This method represents a viable option in those cases in which access is restricted for security reasons, or where TLS does not have a direct line of sight, since it allows to obtain precisions on the order of centimetres with a very high efficiency in cost and time. However, UAVs also have limitations such as problems accessing the interiors of buildings, so as long as there is no progress in that field, this methodology is especially limited to exterior HBIM.

This study has shown that it is possible to use a method based exclusively on images obtained from UAV in order to obtain a reconstructed model that allows visualization as well as the archiving and registration of documentation with a view to carrying out future restoration projects.

Disclosure statement

No potential conflict of interest was reported by the authors.

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