3D MODEL OF LUGO'S ROMAN WALLS (GALICIA-SPAIN) USING A TERRESTRIAL LASER SCANNER AND UNMANNED AERIAL VEHICLE.

ABSTRACT

Nowadays, there is a growing interest in the application and development of new digital spatial technologies for 3D data capture, analysis and visualisation and the subsequent documentation, investigation and conservation of cultural heritage.

We carried out a survey of the wall's boundary including both internal and external stone facings as well as the parapet. We used mainly modern technologies, such as TLS (Terrestrial Laser Scanner) and UAV (Unmanned Aerial Vehicle). But we didn't neglect other technologies such as classical surveying and GPS, always necessary for providing support for data capture and close range photogrammetry for getting a real virtual model.

The result was the 3D model of the Roman Walls, plus a series of products, like sections and orthophotos, which can be used to provide precise measurements for studying the geometry of the walls and analysing its structural problems, especially in those areas that have suffered a greater degree of degradation.

Keywords: *Geometric documentation, Terrestrial Laser Scanners (TLS), Unmanned Aerial Vehicle (UAV), Roman Walls.*

1. INTRODUCTION

Tangible cultural heritage documentation can be approached from various angles because of its diversity. Yet, all of them agree on the need for geometric documentation as the basis for the knowledge, conservation, restoration or simply dissemination of the monumental remains of past cultures.

The geometric documentation of the elements of cultural heritage, either archaeological sites or historical buildings, refers to both the shape and the size of the elements and their spatial arrangement from a local and global perspective. Geometric documentation can be 2D or 3D and ranges from maps at different scales, orthophotos, floor plans, elevations and sections, to perspectives, 3D models or virtual reconstructions.

Today, the different phases of the geometric documentation process, i.e. data capture, processing and output, are undergoing a vertiginous process of change. In recent years, computers and technology have remarkably evolved and have provided geometric documentation with a variety of means that have brought about new procedures and methods. Such procedures and methods tend to improve data capture systems and process automation, thus increasing productivity and improving the quality of results.

From the point of view of data capture, various techniques are used. Currently, traditional techniques, such as topography, GPS and conventional terrestrial and aerial photogrammetry, coexist with more modern techniques, such as laser scanners, both terrestrial (TLS) and aerial(LIDAR),or the most recent Unmanned Aerial Vehicle (UAV) photogrammetry.

Deciding on the most suitable technique for a given project will depend on the aims and the available resources. However, there seems to be no single answer. In our opinion, the solution is not excluding but combining and integrating different techniques, particularly in cultural heritage applications, in which combining the best geometry of some techniques and the best radiometry of other techniques seems an interesting line of action.

The research presented in this paper integrated UAVs and TLS technologies without neglecting other more traditional techniques such as GPS or digital terrestrial photogrammetry for the complete topographical survey of the Roman walls of Lugo with high definition in some representative zones, such as the Miñá gate. The result was a3D model of the Roman Walls, plus a series of products, such as plans and orthophotos, which can be used to provide extremely precise measurements for the study of the geometry of the walls and the analysis of their structural problems and distortions, particularly in areas that have suffered a greater degree of degradation.

2. BACKGROUND

2.1. Terrestrial Laser Scanner (TLS)

In 1917, Albert Einstein acknowledged the existence of stimulated emission and laid the theoretical foundations for the laser but, due to the technical limitations of the time, it was not until the 1950s when ways were found to use laser devices. In 1960, Theodore H. Maiman made the first laser operate at the Hughes Research Laboratory in California.

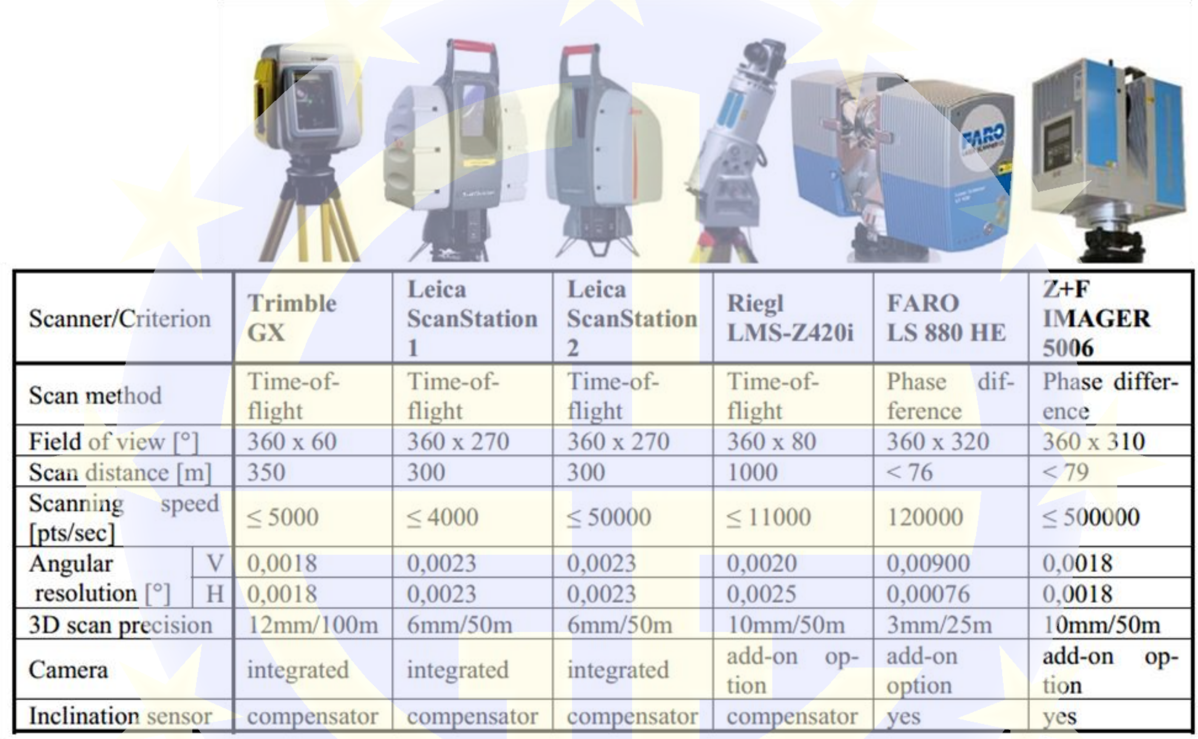
A laser is a device that emits light (electromagnetic radiation) through a process of optical amplification based on the stimulated emission of photons. The emitted laser light is notable for its high degree of spatial and temporal coherence, unattainable using other technologies. The term laser is an acronym for Light Amplification by Stimulated Emission of Radiation.

A 3D laser scanner is a device that projects a structured laser line over the surface of an object in order to collect 3D data. The large amount of points captured by a 3D scanner is also termed “point cloud” and consists of a collection of XYZ coordinates in a common coordinate system that portrays the spatial distribution of the surface of the scanned subject. It may also include additional information, such as an intensity or RGB value.

Early in the 21st century, 3D laser scanning revolutionized the automated capture of large point clouds of an object’s surface in a systematic pattern at a high rate (hundreds or thousands of points per second), achieving the results (i.e. 3D coordinates) in (near) real time and with associated intensity or colour values (Böhler, 2006).

Laser scanners (used from the ground, Terrestrial Laser Scanners (TLS), or from the air, Airborne Laser Scanners (ALS), frequently referred to as lidar) are active sensors that operate on one of three ranging principles: time of flight, phase difference or triangulation. TLS using time of flight or phase comparison are more suited to topographical surveys of medium to large elements (ranging from a few meters to kilometres), whereas triangulation systems are ideal for recording small to medium objects, small architectural features such as detailed carvings or precious or delicate cultural heritage artefacts, insofar as the distance range is less than a few meters.

Table 1 Provides a short summary of some midrange TLS available in the market and their characteristics, including typical system accuracy and typical operating ranges. The model used in this project is framed in red (www.trimble.com).



Scanner/Criterion	Trimble GX	Leica ScanStation 1	Leica ScanStation 2	Riegl LMS-Z420i	FARO LS 880 HE	Z+F IMAGER 5006
Scan method	Time-of-flight	Time-of-flight	Time-of-flight	Time-of-flight	Phase difference	Phase difference
Field of view [°]	360 x 60	360 x 270	360 x 270	360 x 80	360 x 320	360 x 310
Scan distance [m]	350	300	300	1000	< 76	< 79
Scanning speed [pts/sec]	≤ 5000	≤ 4000	≤ 50000	≤ 11000	120000	≤ 500000
Angular resolution [°] V	0,0018	0,0023	0,0023	0,0020	0,00900	0,0018
H	0,0018	0,0023	0,0023	0,0025	0,00076	0,0018
3D scan precision	12mm/100m	6mm/50m	6mm/50m	10mm/50m	3mm/25m	10mm/50m
Camera	integrated	integrated	integrated	add-on option	add-on option	add-on option
Inclination sensor	compensator	compensator	compensator	compensator	yes	yes

Time of flight, the technique used in this research, is based on the principle that a laser pulse is sent to the object and the distance between transmitter and reflecting surface is computed from the travel time between signal transmission and reception (Boehler, W, Marbs, A., 2002). Because the speed of light is well known and the time elapsed between the emission and reception of the pulse can be measured, it is possible to calculate the distance by the equation (Lichti and Harvey, 2002):

$$\boxed{D = \frac{1}{2} \cdot c \cdot \Delta t}$$

where:

D = sensor-to-object distance

c = speed of light in vacuum ($3 \cdot 10^8$ m/s).

Δt = time the signal took to return to the scanner.

In most systems, highly precise mirror systems control the horizontal and vertical angles of the beam, causing the pulse to move across the surface in a regular manner. The distance range is combined with angle encoder measurements to provide the three-dimensional location of a point. Each system then produces a data set that consists of multiple XYZI values (where “I” represents the scanner intensity value).

Today, TLS is a fairly mature technique with multiple applications related to cultural heritage, mapping, civil engineering (structural control and inventory), industry, environmental studies, forestry and geology, medicine (prosthetic design and dental surgery), criminology (accident reconstruction and interior scenes) and tourism (virtual tours).Yet, research in this technology is still open, but in process of consolidation and exploitation.

During the last few years, TLS has been a great field of research and advances in measurement and representation techniques for the geometric documentation of heritage. Actually, there is an extensive literature on a variety of heritage structures and elements, from small pieces and findings to large monumental, isolated buildings and archaeological sites, both at the national (Biosca, et al., 2007; Buil, y Núñez, 2008; Mañana, et al., 2009; Baceiredo y Baceiredo, 2010; Lerma et al., 2010) and international(Frank, 2003; Peripimeno, 2005; Arayici, 2007; Lambers et al., 2007; Entwisle, McCaffrey y Abrahams, 2009)level. This does not mean that this is the only optimal technology, but it must be taken into account, mainly if there are no automated photogrammetric procedures from multiple images available (Petti et al., 2008).

Besides being a non-invasive, light-independent technique that captures data fast and can be used to digitize any element or terrain, TLS has the advantage of providing immediate measurements with great precision (even millimetres), which allows for immediate digital reconstruction and 3D modelling from point clouds. Moreover, it is an excellent sensor for documentation of irregular surfaces or complex geometries such as altarpieces, arches, sculptures or archaeological sites and buildings with great ornamentation (sculpture, columns, pilasters, medallions). In contrast, lidar is used only in large topographical surveys or virtual modelling of groups of buildings or cities.

However, despite their advantages, laser scanning sensors have also some drawbacks, e.g. the technology is still expensive, it does not allow for the selection of a specific point, and random point selection often generates imprecision, especially in the exact representation of object edges. In addition, although most TLS incorporate image sensors that provide radiometric information, the resolution of radiometric information is low. Some post-processing operations such as point cloud clearing are time-consuming and laborious. On the other hand, the development of methods and tools for the automatic acquisition and efficient extraction of the geometry of different elements in order to obtain a final product suitable for heritage documentation, remains an open line of research.

Therefore, laser scanning is not a comprehensive and definitive solution for 3D modelling, at least in applications related to different modes of architectural and archaeological heritage (Boehler 2004, Guarnieri 2003, Demir Remondino 2004 and 2004, González Aguilera, D. 2007) in which modelling requirements and complexity significantly increase from the point of view of geometry as shape (González Aguilera, D. 2007).

2.2. Unmanned Aerial Vehicle (UAV)

An Unmanned Aerial Vehicle (UAV) is an aircraft without a human pilot onboard. The flight is either controlled autonomously by computers in the vehicle, or under remote control on the ground or in another vehicle.

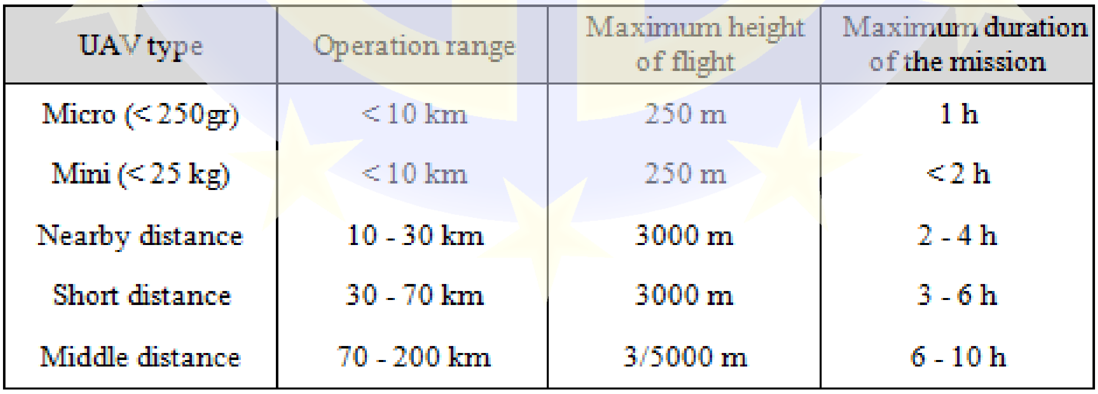
The development of UAVs has been strongly motivated by military applications. The United States Air Force (USAF) started investigating the use of UAVs in the early 1960s, but civilian research did not begin until the early 1990s. With a growing number of civil applications, because of their potential for remote data acquisition in dangerous environments and/or inaccessible zones, rapid and low cost, UAVs are gaining more and more attention, both for scientific and commercial civilian purposes. Agriculture, environment, engineering and civil protection, among other areas, have successfully adopted this technology for many of their tasks.

From the perspective of spatial data capture, UAVs equipped with a digital camera have revolutionized the world of photogrammetry. UAV photogrammetry can be understood as a new photogrammetric measurement tool (Eisenbeiss, 2009), a low-cost alternative to traditional aerial photogrammetry systems on manned aircrafts that can reduce both the cost and time of conventional flights. In addition, UAVs fly at low altitude thereby increasing the resolution of the captured images and opening up new applications in the domain of short distance and the combination of aerial and terrestrial photogrammetry.

An UAV system for photogrammetry consists of an aerial based platform (helicopter and airplane, principally) equipped with imaging cameras, including video cameras, thermal or infrared camera systems, multispectral cameras, range cameras sensors and airborne lidar sensors, or a combination thereof depending on the payload of the UAV. Furthermore, for the determination of the trajectory, UAVs feature by default an integrated GNSS/INS system (global navigation satellite system/ inertial navigation system), barometric altimeter and compass systems (Eisenbeiss, 2009).

There are a wide variety of UAV systems with different shapes, sizes, configurations and characteristics. Table 2 provides a classification of UAVs, focused on mini UAV systems insofar as they are the leading contributors in our field of interest.

Table 2 Provides an UAV classification (Eisenbeiss, 2004)



UAV type	Operation range	Maximum height of flight	Maximum duration of the mission
Micro (< 250gr)	< 10 km	250 m	1 h
Mini (< 25 kg)	< 10 km	250 m	< 2 h
Nearby distance	10 - 30 km	3000 m	2 - 4 h
Short distance	30 - 70 km	3000 m	3 - 6 h
Middle distance	70 - 200 km	3/5000 m	6 - 10 h

Only a few authors have been concerned with UAV systems used for the acquisition of aerial photographsin cultural heritage because this is a very recent technology. Yet, there is growing interest towards this technology because of the aforementioned advantages. UAV photogrammetry has been used to data capture in the archaeological site of Pinchango Alto, Peru (Eisenbeiss, et al., 2005); Copán, Honduras (Eisenbeiss, et al., 2010); Vergina-Aegeae, Greece (Patias, et al., 2007); Drapham Dzong, Bhutan (Gruen, et al, 2009); and Pava and Veio, Italy (Sarazzi and Taufer, 2008; Chiabrando et al., 2011), with satisfactory results that offer a promising future for the use of these systems.

3. THE STUDY SITE: THE ROMAN WALLS OF LUGO

The city of Lugo, Galicia, Spain, is built on the remains of the old *Lucus Augusti*, surrounded by Roman walls (Fig. 1). The walls were built in the later part of the 3rd century by the architect Vitruvius, and are located in the historical city centre. The Roman walls of Lugo are among the best-preserved walls in the world and are the only ones of their kind with completely intact walls. The entire length of the walls is about 2 km, enclosing an area of 34 ha. In 2000, the walls were inscribed on UNESCO's World Heritage List as "the finest example of late Roman fortifications in western Europe", and have also held the status of Spanish monument since 1921.

Figure 1: Location of the city of Lugo, Galicia, Spain.

Figure 2: Gates of the Roman Walls of Lugo.

The Roman Walls of Lugo consist of 70 towers, spaced at regular intervals around the walls, and 10 gates (Fig. 2), five of which are ancient and date from Roman times and five are recent and were built after 1853.

There are five stairways and a ramp that give access to the parapet walk, and a number of double staircases within the thickness of the walls that give access to the towers from the parapet (Fig. 3).

Figure 3: Miñá gate (left), Mosquera tower (centre) and the parapet (right).

4. MATERIALS AND METHODS

In our research, we carried out a survey of the walls’boundary including the internal and external stone facings and the parapet. We used two different technologies for data capture (Fig.4), a TLS and a UAV system. Yet, we needed other technologies such as GPS, which is necessary to provide support for data capture and to georreference our data in a global coordinate system.

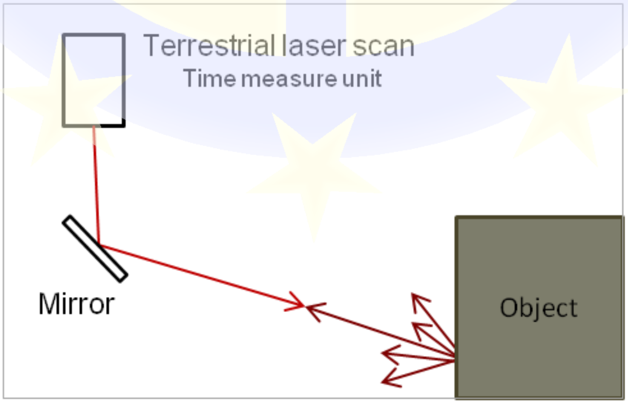


Figure 4: UAV, TLS and GPS collecting data.

Thus, the methodology can be divided into four fundamentals phases: establishment of a micro-geodetic network around the walls; TLS data collection and processing; UAV image acquisition and processing, which include the phases of planning, capture and processing; and, finally, combination of TLS-UAV data and generation of the results.

4.1. Micro-geodetic network around the walls

The shape and size of the wall (around 2 km) required the use of multiple TLS stations and several working days. In addition, in certain areas, future actions have been planned that require the use of conventional surveying techniques. To guide and carry out the work, and to be able to link directly the data for future actions, we need a micro-geodetic network around the wall and a series of fixed stations secured by Allen screws, where any type of topographic instrument or targets can be fastened (Fig. 5).

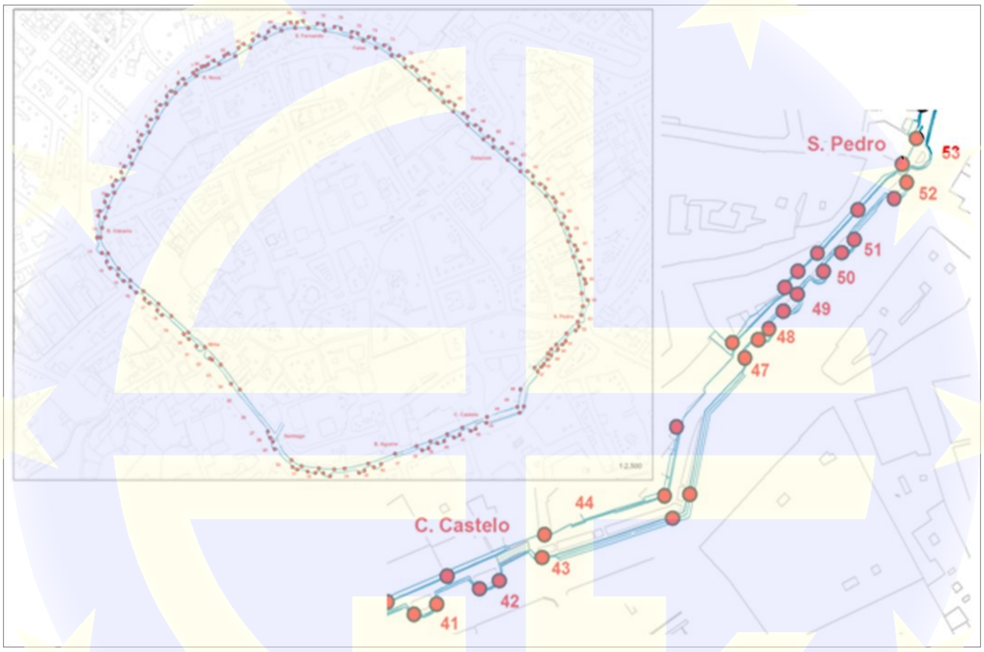


Figure 5: Sketch of fixed stations around the wall.

Because a geodetic link was required to provide network stations with absolute coordinates, a reference station was placed on top of the SIT Building (Spatial Information System at the University of Santiago de Compostela), and its readings were taken from three REGENTE (*REd GEodésica Nacional por Técnicas Espaciales*) geodetic points by GPS techniques, using the method of static positioning. To give coordinates to the station, the coordinates were measured using GPS techniques, particularly the Real Time Kinematic (RTK) method. In this work, we used Trimble5800 GPS receivers.

4.2. TLS data collection and processing

In the planning phase, we studied the optimal location for the laser scanner in terms of data collection, considering the characteristics of the equipment, such as sensor-to-object distance or occlusions, and the difficulties of the area, among which flow of cars, vegetation and presence of a large number of people, at particular times of the day, insofar as the walls are a leisure area and the commercial and cultural centre of the city. The planning phase is essential to ensure a complete survey of all elements.

For point cloud collection, the Trimble GX Advanced 3D laser scanning system (www.trimble.es) was used. The scanner features for the field of view are 360° in the horizontal direction and 60° in the vertical, both 38° up the horizontal and 22° down the horizontal, which is an important factor that can limit fieldwork. To ensure the required quality, the fast-mode scanning method was used by setting mesh resolution at 2x2 cm. The longest range scan mode was used in specific areas where there were details or elements of interest, or where further actions were planned, as in the Miñá gate, where a study of deformation was carried out. The mesh resolution defined for the longest range scan mode was 1x1 cm.

The placements of the scanner were connected to ensure proper orientation between the different point clouds. In this case, a series of Trimble-brand targets were used.

To improve the quality of the images, we captured digital images with a Canon EOS 400D camera with 10.1 megapixels and a focal fixed at 18 mm, in specific areas with details of interest because the camera of the scanner did not provide the desired quality for this work. The photos were taken using terrestrial photogrammetric processing.

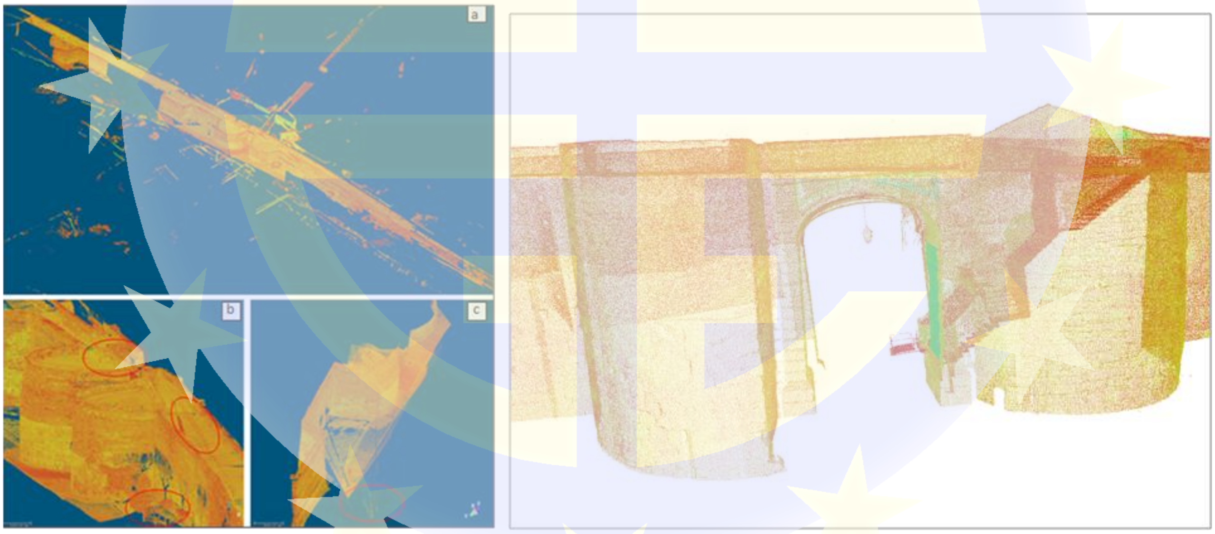


Figure 6: Left: point cloud before being processed and filtered for the generation of the meshes. Right: point cloud of the wall without "noise" and original point cloud.

The first procedure in the processing of scanned data processing consisted of registration and georeferencing operations. This was accomplished by matching common targets. The next step was data filtering and cleaning in order to eliminate the noise from the image (Fig. 6), alignment of partial scans, and hole-filling. Then a mesh of triangles was created by using the 3D mesh method to transform the point clouds into a triangular mesh. We generated multiple meshes of the different parts of the wall because a single mesh was unmanageable for a PC (Fig. 7).

The last procedure in this phase was texture map processing in some areas. The photographs must have been previously processed with digital image treatment software, PhotoShop CS4 in this case, to balance the hue, brightness and contrast of the images. To georeference the images, homologous points between the images and the point cloud were used. Finally, the process automatically allocated texture. To achieve that, the images were combined with the mesh of triangles, which produced the real 3D model of some areas of the wall, as a series of products for specific studies and analyses of the wall (Fig. 8).

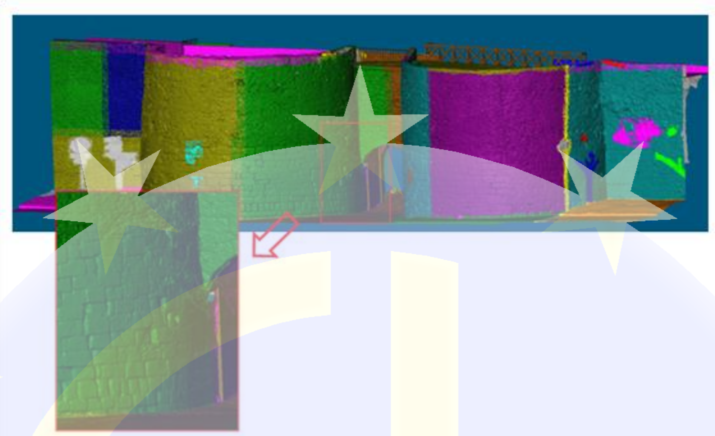


Figure 7: Mesh of triangles for the Miñá gate, with details of the accuracy of the masonry of one of the towers.

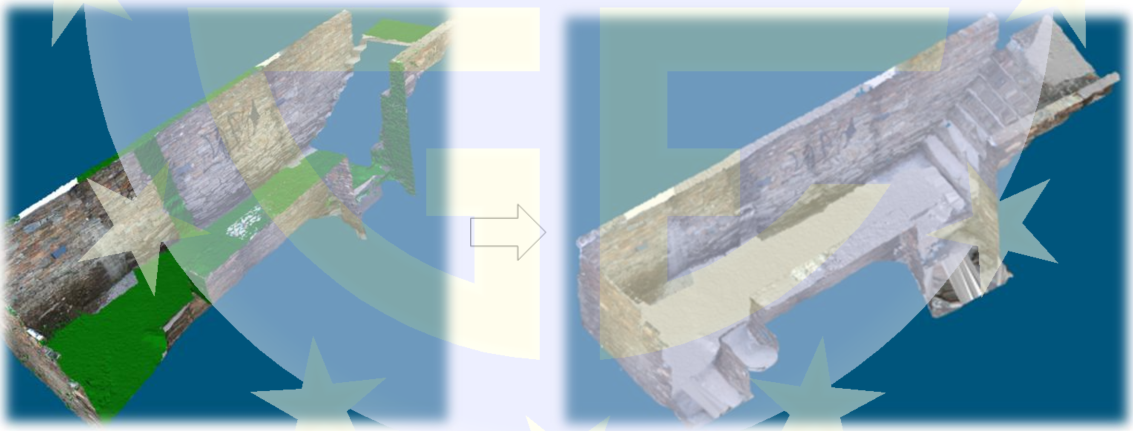


Figure 8: Texturing of the triangular mesh in one of the early stairs on the parapet of the wall.

4.3. UAV image acquisition and processing

The parapet images were obtained with a Microdrone GmbH MD4-200 UAV (Fig. 9) because of the difficulty of obtaining them with other systems such as helium balloons or complex systems of poles. The camera of the system was a Pentax Optio A40. The drone was a helicopter with four propellers that contributed to a very stable aerial vehicle. Since the drone was fully equipped with sensors such as GPS and INS, it could fly, take-off and land autonomously.

Figure 9: Microdrone GmbH MD4-200

Before take-off, a flight plan must be developed by defining the area that must be flown over on a map, based on Google Earth. The microdrone software automatically generated the flight plan based on a number of parameters, among which altitude, overlap or camera. Image acquisition was performed according to the fight plan.

In this case, we flew only over small areas of the wall to improve the 3D models of some areas of interest and to assess the possibility of flying around the entire wall, which would require special permits in order to close the walls during image capture (Fig. 10).

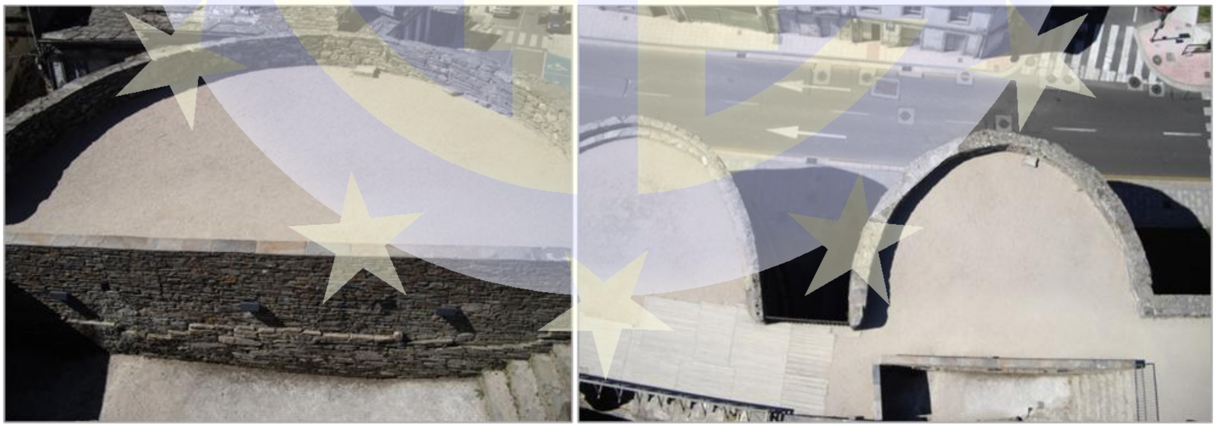


Figure 10: images of the parapet of the walls at the Miñá gate from the UAV camera.

The next step was image processing. We considered two options: processing images using the conventional photogrammetric method with non-metric cameras, which involve camera calibration, image pre-processing, aerial triangulation, digital terrain model (DTM) extraction and orthophoto production, or performing a simple image rectification by using a DTM from the TLS process to get the orthophoto. Our first goal was to get the textured model of the parapet and generate the orthophoto from this model as a derivate product. Accordingly, we chose the second option, such that we only had to pre-process the images to do the radiometric adjustment for the improvement of image quality and, finally, establish the correspondence between the image points and the model points in order to obtain the rectified images from the UAV and the textured model.

5. RESULTS

The digital 3D model of the point cloud and the meshed surface of the Roman walls of Lugo are the first results of this work. Both outputs have been obtained directly from the TLS. The raw and recorded coloured point clouds generate a complete, comprehensive and continuous model, suitable for use in various applications. Overall, the estimated accuracy of 3D point coordinates is less than 2 cm (Fig. 11).

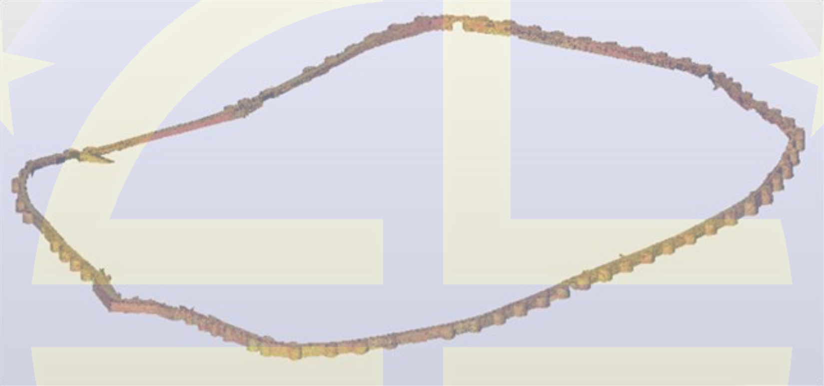


Figure 11: Meshed point cloud showing a portion of the Roman walls of Lugo

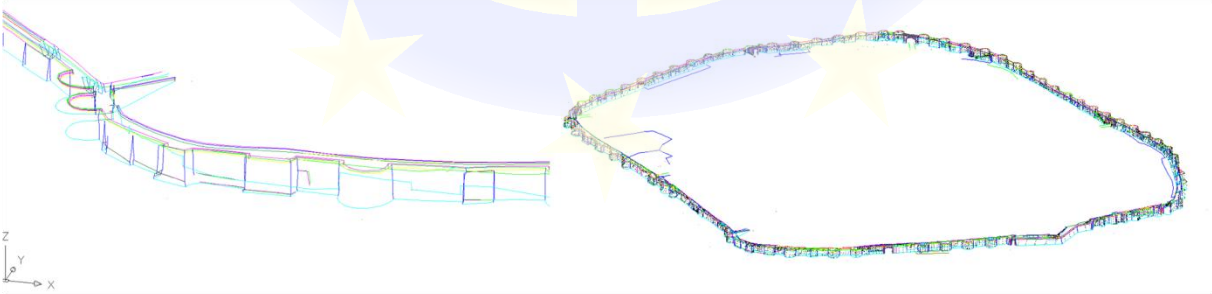


Figure 12: Vector 3D model of the Roman walls of Lugo

Line drawings are generated from the mesh of points by using the point cloud as the basis from which geometric features are traced, thus creating a vector model (Fig. 12) and a number of plans, sections and elevations at 1:50 scale (Fig. 13- right).

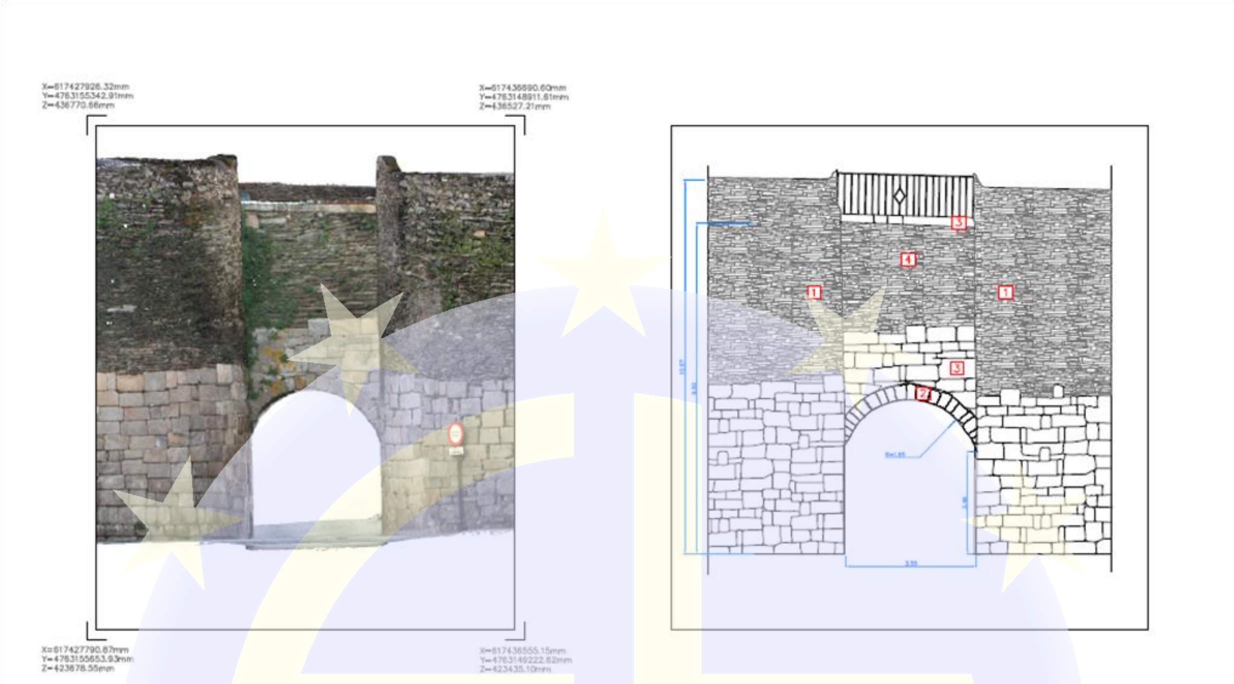


Figure 13: Orthophoto (left) and line drawing (right) of the Miñá gate .

Another output is the textured surface model of some areas of interest, which has been obtained by combining TLS data and terrestrial and UAV images (Fig. 14). Based on the textured model, a complete set of orthophotographs has been generated at sufficient resolution to satisfy the requirements of many analyses (Fig. 13- left).

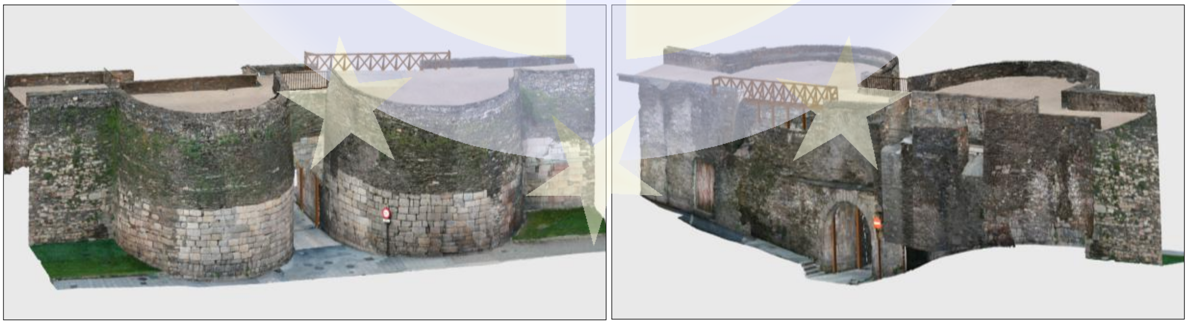


Figure 14: Perspective textured 3D model of Miña gate.

6. CONCLUSIONS

This paper describes the potential of the combination of terrestrial laser scanning and UAV photogrammetry for the documentation of one of the most important monuments in the Spanish cultural heritage, the Roman Walls of Lugo. The integration of these two technologies provides massive and complete information for its record, analysis and visualization.

Nowadays, there is high demand for documentation of cultural heritage objects such as artefacts, sculptures or buildings. Terrestrial laser scanners are meaningful systems for deriving geometrical information, and UAV photogrammetry is a relatively new technology that has steadily emerged strongly in cultural heritage. The lack of contact, the high accuracy and resolution of the 3D models obtained by combining these techniques and their ability to readily obtain measurements in inaccessible areas are some of their advantages. Despite the speed and accuracy of 3D measurements, data processing after capture is rather time-consuming and requires technical knowledge. Because both systems still require the support of other techniques such as GPS or conventional topography, none of them appears to be an integral solution.

According to the results obtained in this project, we argue for the synergy of both technologies, which allows for the use of the strengths inherent to both systems given the complexity of some heritage objects and the lack of a simple method that can provide a satisfactory solution under any measurement conditions. Assuming that the results of integration must be equal to or better than the results of the lack of integration, futures research lines must focus on the improvement of the systems and tools used to manipulate and display the data obtained from the integration of both techniques.

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MAP SIGNALING THE GATES IN THE WALL OF LUGO (GALICIA, SPAIN)

Door list (www.openstreetmap.org)

1. Puerta de San Fernando (Gate of San Fernando)
   Opened in 1853 on the former Gate of Boquete and enlarged in 1962.
2. Puerta Falsa (False Gate)
   Of Roman origin.
3. Puerta de la Estación (Station Gate)
   Opened in 1874 and enlarged in 1918.
4. Puerta de San Pedro (Gate of San Pedro)
   Also called "Puerta Toledana". From Roman times, although modified in 1781.
5. Puerta del Obispo Izquierdo (Gate of bishop Izquierdo)
   Also called the "Prison Gate". Opened in 1888.
6. Aguirre Bishop's Gate (Gate of bishop Aguirre)
   Opened in 1894.
7. Puerta de Santiago (Gate of Santiago)
   Also called "Porta do Puxigo." Rebuilt in the eighteenth century. Above the arch there is a equestrian statue of Santiago, Baroque.
8. Porta Miñá
   Also called "Puerta del Carmen". It is the best preserved from Roman times.
9. Puerta del Obispo Odoario (Gate of bishop Odoario)
   Opened in 1921. Completed in 1928.
10. Puerta Nueva (New Gate)
    Already existed in Roman times. Modified in the Middle Ages and again in 1900.