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Application of Non-Destructive Techniques to the Recording and Modelling of Palaeolithic Rock Art

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1. Introduction

1.1 Motivation

According to Spanish legislation and international organisations such as UNESCO, the Council of Europe and the European Union, historical and artistic heritages should be preserved and placed in the service of society for either cultural, scientific or educational purposes. Thus, it is necessary to document and invest in their preservation, restoration, rehabilitation and/or archival for subsequent scientific studies (Elwazani, 2003), in addition to documenting their dissemination and social value. Archaeological remains are part of peoples' historical artistic heritage and represent a testimony of their past. The attitude and sensibility towards this cultural inheritance say much about our future as a society.
The documentation of general heritage and particularly archaeological heritage properties is indispensable before performing any type of measure or intervention. Such documentation implies recording, storing, cataloguing and measuring the elements that compose the heritage property. With regards to archaeological heritage, these tasks are developed both with elements that comprise movable heritage (for example, bone and lithic industries) and with elements that comprise non-movable heritage (for example, buildings, fields and caves). The geometric component of archaeological documentation begins with measurement and has the objective of a graphical representation, using multiple strategies and support. The act of measuring implies a quantification of the spatial characteristics of an object, especially its shape, dimensions, orientation and location, both in its immediate environment and in relation to the global geographic context.
In the geographic documentation of heritage, the measurement and graphical representation are indivisible tasks. Particularly, the traditional procedures of documentation and graphical representation are based on employing equipment that has a low cost and is easy to use. Despite the effectiveness of these procedures, they exhibit a series of inconveniences, such as the large amount of time required to acquire data, the limit of work within a two-dimensional scope, the loss of information during data transfer and the need to physically

access the structure. Primarily, it is difficult to obtain reliable geometric data on irregular structures, as is the case for archaeological remains, which means that the precision obtained from this application is relatively low (Fossati et al., 1990). In recent years, due to the spectacular development of geomatic techniques and the evolution of the content and structure demanded in the documentation of heritage (Cannataci et al., 2003), a considerable increase has been noted in the use of techniques such as close-range photogrammetry and laser scanning, which provide reliable graphical and metric information on objects. These techniques allow digital archives to be obtained in various representation formats: 3D models in CAD format, 3D visualisations, conventional planes in 2D, orthoimages, reconstructions and virtual animations. However, despite the advances, the generation and visualisation of 3D models in archaeology are not as in demand as would be expected, due to various factors including (a) the high cost of 3D, (b) the difficulties for non-experts to easily obtain quality 3D models, (c) the belief that 3D is mainly an additional aesthetic factor and (d) the difficulty of integrating 3D "worlds" with other classic 2D archaeological data.

The metric documentation of heritage is an excellent opportunity that allows us to integrate technology, history, development and innovation so that various experts in this field have the possibility of applying precise, non-destructive tools for the documentation, modelling and analysis of traces of Palaeolithic art. In addition, and just as important, the possibility of virtual recreation combined with the variable of time will allow for preservation of places with massive visits, present hypothesis and recreation of the site's evolution, without forgetting the possibility that handicapped will be able to enjoy and appreciate this type of places without difficulty in access.

The **objectives** of this study revolve around three general lines of investigation:

1. Three-dimensional digitisation of Palaeolithic art corresponding to two caves in the eastern part of Asturias by means of advanced data collection systems that are non-destructive, non-invasive and automated.
2. The development of information processing strategies that will provide three-dimensional reconstruction and the acquisition of cartographic products that correspond to the Palaeolithic art of two subterranean caverns in the eastern part of Asturias.
3. The implementation of a Spatial Information System that permits the management and diffusion of the Palaeolithic art found in caves.

1.2 State of art

In this subsection a brief state of art about non-destructive techniques applied to rock art recording and modelling is presented. Furthermore, this subsection has been developed following a twofold level: the sensor level, in which a description of the main sensors applied to rock art recording is provided; and the processing level in which the main algorithms and strategies for rock art modelling are described.

- *Methods and Surveying Equipment*. Classic surveying methods based on measuring angles, distances and variations in height have been used in various studies on caves and subterranean cavities (Lopetegui et al., 2004). The equipment used for these purposes ranges from expeditious teams consisting of runners with tape measures, who measure short distances directly without much precision, followed by the classic theodolites, which permit the measuring of points based on indirect methods such as simple or multiple intersections (Ghilani and Wolf, 2006) supported by stadimetric systems; there are also modern complete stations to directly and simultaneously measure angles and distances without the need for reflective elements, considerably reducing field work. Currently, the use of popular GPS positioning systems has been added to these surveying methods to include the positioning and global georeferencing of the caves in the mapping of the area.

- *Methods and Photogrammetric Equipment*. From close-range photogrammetric methods, it is possible to derive measures of the images and to generate scale three-dimensional reconstructions. In addition, the images previously corrected for perspective and distortion can serve as an information source, providing realism to the reconstructed 3D models. In this sense, close-range photogrammetry entails an adequate system for measurement when dealing with the reconstruction of simple objects with a high degree of precision and a low cost (Chandler and Fryer, 2005). Thus, professionals in photogrammetry have developed different approaches to metrically document prehistoric art, from the more classic photogrammetric techniques based on the use of stereoscopic vision (Rivett, 1979), to three-dimensional modelling based on multiple convergent images (Ogleby, 1999). However, even though photogrammetric methods represent a universal, low-cost alternative, their application in subterranean scenarios such as caves and subterranean caverns is less common, as the conditions of accessibility and visibility are very restrictive and the geometries represent large complexities with alternating concave and convex shapes. Certainly, the successful application of photogrammetric systems in caves and subterranean caverns will demand time, skill and advanced knowledge on the part of archaeologists and pre-historians.
- *Methods and Laser Equipment*. Currently, terrestrial laser scanners constitute the latest breakthrough in the field of measurement, allowing massive amounts of information to be captured on the shape of objects by means of the measurement of angles and distances. They do not require operator intervention for visual determination and obtain thousands of points per second. There are variants of these instruments according to their measuring principle and range: long-reach laser scanners have ranges that vary from two to three metres, as a minimum distance, to a maximum distance of one kilometre, providing clouds of points with a precision similar to that of a total surveying station, thereby decreasing the measurements and increasing the distance between the object and the laser scanner; medium-range laser scanners vary from one to two metres, as a minimum distance, to a maximum distance of 350 metres, which is ideal for applications related to both the exterior and interior of immovable heritage sites (Robson-Brown et al., 2001; Cavers et al., 2008); short-range laser scanners are used for recording movable elements (Donelan, 2002; Trinks et al., 2005) and characteristically obtain precisions of up to five microns with a maximum measurement distance of two metres.

The development of the instruments, methods and geomatic techniques reviewed and applied to Palaeolithic art in subterranean spaces indicates that the production of distinct cartographic products requires one to consider the complexity of the object.

The application of new advances in the field of geomatics to the documentation of Palaeolithic deposits demands an adaptation of the methods and techniques, which are aimed at obtaining graphic and infographic products. The morphometric complexity (presence of concavities and convexities) of these environments has the consequence of generating multiple occlusions for data capture. Therefore, the combination of sensors and geomatic techniques is the recommended solution (Beraldin et al., 2006).

1.3 Summary

On this basis, this chapter on "Laser Scanning, Theory and Applications" presents an approach that has been developed and applied to two emblematic Palaeolithic caves. The structure of the chapter goes as follows: After this Introduction, in the second part, we will tackle with the specific methodology developed using non-destructive techniques and articulated in four steps: planning and data acquisition; ii) data processing; iii) modelling and cartographic products generation; iv) spatial information system development. In the third part, we will outline and discuss the results obtained. A final part will devoted to the main conclusions and the expected future developments.

2. Methodology

This section includes a detailed description of the approach developed: from the design and execution of the field campaign to the processing schemes that allow us to deliver three-dimensional models, cartographic products, as well as the spatial information system which represents the best tool to manage and diffuse the Palaeolithic Rock Art.

Given the geometric and radiometric characteristics of the caves under study, laser scanning appears to stand out as the most ideal geomatic technology to undertake the documentation and three-dimensional reconstruction, as this technique provides quality results for complex surfaces without requiring direct contact with the object or the availability of lighting within the cave. However, laser scanner technology suffers from various inconveniences that should be taken into consideration: a high cost, an unorganised and complicated nature of capturing information and the impossibility of providing data that incorporates true colours at a high resolution. Therefore, the methodology presented here proposes an integration with other non-destructive geomatic techniques, such as close-range photogrammetry, to provide an integral documentation and three-dimensional reconstruction while serving as the basis for the development of a spatial information system that permits the management of this archaeological heritage and its value in society.

The methodology developed here presents two clearly differentiable work phases:

- *Field work*. During this phase, the different sensors, a digital camera, a panoramic camera and a terrestrial laser scanner are configured with their basic parameters, and data acquisition is carried out following the protocols and basic rules that are particular to underground sites.
- *Laboratory work*. During this phase, the acquired information is individually processed and subsequently integrated to obtain cartographic products along with a spatial information system that adjusts to the real needs demanded by archaeologists, pre-historians and heritage managers.

Figure 1 summarises the methodology applied to the non-destructive techniques developed and practiced in two caves with Palaeolithic art in the eastern part of Asturias (Spain).

2.1 Equipment used

Below are the most relevant technical characteristics of the geomatic sensors employed during data collection in the fieldwork phase:

- A Nikon D80 digital reflex camera with a Nikkor AF DX fisheye lens is used, providing a field-of-view of close to 180º and reducing the number of shots necessary to generate panoramic images. To guarantee the immobility of the point of view and the angular regularity in the direction of the shot axis, this camera is set on a panoramic head that offers five degrees of freedom, including three translations (X, Y and Z) and two rotations (horizontal and vertical).

- A Canon 500D digital reflex camera is combined with the previous camera to capture detailed material. The obtained images are stored in RAW format for the digital development stage.

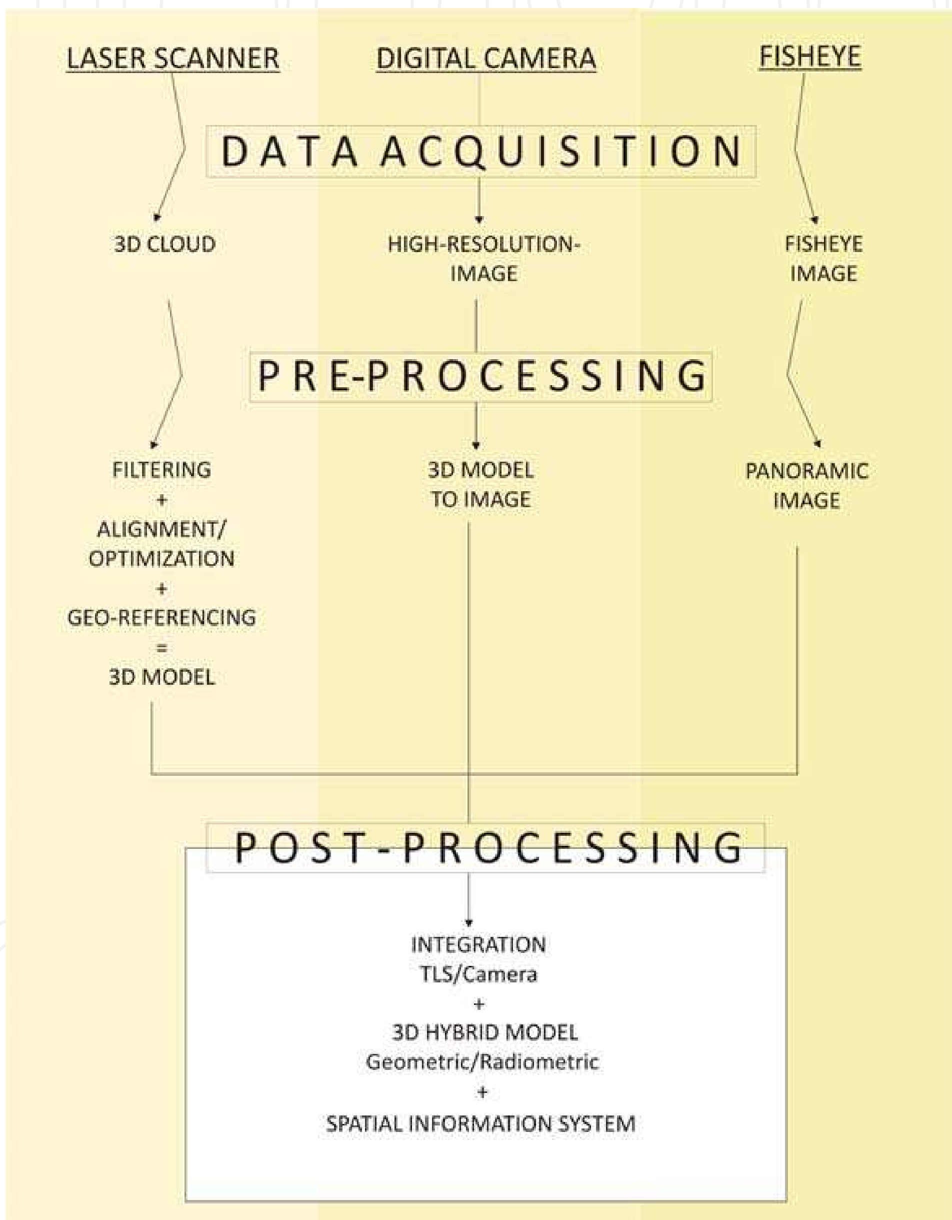


Fig. 1. Methodology for the non-destructive techniques developed and practiced in caves with Palaeolithic art in the eastern part of Asturias (Spain).

	NIKON D80	*CANON 500D*
Type of sensor	CCD (DX format)	APS-C CMOS
Resolution of sensor	10 MP	15 MP
Image size	3,872 x 2,592 pixels	4,752 x 3,168 pixels
Sensor size	23.6 x 15.8 mm	22.3 x 14.9 mm
	NIKKOR AF DX lens	*CANON EF-S lens*
Focus	18-70 mm	18-55 mm
Angle of view	76º - 22.5º	74.3º - 27.8º
	NIKKOR Fisheye lens	
Focus	10.5 mm	
Angle of view	175º	

Table 1. Technical specifications of the cameras employed in the study and their respective lenses.

- A Trimble GX Terrestrial Laser Scanner, of a medium range based on the operational principle of flight time, is employed. This is a motorised instrument that permits automatic angular and distance measurements in real time. Refer to Table 2 for more technical parameters for this equipment.

Manufacturer	Trimble
Model	GX
Range	Optimal at 200 m, with 350 m of overscan capacity
Resolution	3 mm at 100 m
Precision	1.5 mm at 50 m
Speed	Up to 5,000 pts/s
Field of vision	Horizontal: 360º Vertical: 60º
Weight	13.6 Kg
Size	340 mm x 270 mm x 420 mm

Table 2. Technical specifications of Trimble GX, Terrestrial Laser Scanner.

Along with these sensors, different accessories for each piece of equipment (tripods, rotating tripods, lenses and targeting plates) as well as the auxiliary materials needed to adequately illuminate the cave (wiring, generators and cold light sources) were used.

3.2 Fieldwork

The fieldwork can be summarised in the following phases:

a. *Planning*: Before undergoing any documentation work, the objectives and needs should be clearly and concisely established, especially in subterranean spaces where conditions may turn out to be adverse, from the physical characteristics of the environment such as the lighting, humidity and accessibility, to the technical characteristics that should be resolved with the correct methodology and materials.
   The process of taking photographs is significantly affected by the complicated work conditions in a cave (the lack of lighting, heightened humidity, presence of dust and so forth), resulting in difficulties in obtaining adequate photographs. Therefore, it is

necessary to consider a few basic principles when determining the photographic material and equipment. The recommended equipment includes a photographic lens that is as bright as possible and has a short focal length to maximise angular coverage in narrow spaces. The reflex camera should be protected due to the possibility of airborne dust and/or water in the interior of the cave. With respect to the management of the camera, the lighting conditions require manual focus along with the lowest possible sensitivity (ISO) to reduce the possibility of noise in dark areas of the images. In addition, it is necessary to employ a tripod for long exposure times and a remote control to avoid unexpected vibrations when taking the photos. Acquiring images in RAW format allows for better image quality (no artefacts), an adjustment of white balance and a reduction of noise in the image.

With respect to lighting, it is necessary to place lamps at the site (according to its dimensions) to provide indirect light. It is also necessary to use a free bulb for dynamic illumination, that is, to add light to the darkest zones of the site during the exposure time of the camera.

b. *Laser shots*: Laser data are acquired according to some rules and basic principles established specifically for interiors and subterranean locations.

Planning for obtaining the data with the laser scanner is an essential task because it determines the subsequent information processing. In the case of subterranean caverns, there is a set of relevant factors that influence the planning for the job of data capture, and these are listed as follows.

The first factor to consider is the complexity of the geometry. The detailed heterogeneity of the concavities and convexities present in the interior of a cave, along with the occlusions (shadows) generated by stalactites, stalagmites and columns, limit the reach and effectiveness of the laser scans. Consequently, a greater number of stations are required, and the equipment performance is lower.

Secondly, the need to station the scanner in successive positions throughout the cave requires the visualisation of reference points common to several shots to facilitate the fit between them. Given the lighting conditions of the cave and the geometric conditions, this problem requires the use of artificial aiming devices (targets and areas) that are placed in the overlapping zones of contiguous laser stationing points, such that the fitting among images can be performed to guarantee the geometric quality of the set.

Another factor to consider when planning laser shots is the height of the ceilings in the halls and corridors of the cave. The physical constitution of the laser equipment limits the scan to a deflection angle of 40º above the horizontal, thus establishing another unfavourable condition for the execution of scanning work.

A final factor in the planning of laser shots is the arrangement, shape and geometric characteristics of the relevant elements for data acquisition. In general, the position of the scanner must be accommodated in a manner that optimises the representation of the areas of greatest archaeological and/or artistic interest.

Work in underground tunnels, however, presents some advantages over work performed above ground. One advantage is that the environmental conditions (lack of light, humidity and temperature) are very stable, which benefits the homogeneity of the conditions of the shots from both geometric and radiometric points of view. Additionally, there is no interference from objects foreign to the site, such as moving vehicles or people, or from static elements such as signalling or urban furniture, which introduce noise and disturbances to the process.

c. *Taking high-resolution images*: High-resolution images are acquired by means of a conventional digital camera following the principles and basic rules of close-range photography. These rules can be summarised in the following series of basic instructions:
1. Recognise the object by means of a simple sketch representing the layout or structure, taking into account the limitations of this process; e.g., limited visibility, hidden locations and obstacles. This recognition will allow for the definition of the areas of the object that will be modelled by means of multiple convergent images and of other areas that will be modelled by stereoscopic procedures. In general, the latter procedure is employed when the surface of the cave is irregular and continuous, and the former procedure is employed when the surface is simple enough to be able to be represented by a series of discrete points identified in the images (for example, flat surfaces with paintings).
2. The distance of the shot should correspond to two basic contradictory rules. On the one hand, the camera should be situated as close as possible to the object so that the scale will be as large as possible (precision criterion). On the other hand, greater distances will yield wider photographic coverage (efficiency criterion). This paradox is resolved according to the technical requirements of the project.
3. For modelling based on multiple convergent images, each area of the object should be preserved in at least three images taken from three different points of view, while maintaining the same distance to the object (if possible) and assuring that there is enough overlap among different areas of the object. A possible way to perform this task is to establish a path that is parallel to the borders of the object by shooting three images for each given interval of time: one of these with a shot angle that is more or less perpendicular to the wall and the other two with slopes of 45º to the left and right of the initial direction.
4. To achieve stereoscopic modelling, each area of the object should be preserved within the stereoscopic coverage zone of a pair of frames. The geometric paradigm to materialise this configuration is the so-called normal case in which all of the elements under consideration are orthogonal among themselves. In essence, the base (the vector between the two shots) is horizontal and parallel to the object (to the median plane of the object), and the axes of the shot are perpendicular to the object.
5. For definition of the Cartesian plane associated with the object, it is essential to determine both the distance between the points that appear in the images and the vertical direction. This yields the scale along with the basic orientation of the model.
In addition to these images, which give way to geometric and radiometric modelling of the cavern, a second series of high-resolution images should be taken with the goal of providing texture to the point cloud or triangle mesh (if applicable) obtained by the laser scan. These images should consequently cover the surfaces captured with the laser. This process is highly recommended to facilitate the subsequent process of the projection of photographic information over the modelled surface so that the point of the photographic shots approximately coincides with the point of the laser position.

d. *Taking panoramic images*: A panoramic image is an image that catches the entire viewing spectrum. It may be cubic, cylindrical or spherical, but always has the distinctive characteristic that it is viewed from the inside so as to create the sensation of being immersed in a given scene. Such representations are not metric but transmit a feeling of great believability and consequently have great communicative power. They can also be linked with other panoramic images through hyperlinks to create complex virtual visits that allow for the documentation of remote and inaccessible places in a way that is authentic, easy and visually attractive.

When shooting panoramic images, there should be no parallax. That is, it is necessary to guarantee that all of the images are taken from a single point of view.

The geometric foundation of these images is based on the projection of the images onto a mathematical surface (cube, cylinder, sphere) so that a single "image" is created from several initial images. These images can be stored in standard image formats (JPEG, GIF, TIFF and BMP) and be viewed by means of the appropriate software so that the user can choose the viewing directions by moving the mouse.

The following matters must be considered regarding the protocol for shooting panoramic images in subterranean caverns:

1. An objective with a large angular field (fisheye) should be used so that the number of shots in the field will be reduced to a minimum; in our case, there were six horizontal images (one each 60º) and one more image in the direction of the zenith.

2. To ensure perfect immobility of the point of view and also to control the regularity of the distribution of shot directions, a swivel attached to a tripod should be employed to facilitate the above-mentioned five degrees of freedom.

3. In addition to these geometric considerations, some precautions regarding lighting should be taken into account. As in the case of high-resolution images, it is necessary to provide lamps throughout the scene to provide indirect light, avoiding overexposed areas. Furthermore, to ensure the most homogenous illumination possible for the entire scene, a movable bulb that provides light to the least lighted areas (recesses and so forth) should be used. In addition, the availability of lighting in the directions that are farthest from the shot axis will prevent blurry photos.

Although lighting is an important factor, it is not a critical one: it is not necessary for all of the individual shots that make up a spherical panoramic image (seven for our particular configuration) to have exactly the same exposure, as the subsequent process of image mosaicking can obtain a smooth radiometric gradient.

e. *Establishment of control points*: Various singular points materialised by artificial markers (cards and spheres) are distributed throughout the entire cave and raised with the terrestrial laser scan with a double purpose: to register all of the sensors (cameras and laser scanner) under the same reference system and to georeference both sets of data (point clouds and images) in the already existent archaeological framework provided by the archaeologists. Furthermore, the definition of the reference system permits the establishment of a clear and unambiguous altimetric system (point of zero dimension) that is fundamental in the monitoring of the excavation. Finally, a global geo-referencing of each cave is provided based on external control points acquired with GPS. To this end, the last stage of the alignment consists on georeferencing the model according to the official Datum, ETRS89, using the three closest GNSS stations of the work area and the official EGM08 geoid model.

2.3 Laboratory work

Three sequential phases are applied: the first leads the independent pre-processing of each acquired data set (high-resolution images, panoramic images and laser data); the second phase establishes a record of the sensors (digital camera-laser scanner, panoramic camera-laser scanner and digital camera-panoramic camera); the third and final phase leads to a modelled set with all of the hybrid data and generates a system of spatial information that allows for the management and diffusion of the caves and their art.

Independent information processing

a. Pre-processing of high-resolution images.

0. The first step is the digital development of RAW images. As the RAW format allows for the storage of 10 to 16 bits per channel in comparison to 8 bits for the JPEG format, the image has enough degrees of freedom to modify the exposure, white balance, sharpness and tones.

1. Then, the internal geometry of the camera (or cameras if more than one is used in the shooting process) is determined. That is, the position of the point of view (centre of the object) is determined with respect to the CCD sensor, as well as the radial and tangential distortion of the object. These parameters are calculated in the process of geometric calibration in which the values are established to allow for mathematic modelling. The calibration process is performed according to a specific protocol that consists of taking a series of photographs of a mesh to form the geometric grounds that define a pattern of known dimensions. The extraction and correspondence of the points of interest of each image and their subsequent calculation by means of a bundle adjustment process allows the desired parameters to be obtained.

2. Subsequently, the external geometry of the cameras is determined. That is, the positions of the cameras are calculated with respect to the object at the moment of the shot. This step also requires the calculation of the orientation of the shot axis. It is a process of inverse intersection (spatial resection), whereby once various control points are known for the object, as identified by two or more photographs, the spatial and angular positions of the cameras are determined.

3. Once the anterior steps have been resolved, the identification of two or more homologous images of elements (points, lines) allows for reconstruction in the space of the lines that correspond to the rays of light from the object. Therefore, it also allows the inverse process (direct intersection) to be performed and permits the reconstruction of the object based on the images. Thus, this process requires at least two images of the same element of the object to be managed (Figure 2).

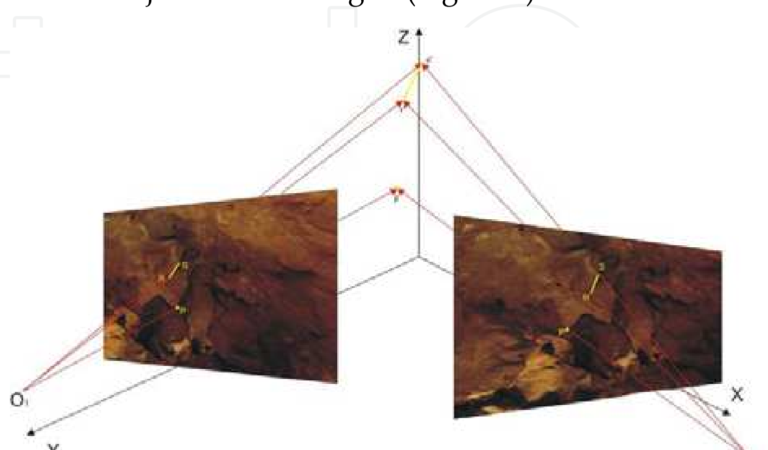
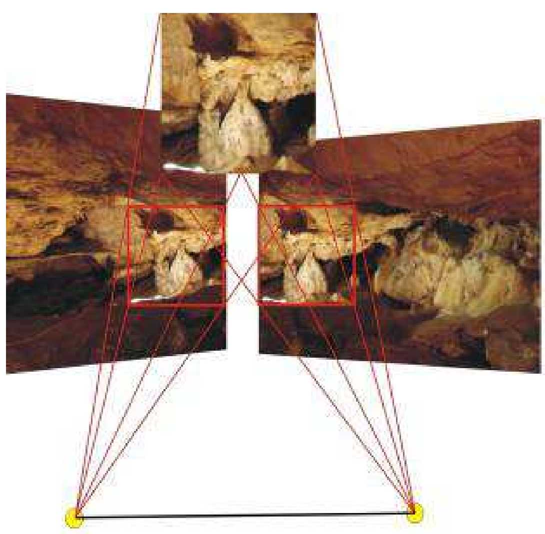


Fig. 2. The object can be reconstructed from the reconstruction of homologous perspective rays (direct intersection).

In the case of a stereoscopic image, this process takes advantage of the ability of human vision to fuse two images (planes), taken from points sufficiently close together, to generate a three-dimensional model.

1. Obtain pairs of images that correspond to the left eye and the right eye.
2. Allow the left image to only be viewed by the left eye and the right image to only be viewed by the right eye (with anaglyphs, polarising filters or stereoscopes). If this is achieved, a stereoscopic view is formed in the brain of the observer; this will be better established if the photographic base (the distance between the two points of view) is greater than the physiological distance between the two eyes.
3. Introduce a separate measuring device for each image to provide the observer with a three-dimensional browser ("floating mark") that allows the 3D dimensions of the object to be derived (Figure 3). To achieve this, the relative positions that the cameras occupy at the moment of the shooting should be rigorously recreated. The geometric model used for this is identical to that used in the anterior case.



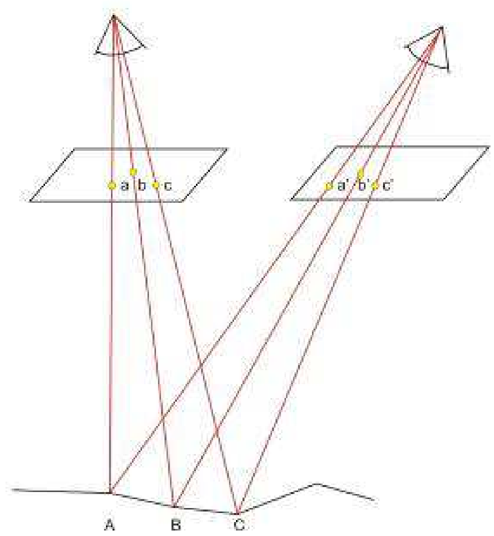


Fig. 3. Left: Principle of the stereoscopic pair. The visualisation of the left image by the left eye alone and of the right image by the right eye alone leads to the plastic display of the photographed object. Right: Principle of the "floating mark": the left and right marks are interposed in the optical path of the left and right eye, leading to the perception of a single mark that runs the depth of the object, that is, the mark "floats".

b. Panoramic image processing.

The processing of this type of image consists of the following basic steps:

1. Link the adjacent images, for which it is essential that the original images contain a determined overlap or covering between them. This step can be performed by identifying homologous points, that is, common points between the images.
2. Once a geometric model is established common to all of the images, the pixels of each of them are then projected onto a single geometric surface, a sphere, cylinder or cube. This is also the time to correct the effects of geometric distortions of the lens, which are considerable when using a fisheye lens.
3. To store these panoramic images in the normal rectangular format, we should take into account that a cylinder has a surface that can be projected onto a plane, while a sphere does not. In other words, in the case of a sphere we need to employ a

mathematical model that allows a sphere to be projected onto a plane, most appropriately the equirectangular projection.

4. The final step consists of the completion of the panoramic image. With spherical images, their lower part will show the panoramic head and the tripod if the image has been taken in the nadir direction, or there will be an empty area if the nadir image has been omitted. The normal image processing technique provides possibilities to complete these zones so that the sphere does not present any empty areas.

Note that these panoramic images exhibit considerable distortions such that there is no sense in direct visualisation. To explore panoramic images, additional algorithms should be implemented that have the function of selecting a sector of the panoramic image and presenting it, free of distortions, on a display window. It is essential that this sector can sweep, under user control, the "latitude and longitude" of the entire sphere.

c. Basic pre-processing of laser data: purification and filtration. Pre-processing of the laser data consists of a long and laborious task, where the organisation, depuration, fusion, georeferencing and filtration of the point cloud are essential to obtain a precise metric product, in 3D, of reality.

   The large quantity of information generated by the laser scanner makes it necessary to purify and filter the point cloud. This task consists of eliminating those points that are not of interest for the documentation of the object. The presence of noise or unnecessary data is one reason for using filtering and segmentation tools to purify the data. The purification should be carefully performed to avoid the elimination of relevant information. Segmentation allows for the isolation and extraction of information that is important for the inventorying and cataloguing of objects such as prints, drawings and paintings.

d. Advanced pre-processing of laser data. This consists of aligning the shots and generating the meshes. The alignment or recording of the different shots or scans allows the positioning of the object to document a single reference system. A local or global reference system is established through the definition of an origin and the directions of the X, Y and Z axes, with the data laser in a single common system. For this, it is necessary that the shots with the data laser have overlaps greater than 25% to achieve sufficient precision in the alignment (fusion of clouds) and to avoid problems with or the impossibility of aligning the shots.

   The fusion of distinct point clouds can be done in two ways: (i) automatically, through the use of artificial signals (cards, spheres, etc.) that are automatically recognised by the laser scanner; (ii) manually, though the identification by the user of at least three homologous points corresponding to the object. In both cases, the resolution of the alignment will consist of the calculation of a solid-rigid three-dimensional transformation consisting of three translations and three rotations.

   In contrast, the aligned laser point cloud constitutes a mass "report" of points that is discontinuous and lacks a geometric structure to facilitate manipulation. Therefore, it is necessary to create a graphic model in the shape of the surface, allowing the point cloud to be managed and exploited. Particularly, a mesh structure is created from the raw point cloud based on the technique of 2.5D Delaunay triangulation and the incremental method (Bourke, 1989), incorporating improvements in geometric and topological constraints such as the maximum length sides of triangles and the topology of adjacent triangles.

Once the model of surfaces is constructed, it can be explored and processed with different goals such as acquiring the curvature, mapping the texture or calculating the volume.

e. Integration of data from the laser scanner-digital camera sensors.

The joint processing of information corresponding to complex scenarios, such as caves and subterranean caverns, consists of a multidisciplinary field of investigation with various challenges and difficulties, especially if one aspires to fuse the information from high-resolution laser scanner and digital camera sensors. Thus, the non-destructive techniques of close-range photogrammetry and laser scanning can be jointly exploited, with the aim of achieving comprehensive three-dimensional reconstruction in these complex scenarios.

The problem of integrating (recording) the high-resolution images and the laser model is intimately related to the problem of positioning the camera, which provides a projection model between the 3D laser data (object space) and the 2D image (image space). This projection is characterised by a rigid transformation (rotation and translation) together with the model of the camera (calibration), also known as the determination of the external and internal parameters, respectively. Rigid transformation will consider the correspondence between the 3D points of the object space and the 2D points of the image space as input data, while the model of the camera establishes the form in which the points are projected onto the image plane.

As a result of the registry of both sensors, a re-projection of the high-resolution images can be established over the three-dimensional laser models (Figure 4) to obtain photo-realistic models of the cave and the panels.

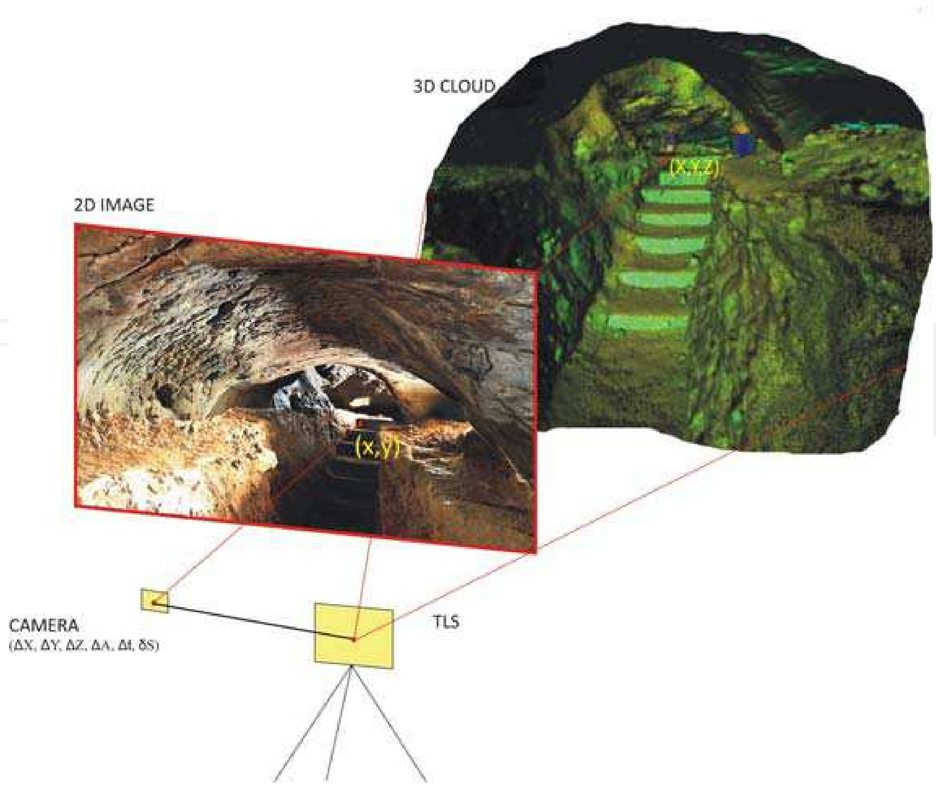


Fig. 4. Registry of the laser scanner and digital camera

Hybrid modelling of the information

f. Acquiring the derived hybrid products: orthophotos.
   An **orthophoto** is currently considered an efficient, low-cost product that allows the radiometric and geometric quality of the object or scene to be united into the same format. The capacity of the laser scanner to acquire dense three-dimensional models in only a few minutes, along with the development of information integration strategies, has allowed the process of orthoprojection to be applied to complex scenarios such as caves and subterranean caverns.
   Therefore, along the lines of the previously established integration of the laser scanner and digital camera sensors with the idea of continuing to broaden the products derived from the hybrid modelling of information, below are the steps followed in the generation of orthophotos that correspond to prehistoric panels. For this purpose, the previously registered high-resolution image and the improved and completed laser model are considered as input data.
   Using the method of anchor points (Kraus, 1993), it is possible to project onto a photographic texture. This method consists of applying an affine transformation to each one of the planes formed by the optimised triangular mesh, which was obtained from the point cloud determined by the laser. Through the condition of collinearity, the pixel coordinates of the vertices of the mesh are calculated, and the mathematical model of the affine transformation directly relates the pixel coordinates of the registered image and of the orthophoto (Figure 5).
g. Generation of a spatial information system
   The rigorous graphical representation of the subterranean caverns as a tool for management, monitoring, intervention, interpretation, visualisation or disclosure may be very important, but it can also be a basic tool for the structuring of information relative to the object.
   As in the case of geographic information systems, graphical information may be used to provide a structure to another type of information of a literal character or of a graphical character distinct from any other characteristic (sound, video). The graphical file is thus converted into a database that can be efficiently employed by an expert or by a researcher to perform consultations or determine analysis processes.

The main characteristics of the spatial information system are:

a. Completeness: the entire cave is documented, including areas that were being analysed at the time.
b. Interactivity: panoramic images that cover the entire scenario are generated, allowing any element of the cave to be examined.
c. Complementary documentation: the panoramic images have links to detailed photographs, videos, laser derived products and literal information, complementing the navigation experience.
d. Spreading: it is possible to distribute the information and spread the cultural heritage by remote access or by physical installations in an interpretation centre. The system can also be modified to make it a system for teaching or for disseminating knowledge to the public.

3. Case studies

In this section two relevant Palaeolithic caves located in the north of Spain (Asturias), La Loja and Buxu, have been recorded and modelled through the approach described. A brief

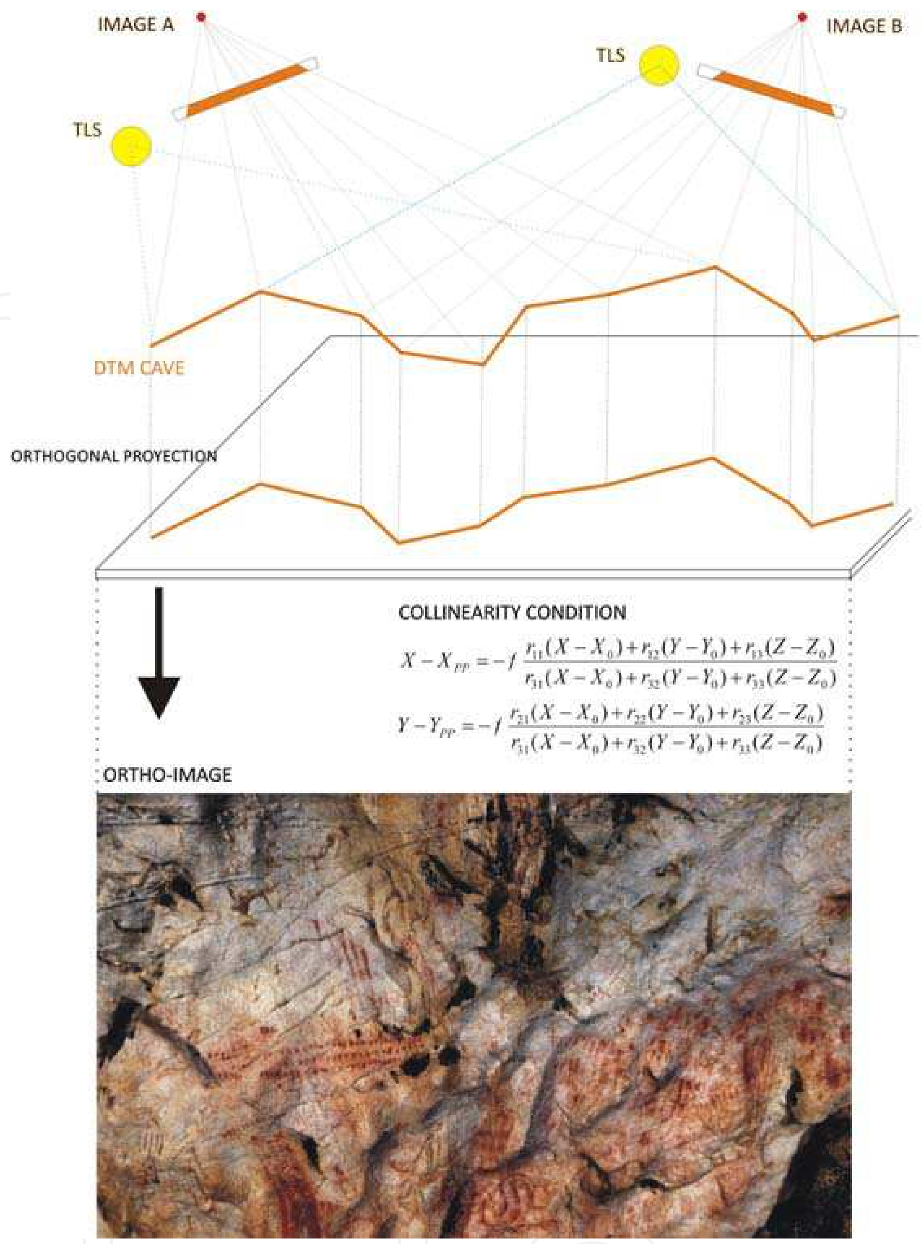


Fig. 5. Orthoprojection process and orthophoto generated on a prehistoric panel

description of the importance of the each cave is provided remarking the main Palaeolithic art of each cave. Furthermore, from a technical point of view, a brief comment about the constraints of each case of study and the way they have been solved is discussed.

3.1 Buxu cave

The Buxu cave is located 2 km from Cangas de Onis, Asturias, Spain. It was declared a historic site on June 29th, 1985. It was discovered in 1916. Archaeological excavations were performed in the vestibule of the cave, bringing to light the remains of the Upper Palaeolithic. Among the manufactured artistic objects, there was a sculpture of a bird carved on the tusk of a cave bear. The deepest parts of the cave contain the rock art that has brought renown to the cave throughout entire world. The art consists of abstract signs and animal figures carved or painted onto the rocks of the walls. Among the signs are enigmatic tectiforms, a type of gird or net. They were carved by the Solutrean occupants of the archaeological deposit of the vestibule. Among the animal figures are some goats carved or painted in black, and the figures from the deepest shrines of the cave include two beautiful horses carved in great detail and a deer shown during the rutting period (Figure 6).

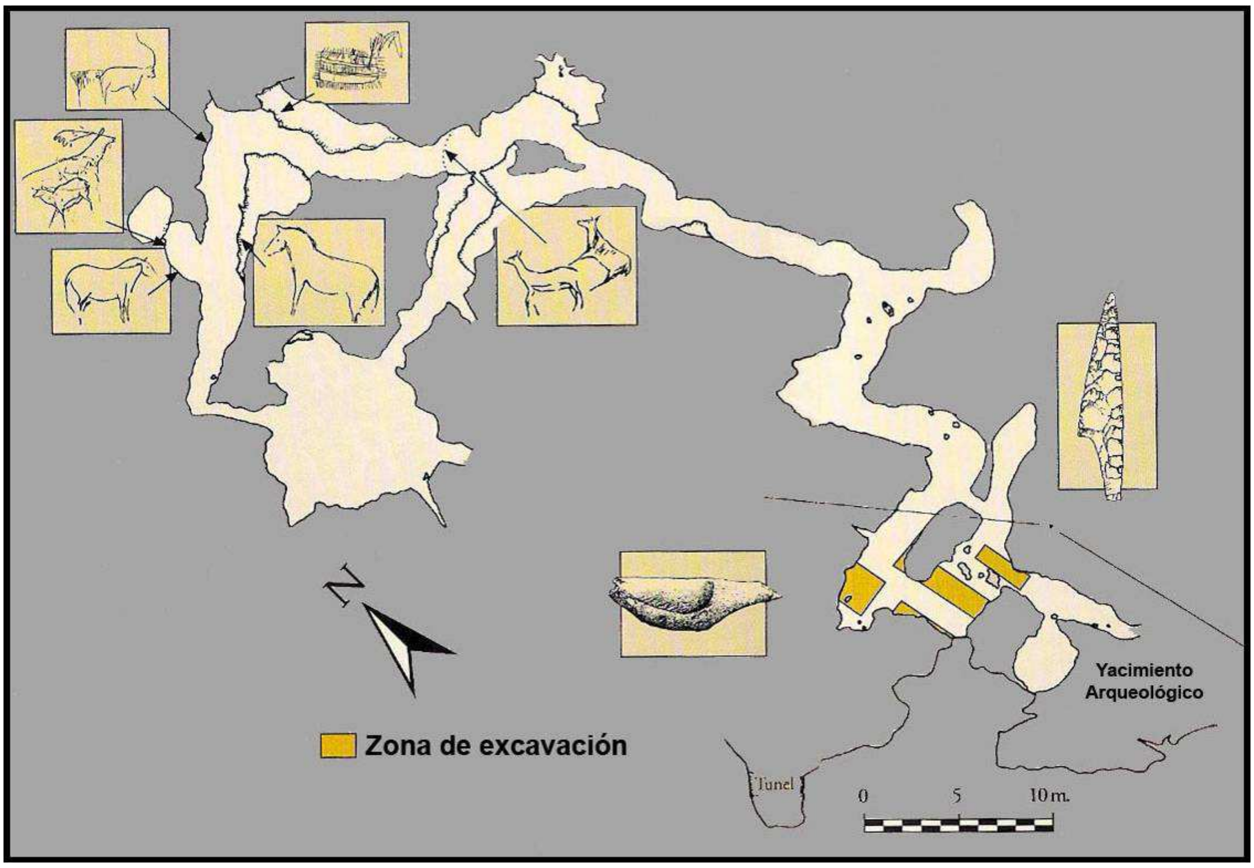


Fig. 6. Layout of the Buxu cave.

During the acquisition of laser data, we used a Trimble GX flight-time laser scanner. As is observed in Table 3, the resolution of the mesh varies from 10 and 20 mm to 10 m and 5 mm to 10 m in the panels and areas of artistic interest. The data were obtained from a local reference system, materialising the vertical axis, and had an overlap of around 30%. The number of raw points captured was 35 million. After filtration and optimisation of the points, the complete model had 33 million points. The number of hours used with the laser scanner was 50. During the initial planning, 25 scanner positions were set. The difficulty of mobility in the interior of the cave and the small spaces, combined with the complexity of the geometry of the cave, led us to perform a larger number of positions than that originally established, resulting in 34 positions. In addition, restrictions of the apparatus had to be considered, that is, the vertical angle and the minimum distance from the object to the scanner (2 m), increasing the data acquisition time and thus requiring more positions. The alignment of the point clouds was performed by means of manual alignment with homologous points and three-dimensional solid-rigid resolution.

Nº laser stations	34
Step mesh	5-10-20 mm to 10 m
Reference system	Local (level)
Overlap	30%
Nº points captured	$35*10^6$
Nº points optimised in model	$33*10^6$
Nº laser hours	50 h

Table 3. Summary of laser data of the Buxu cave

For the spherical images, we used a Nikon D80 camera with a fisheye lens and a photographic swivel. Cold light was used to illuminate the scenes. A total of 126 spherical images were shot, forming the spatial information system of the cave (18 stations) and allowing a virtual visit to the interior of the cave.
The terrestrial laser scan is a "non-destructive" technique that allowed a series of derived products to be obtained from a mathematical model, such as volumes, areas, transversal sections and so forth. The most relevant is the orthoimage. In Buxu, we obtained orthoimages from the rock paintings and the carved tectiforms, as can be observed in Figures 7 and 8.

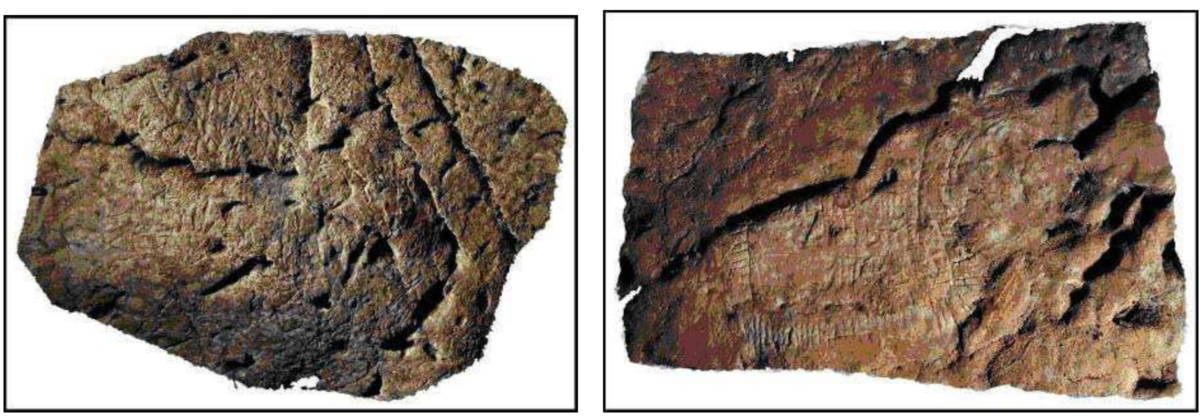


Fig. 7. Large tectiform (left) and carved tectiforms (right). Buxu cave.

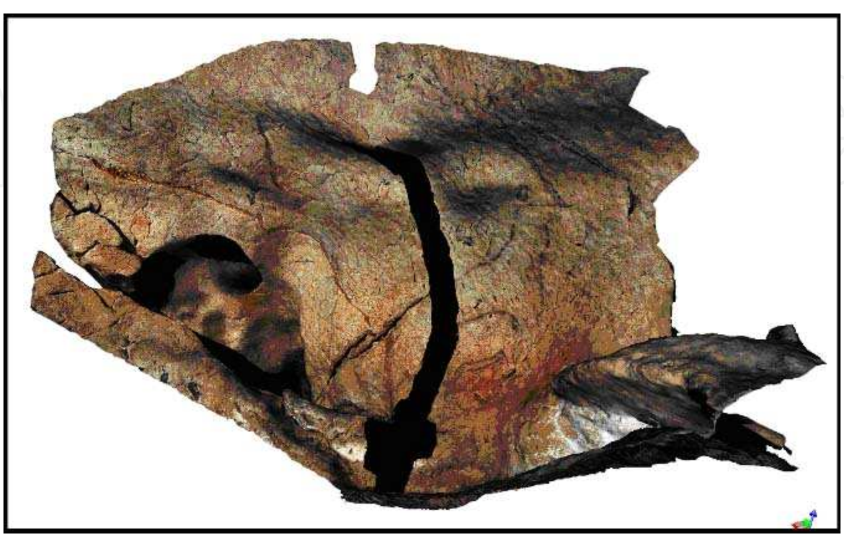


Fig. 8. Horse, goat and large deer. Buxu cave.

In addition, we can obtain other products such as the layout of the cave from the laser model (Fig. 9).

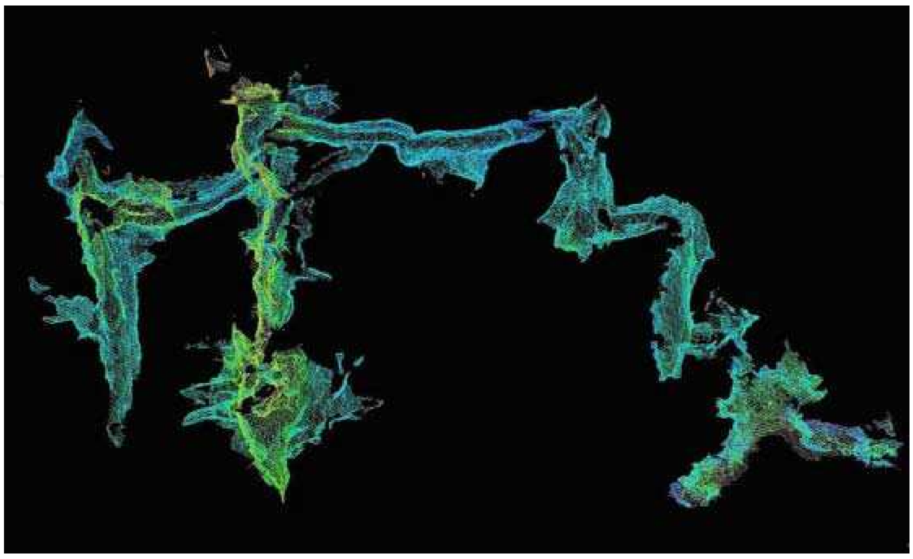


Fig. 9. Layout obtained from the laser data. Buxu cave.

3.2 La Loja cave

This cave is one of the most important known Palaeolithic enclaves of the Peñamellera Baja. Its prehistoric importance was established for the first time in 1908 by prehistorians H. Brehuil, M. Mengaud and H. Alcalde del Río. It is a small cave, just 102 m in total length, and its mouth opens over a limestone wall about 4 m from the ground. The first painting is found about 2 m from the entrance. It is a red symbol. At around 50 m from the entrance, about 4.5 m from the ground, there is a large panel of carvers measuring 1.80 x 0.70 m. The figures represented on this panel are animals (Figure 10).

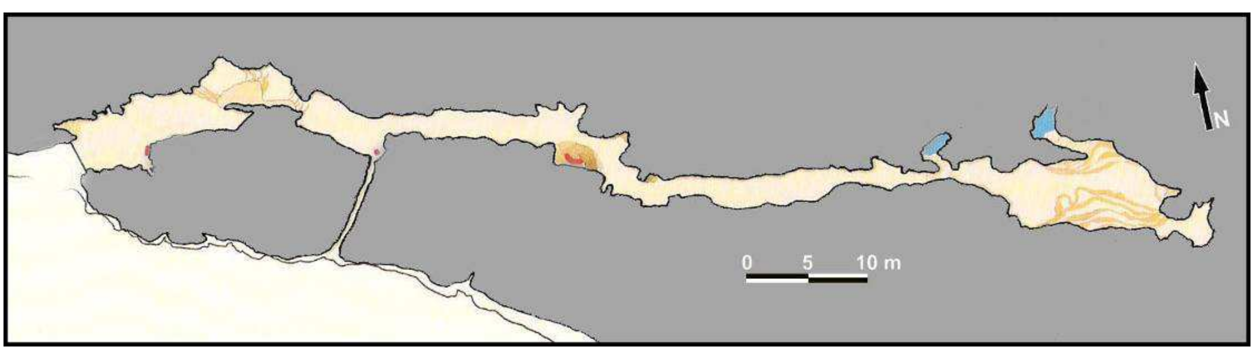


Fig. 10. Layout of the La Loja cave.

In this work, we used two Trimble GX laser scanner equipments, with the advantage of reducing the amount of time in the field. The major disadvantage of working in the cave of La Loja is the presence of water, both in the floor of the cave and in filtrations from the ceiling. Nothing can be done regarding this problem except to work with some appropriate safety measures and to take special care with each scanner position. As we can observe in Table 4, there were 29 positions with a mesh resolution that varies from 10 and 20 mm to 10 m and 5 mm to 10 m in the panels and areas of interest of the rock art. As in El Buxu, we worked with a local reference system, materialising the vertical axis, and had an overlap of around 45%. The number of raw points captured was 28 million. With the filtered and optimised model, we have a complete model of 22 million points. The number of hours employed with the laser scan was 35 hours. In this case in particular, the mobility within the cave is greater than that in El Buxu, but it also has higher ceilings that require the use of a professional swivel to incline the equipment and register those areas. The restrictions of the apparatus in the vertical angle and the minimum distance to the object to be scanned provide the same problems, resulting in an increase in the time to capture data. The alignment of the point clouds was performed through manual alignment with homologous points and Helmert 3D resolution. For the virtual visualisation, 112 spherical images were obtained for a total of 16 panoramas.

Nº laser stations	29
Step mesh	5-10-20 mm to 10 m
Reference system	Local (level)
Overlap	45%
Nº points captured	$28*10^6$
Nº points in optimised model	$22*10^6$
Nº laser hours	35 h

Table 4. Summary of laser data in the La Loja cave.

The Canon 500D camera was employed with its corresponding lens (see Table 1) following the recommendations for photography in the interior of caves for the radiometric record (see section 2.2). Below are the orthoimages obtained from the triangulated model and the radiometry (Figs. 11 and 12).

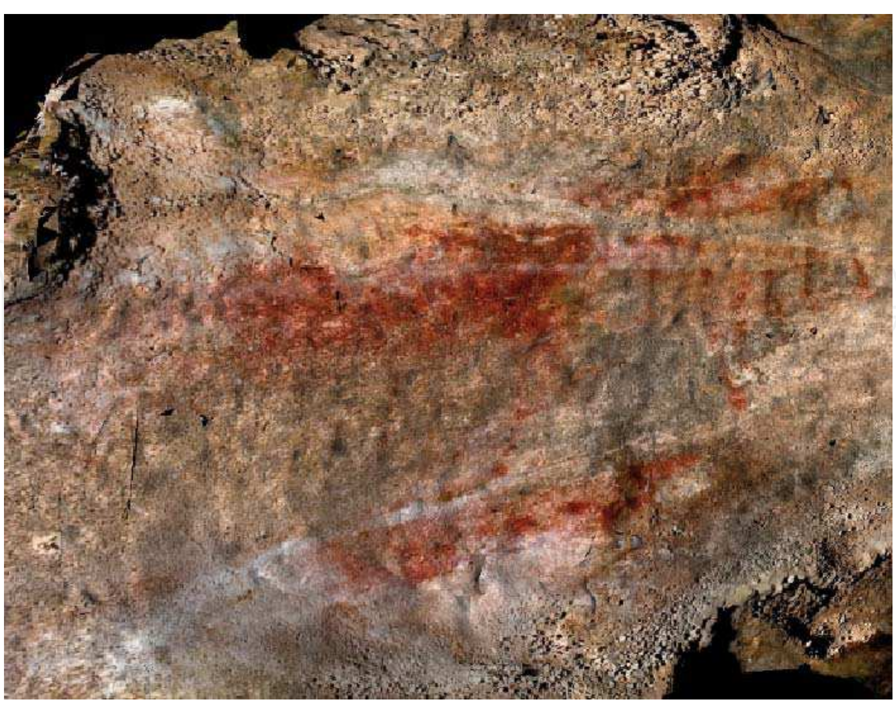


Fig. 11. Red sign. La Loja cave.

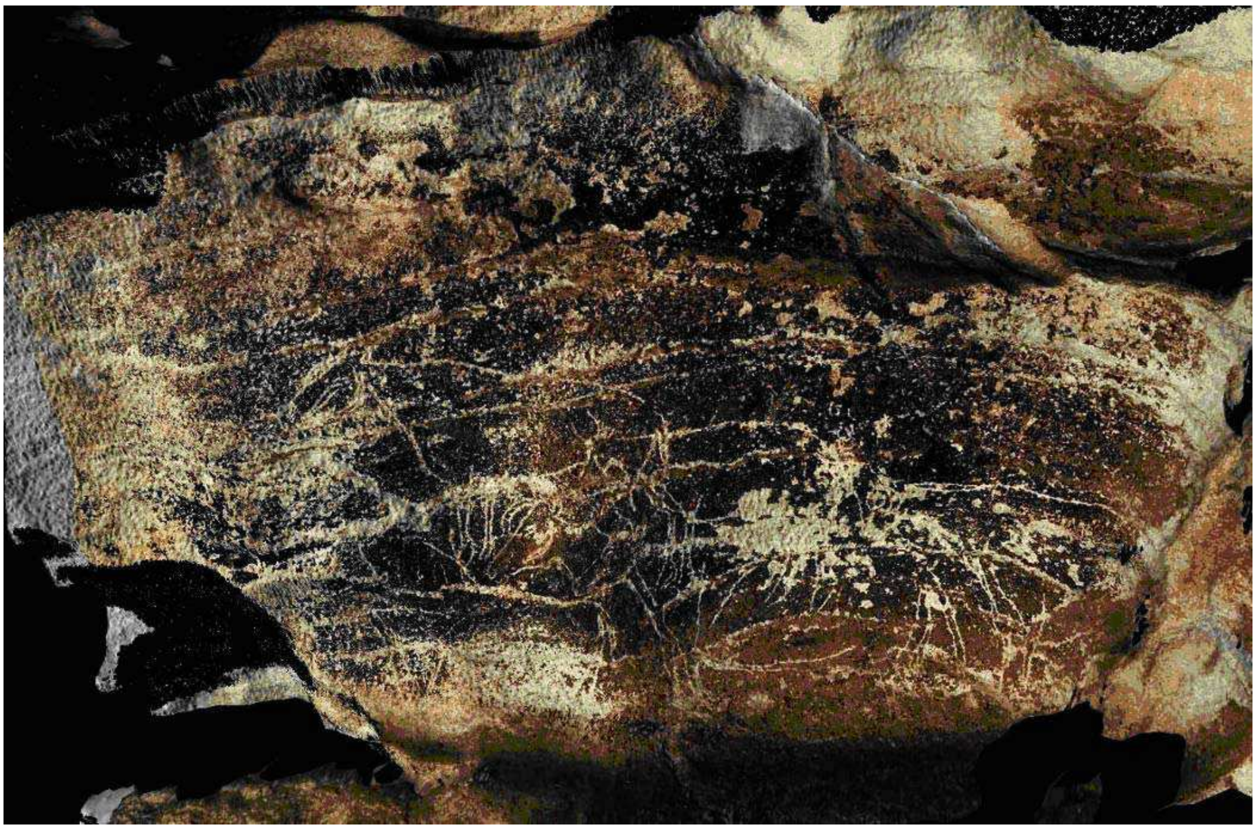


Fig. 12. Large panel. Orthoimage. La Loja cave.

4. Concluding remarks and future perspectives

This section will remark the essence of the research together with the main advantages and disadvantages of the approach.

The **benefits** derived from this study can be summarised as follows:

- The cataloguing of Palaeolithic art information is an indispensable element for the acts of conservation, maintenance and restoration.
- The integration of Palaeolithic art information into a spatial information system is an essential tool for its management.
- The diffusion and enhancement of this information through web services can multiply the outreach of the information.
- An enhancement of digital accessibility and an elimination of the barriers for people with disabilities can be achieved by means of virtual reality and increased technology.
- The model for action can be extended to other environments as a result of the methodological and instrumental developments that have been established.

In turn, the main disadvantages of this methodology are the following:

- There are technological limitations related to laser instruments, including the difficulty of finding a reasonable compromise between the capture speed, capture distance range and precision. Given the novelty of this technology, future improvements are expected in the performance of the equipment that will allow optimisation of the fieldwork.
- The capacity of the information processing is conditioned by the volume of information that must be handled. The design of more efficient processing algorithms and the

development of informational equipment will allow the laboratory work time to be reduced.

- The proposed workflow has a certain complexity in the processing and data integration phase. Therefore, this phase is susceptible to simplification through the automatisation of certain tasks (the elimination of noise, the optimisation of the triangular mesh and so forth).
- It is difficult to incorporate TIN models in environments of 3D visualisation that are flexible and efficient. When these difficulties are overcome, a greater popularisation in the use of these products will be achieved, and there will consequently be an increase in the demand for them.

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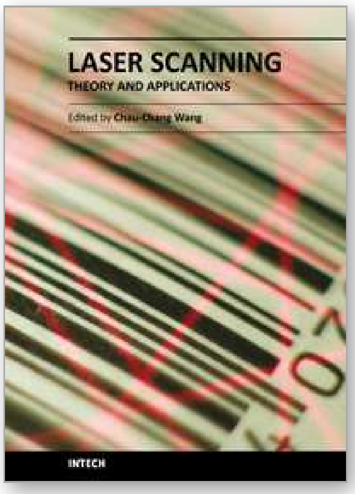

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Ever since the invention of laser by Schawlow and Townes in 1958, various innovative ideas of laser-based applications emerge very year. At the same time, scientists and engineers keep on improving laser's power density, size, and cost which patch up the gap between theories and implementations. More importantly, our everyday life is changed and influenced by lasers even though we may not be fully aware of its existence. For example, it is there in cross-continent phone calls, price tag scanning in supermarkets, pointers in the classrooms, printers in the offices, accurate metal cutting in machine shops, etc. In this volume, we focus the recent developments related to laser scanning, a very powerful technique used in features detection and measurement. We invited researchers who do fundamental works in laser scanning theories or apply the principles of laser scanning to tackle problems encountered in medicine, geodesic survey, biology and archaeology. Twenty-eight chapters contributed by authors around the world to constitute this comprehensive book.