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Large Scale Project Architectural Surveys

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Abstract. In this article, methodologies are developed of complex surveys, using the Terrestrial Laser Scanner (TLS) technology, both for the characteristics of the building, the documentation particularities of the different spaces and the size of the monumental complex. The developed study case is the monumental complex of the Palacio Real Mayor, part of the Museo de História de la Ciudad de Barcelona (MUHBA). The monumental complex is divided into: The Salón del Tinell, the Chapel of Santa Ágata, and the Romanesque Arcs under the Tinell. This study case requires a high number of positions due to the compartmentalization of the spaces and the degree of interconnection between levels, in both the interior ones and to the four attached exterior spaces. At the end, a total of 230 TLS positions were realized. As the case study is a project of great complexity of spaces and lighting, with methodologies that distinguish the different areas, highlighting the use in the same project of different equipment such as the Scanner Faro Focus3D 120 and the Faro Focus3D X 330 HDR. As the project has a purpose of disclosure, the colour registration must be photorealistic. Therefore, HDR techniques and photographic projection were used, in relation to the characteristics of the buildings. As a dissemination tool, classification processes of the point cloud were performed emphasizing the characteristics of a set of interconnected buildings. These can be decomposed in a stratigraphic approximation, taking into account the different periods of their construction, which are related to other investigations and allow a greater understanding of the historical evolution of the building. A Romanesque architecture building that is building on ancient Roman buildings, and rehabilitated based on Catalan Gothic architecture.

1. Introduction

This article proposes a methodology for the development of complex architectural surveying projects. Architectural surveys carried out in different phases of scanning, some of them separated years between them, including different buildings, squares and levels. In addition, the different buildings are connected by different levels and routes.

There are few projects of this magnitude and complexity, for example, the *Santa María* Cathedral survey in Vitoria-Gasteiz (Spain) and the Cologne Cathedral in Cologne (Germany) [1,2]. The methodology described in this article delves into the data collection, the high resolution for archaeological and restoration works, the precision and rigor of a project that contemplates several buildings in a monumental complex and the need for a hyperrealistic model to generate teaching material.

This architectural survey seeks to obtain a planimetry and a 3D model of high resolution and precision for archaeological purposes, with a detail of the stone that allows its stratigraphic interpretation to explain the architectural evolution of the building. The architectural survey seeks to document the geometry of the architectural entity (form, dimensions, spatial and temporal context), constitute a witness of the state of conservation of the architectural set at the time of scanning, and form a structural support that allows having a documentation of reference. Complementary to these objectives, this material will be used as a basis to develop multimedia content, with heritage dissemination objectives for an exhibition that will explain the historical evolution of this set of buildings.

The monumental complex of the *Plaça del Rei* (figure 1) consists of several buildings around this square: The *Saló del Tinell*, the *Santa Àgata* chapel, the *Rei Martí* viewpoint, the *Padellàs* house and the archaeological basement: the episcopal group of Barcino, the Salting and *Garum* Factory, the Romanesque *Voltes* and the wine facilities [3]. This basement allows people interested in heritage to walk through the streets of Roman Barcelona, approach the wall of the time, enter a dry cleaner's shop from the 2nd century AD, and contemplate the vestiges of the first Christian community in the city.

This set is part of the Museum of History of Barcelona (MUHBA). This monumental complex is of great archaeological importance, since in the basement are the remains of different stages of the city. These remains include the Roman Barcino from the 1st century BC, the Visigothic Barchinona from the 6th century AD, and medieval Barcelona from the 13th century. Without forgetting the historical importance of the buildings that were erected on these ruins in several historical stages, among them Romanesque and Gothic. These buildings are related to each other, and to outdoor areas such as the *Plaça de Ramon of Berenguer el Gran*, the *Pati of Museu Frederic Marès* and *Plaça de Sant Iu*.

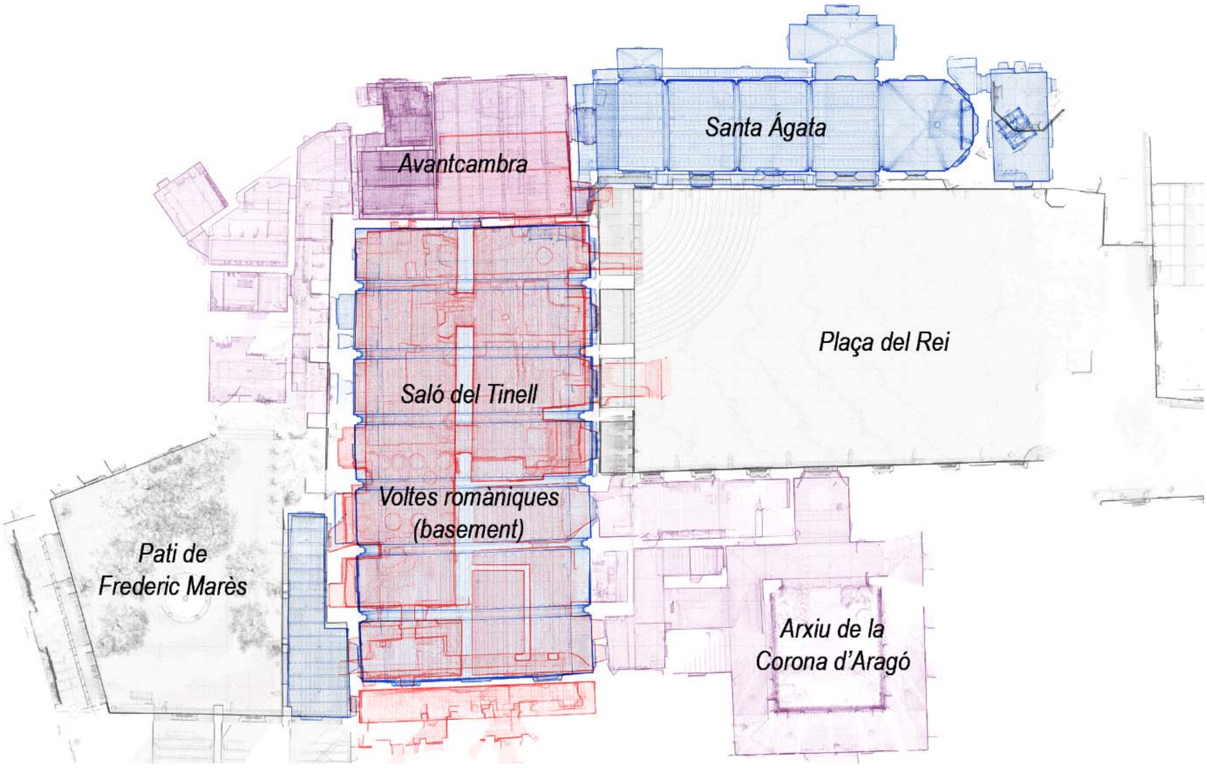

Figure 1. Plant of the monumental complex

To understand these buildings as a unified set, several land laser scanner (TLS) survey projects are linked for each of these buildings. This decision is taken for several reasons: changes due to temporary exhibitions, permits to access certain areas (such as the *Arxiu de la Corona d'Aragó* that connects with a Romanesque *Voltes* area), due to restoration issues, due to accessibility limitations by events, among others. All this poses the challenge of carrying out a project in phases, ensuring the union of spaces that are not scanned, but that are expected to be scanned at another time, possibly in different years. Understanding that there may be changes in these, or in the relationships between the different spaces, ensuring the same rigor among them.

The fact of relating different spaces built at different times, provides information on the historical evolution of the buildings that make up the whole. Information is added to the relationships established in the different spaces. This information helps analyze the stratification of the stone during the construction evolution of the building, or even understand a priori inexplicable deformations without a precise study of the construction process.

Obtaining a cloud of points of sufficient resolution, generates necessary documentation for detailed studies on different fields: the constructive evolution of the building, the spatial relationship of the different rooms or even a study of materials identifying deformities or changes of material.

2. Study Case

The case study focuses on three large areas: The *Tinell*, the *Santa Àgata* chapel and in the basement, the Romanesque *Voltes* that lie beneath *Tinell*. All of them are directly related to the *Plaça del Rei*; all have direct access to this square and all these areas are connected by different routes between them. For this reason, explaining the most recent changes in this square is important (figure 1, 2). There have been changes in access, structural changes have been made to the areas mentioned (especially for the restoration of *Tinell* and the *Plaça del Rei*, which began in 1935 and culminated with the creation of the MUHBA in 1943). In the recovery of the *Palau Reial Major*, the dismantling of the *Santa Àgata* Museum and the rehabilitation of *Tinell* (occupied until 1936 by the community of the old convent of Santa Clara in Barcelona) must be taken into account.

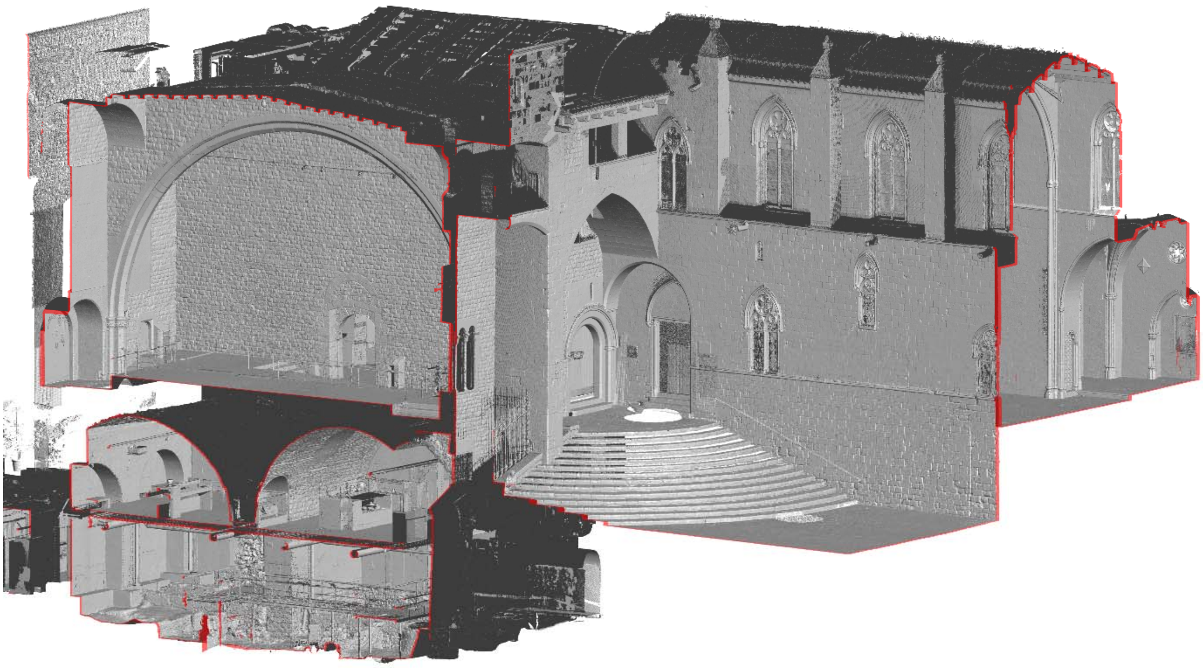

Figure 2. Relationships between levels and the outside

The *Tinell* was built in the 14th century by order of King Peter the Ceremonious. This hall constitutes a representative example of the Catalan gothic of civil character. *Tinell* has undergone several renovations in its history, a reflection of the different stages that the building has lived, being born as the king's audience room in the 14th century, becoming a chapel of the nuns of Santa Clara in the 18th century, and converted into MUHBA showroom. Specialized archaeologists believed that, in the 14th century, under the rule of Jaume II, an old palace of the 11th century of Romanesque architecture was reformed to build a new palace of Gothic architecture. From there the different types of windows that appear in the building, which were a "restoration" of the facade of the twentieth century who tried to imitate as was the palace in the 14th century, are extracted [4].

In 1934, after a long discussion between the city council and several experts, the excavations began in the whole of the *Plaça del Rei*. The plan was to dig up the square, document the remains, and pave the floor again. This intervention also included the part under Sa that housed the Romanesque *Voltes*. In 1936, the works are paralyzed and the square is covered with sand. Finally, at the end of the civil war the restoration of the square is resumed and *Tinell* is intervened, reforming the façade facing the *Plaça del Rei*.

In the basement of *Tinell*, there are the Romanesque *Voltes* (figure 2). The archaeological remains of a neighborhood of workshops and factories of Barcino, with buildings, streets, baths, inscriptions, and fragments of walls on all the Paleo-Christian episcopal set.

The set of the Romanesque *Voltes* is currently part of the MUHBA, as a permanent exhibition of the Roman remains found under the *Tinell* building. In plan, two vaults of 7 and 8 m in width respectively and 33 m in length, that lodge the itinerary of the exhibition in two floors where the different spaces of the Roman ruins and a succession of objects found in them are shown. Through metal platforms that respect the vestiges of past constructions, the space expands or contracts along the route of the exhibition becoming several floors in some points or in small corridors connecting rooms in others.

3. Survey with Terrestrial Laser scanner

The patrimonial survey is carried out in three TLS campaigns: The *Tinell* in 2013-2014, *Santa Ágata* and external context in 2016, and *Voltes Románicas* in 2017. Independent models are generated for the main buildings such as *Tinell*, *Santa Ágata, Avantcambra* and other model for the Romanesque Voltes, even so, all of them have to be understood as a whole.

The developed works began with the building of the Tinell, having the problem that this building presents deformations in all its walls, in terms of defining axes to make documentation of the building. So in this case, arriving at the architectural survey of Santa *Agata* was essential, a more regular building, to be able to adjust the whole model as a whole, so that the facades and sections were perpendicular to most of the walls of this monumental complex, in this case required that the *Tinell* model scanned in 2013 be rotated two degrees on the Z axis, this rotation allowed a better cut of small-sized elements such as the roof beams of *Tinell* and later campaigns in the basement of *Tinell*. Complementary to this, the whole set is georeferenced, based on a topographic survey, to locate the project in relation to the city.

3.1 Equipment used

For these case studies, two different scanners are used. The Faro Focus3D 120 (phase difference scanner) was used in the *Tinell* in 2013 - 2014, and in 2017 the chapel of *Santa Ágata* and the *Avantcambra* was scanned, with the FARO Focus3D X330 (flight time scanner). The capture range of both scanners is 360º H * 305º V and they have a built-in 70 mega pixel camera. The FARO Focus 3D X330 (flight time scanner) is used to scan the *Voltes*, integrating a High Dynamic Range (HDR) system. This system allows to improve the photographic capture of spaces with unfavorable lighting conditions during scanning.

3.2 Planning of the architectural survey

The order of the architectural survey is fundamental for the work carried out, especially in such complex buildings. This architectural survey order follows the following criteria:

- Connection positions that directly relate at least two spaces, with an overlap of at least 30% between the two spaces.
- That quality control can be carried out by means of closed polygonal, in which the beginning and end of the joining process coincide in the same area. This process must be carried out in

different connections between the buildings, taking into account mainly the exits to the different squares (entrances to buildings and balconies), directly between buildings.

- That the union is as direct as possible, understanding that the starting point of the union process coincides with the largest group of possible spaces, in this case with the area of the *Avantcambra*.
- That the base of union is as direct as possible and that the starting point of the union process coincides with the largest group of possible spaces, in this case with the area of the *Avantcambra*.
- The patrimonial survey should have the lowest possible number of occlusions. In this case of study, the height of the *Tinell* and *Santa Ágata* must be taken into account, and geometric complexity in the Romanesque *Voltes* (due to the occlusions produced by the footbridges and Roman remains).

To avoid the occultations generated by the walkways, railings, and different museum elements such as furniture exhibitors, panels and geometries of the place, many positions are taken from the floor of the same remains to achieve a coating without blind spots. With the recommendations of the different teams of archaeologists of the MUHBA, positions are taken under the aforementioned platforms, a few centimeters from the ground (by means of a mini tripod, no more than 5cm from the ground). The positions are very important behind small walls, which from the platforms hide a large part of the floor or even objects of special interest.

The points of union used for the general union of the project are based on linking three scanning areas: The *Avantcambra* route from the *Tinell* plant to the basement that connects with the *Voltes*, the *Tinell* balcony that connects with the *Pati del Marès* (which in turn connects with the *Voltes* from behind), and the main entrance to Les *Voltes* from the *Plaça del Rei* (next to the *Tinell* façade).

In the *Tinell*, three TLS surveys are carried out in relation to temporary exhibitions. The first, with the exhibition "*Indianas, 1736-1847. The origins of industrial Barcelona*". In this exhibition highlights elements with great geometric complexity and a degree of important concealments. The second architectural survey is of the interior, with the room empty, without any exposure. This is done to have all the areas that are hidden by the aforementioned exposure, such as the floor and areas behind soffits. The third architectural survey is the scanning of the exhibition "*El Món del 1714*", which is mainly made up of panels with images and texts, distributed along a path formed by curves and circles.

In 2016, *Santa Ágata* and part of the *Avantcambra* were scanned, thus completing part of the *Palau Reial Major* complex, thus allowing one of the connections that exist with the Romanesque *Voltes* that connect the *Avantcambra* and the ruins.

The entire project consists of 248 positions, half of which are from the area of the Romanesque *Voltes*, and the links for the union with the base. The positions that are carried out are: 38 for the *Tinell*, 86 for *Santa Ágata*, 80 for the Romanesque *Voltes*, 8 for the access by the stairs, 12 for the access by the *Pati d Fredericl Marès*, 6 for the access of the *Plaça del Rei*, 11 for the link with the *Arxiu de la corona d'Aragó* and 7 in the connection of the *Arxiu* and the *Voltes*. The main rooms of the *Voltes* can be reached from three points spread over the floor of the different rooms to cover the entire area.

These spaces work throughout the year as museums, the scanning of the project is very limited by the tourist schedules of the different spaces or rooms. The museum only closes on Mondays, therefore, a specific area is scanned every Monday. In addition to this limitation, the fact that the museum takes advantage of Mondays to mount and dismantle exhibitions, or make special events that prevent the possibility of scanning a certain area is added. The management and planning of the architectural survey requires constant collaboration with the MUHBA and museum workers.

3.3 Union process

For the union of TLS positions and georeferencing of the project (topographical base), the Iterative Closet Point ICP method was used [5], with the itineration of vertices of a grid, using the PolyWorks program (PolyWorks | InspectorTM Standard, from the company InnovMetric), generating with this method groups of closed point clouds in three clusters groups for the base of the project.

The choice of this method is taken for several reasons, the main one is the temporality of the architectural surveys, carried out in different years, which makes difficult to use union points as spheres or adhesive targets, without affecting the building or moving them, in contrast of the ICP processes, which are based on the geometry of the building itself, as a reference for the union of positions. Also because, being a museum, the space suffers constant modifications for the exhibitions and works that houses. The different positions carried out, in some cases conditioned by the time limitation, generate changes between positions of the same space, thus generating a model that contains variable elements according to the exposure in question, these generate superposition's of objects in the point cloud. To be able to detect these elements, when generating a mesh, any object that crosses into space with another is easily distinguishable and proceed to its modification or erasure.

Photographs of specific areas are also projected, such as stained glass windows that require manual photography, in which the walls of the building are completely darkened. So that these areas are visible and have the actual colour of the stained glass, these photographs are projected to the point cloud with the Faro Scene program through control points.

3.4 Colour edition

Being a project for dissemination and patrimonial analysis, the work of colour editing is emphasized to obtain a photorealistic model. In the different study areas, there is a variety of lighting conditions. From very dark areas, to others overexposed due to spotlights, artificial lights or lightings through stained glass. In this sense, the fact of working with a scanning equipment that has an integrated HDR system has allowed to optimize the results.

The main limitation of the HDR system is the increase in data capture time, especially in this case where the fact of being open to the public has only been possible to work one day a week, extending the data capture. The HDR system consists in taking the photographic shot with three different exposures, obtaining a dark, a medium and a clear image, to later combine them. These combinations of images are normally processed automatically, but in the case studies described, due to their light complexity, they must be edited manually. The best information capture by zones is taken from each photo, thus recovering the dark areas without damaging the lighter areas (for example, the light of the bulbs on white walls). This method has a main advantage, which allows to correct the problems of overexposure produced in the openings due to the sunlight or surroundings of the spotlights, which tend to burn the images, thus losing the information of the colour of the elements near the points of light.

4. Relationship of the 3D model with raster and vector planimetry

Due to the irregular geometry of the scanned spaces, obtaining a single model of the whole set provides a main tool to perform an analysis that allows at the same time to see relationships in 2D and 3D, to understand concrete points of the connection between buildings.

The 3D model provides a global view of the spatial relationships of the different zones and levels. From the model, planes that give information on geometry and spatial connections are extracted. Drawings of depth ranges and detail planes are also extracted from the three-dimensional model, which allow to identify changes in the texture of the stone, both to document the current state for restoration processes, and to have a basis for a stratigraphic analysis when identifying changes in the stone and its relationship between levels. This process of exploiting the point cloud to generate information requires filtering the point clouds to solve instrumental and methodological errors such as the mixed edge error [6].

4.1. Identification of difficult visibility areas in both 3D and 2D

The generated information stands out in two aspects, the relation between zones and the detail or resolution achieved, reaching to generate plans at scales of 1/50 and 1/25.

The plane of depth ranges provides information regarding the relationship between the different surfaces, especially those of the *Tinell* with the surfaces below it, in the Romanesque *Voltes*. This helps to understand the alignment of the different interior facades of the complex. Parallel to this, using the raster planes, vector planes are generated that allow working with them in different CAD programs. Through the raster images of the sectioned point cloud, understand how the *Tinell*'*s* floor shares the inclination of the roof of the *Voltes* is possible, reaching in certain points to be separated by scarce 20 cm, as seen in figure 3.

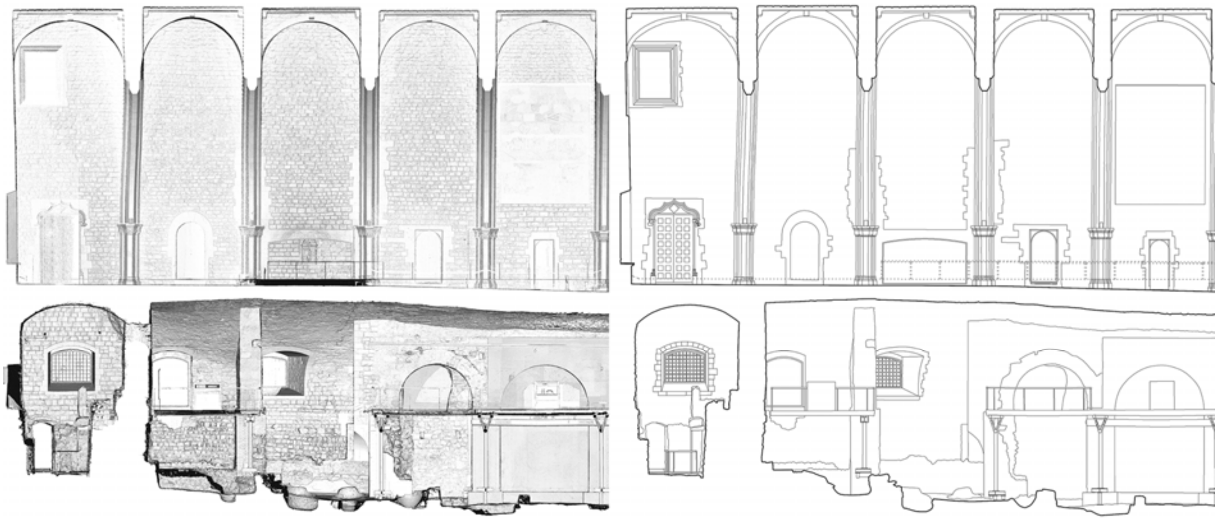

Figure 3. Transverse plane of *Tinell* and *Voltes*, right stratigraphic detail and left vector planes.

This level of resolution and coating has been achieved thanks to having a high number of positions. Many of these positions are difficult to access, but they have been scanned from different areas, or through different floors from where there is a partial view of the area in question. The raster planes are generated at a resolution that allows a file to be made with sufficient precision, with a level of detail of 1 point per millimetre, to ensure that the cracks are detailed, to identify the restorations made by geometric change of the material, to identify the mouldings of the construction elements (such as the canes placed in the formwork as a finish for the roof of *Voltes*), and to be able to generate an exploded view of the types of stone (to differentiate and date the period of each part of the building, as shown in figure 5).

Being able to access areas digitally facilitates the analysis of the building. A very clear example are the roofs of the chimneys and spaces between buttresses between the *Tinell* and the *Pati of the Federic Marès* Museum. This area is difficult to inspect because the roofs are higher than 10 m, in a very narrow area and without any lighting, so they are not visible directly. In figure 4, an overhead view of the roof can be seen. In red, areas of difficult access. This view allows a better understanding of how the original cover Tinell, before the reform of 1936. In the figure, is appreciated that the structure supporting the roof is oriented in the opposite direction to the current, which shows that the direction of the beams and interleaved is orthogonal to the current address.

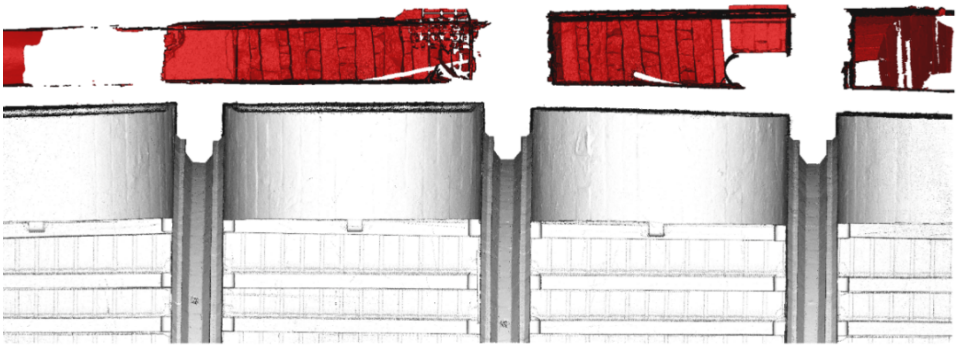

Figure 4. Address of the cover. The interior red area of chimneys direction of the beams in vertical direction, in white cover of the *Tinell* direction of the joists in horizontal direction.

Another example that provides more information thanks to the new architectural surveys, is the reference to the structure of the *Tinell* in relation to the basement. Each Gothic arch is cemented on stone pilasters, which were the basis of the first hall built in the 11th century. In the figure 5 is observed how, where these stone pilasters were modified, is where the deformation of the Gothic arch is accentuated more. Being able to relate the two levels by means of the scanner survey, supported in addition to other archaeological studies, relate these facts is possible.

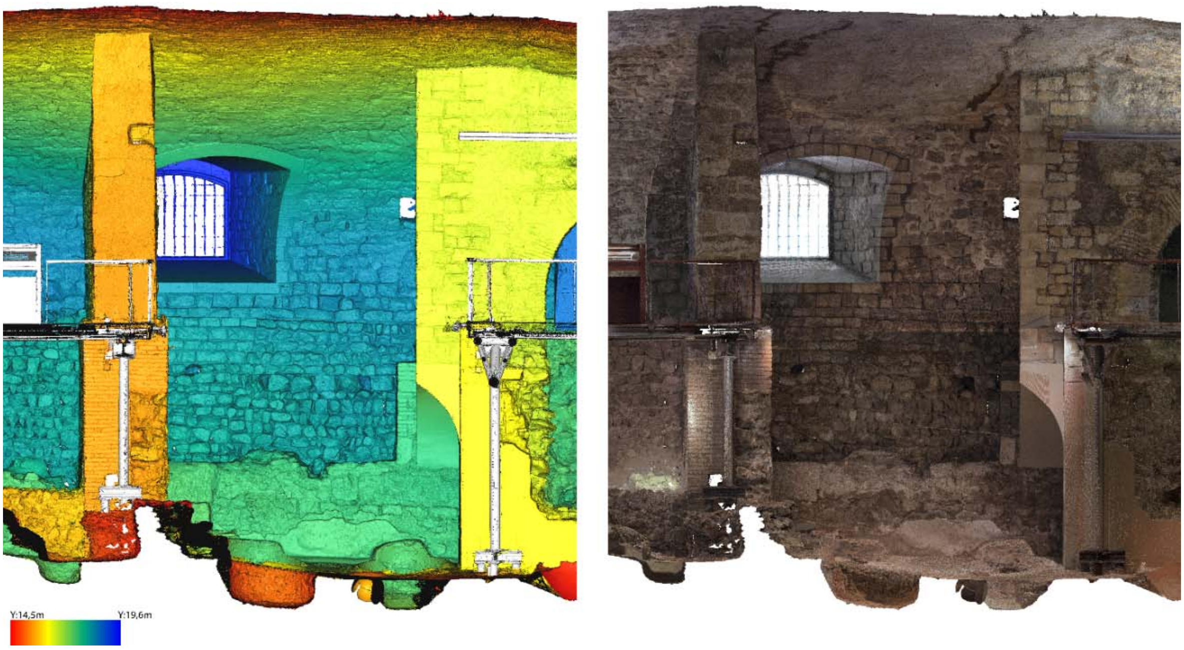

Figure 5. Geometric detail and color. Left depth map with detail of the stone and right color RGB TLS.

Details of the materials are also appreciated thanks to the taking of HDR photographic data, such as coatings in cracks, or changes in the continuity of the materials that, when related to the geometric detail, allow to have an overview of how the evolution of the building. In the case of a developed study, this aspect is fundamental, because the continuity of the material allows to identify changes in the building, especially by constructive techniques, where wall starts that no longer exist can be seen (especially in the basement).

5. Classification of the model

To keep intact the ruins under the Romanesque *Voltes*, the MUHBA has placed a set of walkways and platforms to generate the route of the permanent exhibition of the ruins. Several exhibition modules are also placed with different museum elements and security elements of the museum. The structure that supports the walkways, also work as tensors of the buttresses that support both the *Voltes* and the arches of the *Tinell* on the upper floor (figure 6).

a) b)

Figure 6. Axonometric detail of a longitudinal section. a) Remains of an external circulation, b) Change in the modulation of the structure (arches and vaults) and point of inflection between changes of slope of the vault.

Understanding all the aforementioned elements as ancillary elements, a meticulous process of classification of the point cloud is carried out in order to separate these elements from the "clean" space of the ruins. The process of separating all these elements is done manually. This is because, after several tests for automatically separating by detection processes planes as the RANSAC process [7], when floor and irregular surfaces walls (in terms of planarity), the result does not have the accuracy required for the project. For this reason, the process of separation requires rigor and precision in each element outside the physical space of the ruins.

With the classified elements, a scalar factor is added that allows their separation or hiding in the point cloud. A base is obtained without objects or elements that difficult the vision and understanding of the *Voltes* space, allowing also redesigning the museum elements of space in the future, based on the 3D model of the point cloud.

The classified point cloud allows even able to separate materials according to their texture after better understand the historical stage of its construction. According to the size of the different stones that make up the walls, the final rigging of the surfaces, or even their position in space, are characteristics that help this classification. The architectural survey of terrestrial laser scanners, together with the different archaeological studies, provides enough information to generate the classification.

6. Conclusions

The TLS survey provides basic material to generate a report of the exact state of conservation at the time of scanning, important information taking into account the fragility of the different elements found in the basement, understanding the space as an exhibition hall open to the public all year. Having a 3D model of the different spaces at different levels is necessary to understand how the building works structurally, and put a chronological order on the past renovations or reconstructions thanks to the identification of construction methods.

In the study case proposed, methodologies are identified for long-term projects, being essential in planning to foresee future surveys in relation to the union of the TLS positions. To do this, it is necessary to have the maximum possible external connections and relations between the spaces. The control of connections between zones is also fundamental. In the post-process of the point cloud is very important to take into account the order of the union in closed polygonal, which allow connecting interior corridors with multiple exits to the squares as control points.

The edition of the HDR colour is also essential in spaces with specific artificial lights, focused on archaeological remains and sculptures, which difficult the relationship between panoramas as in different areas of the museum the light is not homogeneous. The detail in the texture of the material of the different surfaces provides information on the different periods of construction.

Due to the complexity of the constructive evolution of the building, several studies are required to understand the historical evolution of the heritage asset. In this set of studies, the TLS survey provides more data for the understanding of the building. At the moment diffusion material is being made that seeks to explain the evolution of the building, in this process the manipulation of the clouds of points is fundamental, especially in the classification processes, since the classification allows to isolate elements of the buildings as a preliminary step to the creation of multimedia material.

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