UNDERGROUND SURVEYING: 16TH CENTURY CELLAR VAULTS IN THE GALERÍA DE CONVALECIENTES, MONASTERY OF SAN LORENZO DEL ESCORIAL

P. Chías [a, *], T. Abad [a], E. Echeverría [a], M. De Miguel [a], P. Llorente [b]

[a] Dept. of Architecture, School of Architecture, 28801 Alcalá de Henares, Madrid, Spain - (pilar.chias, tomas.abad, ernesto.echeverria, manuel.miguel)@uah.es
[b] Dept. of Construction, School of Architecture, Politechnical University of Madrid, Avda. Juan de Herrera 4, 28036 Madrid, Spain - mpazllorente@movistar.es

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ABSTRACT:
Underground surveying of cellars, caves, and architectural spaces, is quite different from surveying on the surface. Researchers must deal with various challenges derived of the lack of natural light, low temperature, and humidity, but also with inaccessibility. But the essential problem in underground surveying is that of orientating the underground surveys to the surface surveys. For this purpose our methodology integrates different geomatic techniques, as the use of a scanner laser in order to obtain a 3D model, as well as classic topography, and GPS to locate accurately the control points according to the official reference frame of the Spanish Geodetic Network. The developed methodology is described and applied to the case study of the cellars of the Gallery of Convalescents (Galería de Convalecientes) in the Royal Monastery of San Lorenzo de El Escorial. These cellars compose an outstanding series of interrelated singular complex spaces. Their study is particularly relevant because of the quality of the stonework, the geometry of the vaults and lunettes, and the stereotomy. The fact that these spaces were neither surveyed nor studied before, must be stressed. And our work will bring into light an important part of the 16th century Spanish architectural heritage. Finally, the INSPIRE Directive becomes an opportunity to integrate cultural heritage datasets into an interoperable framework, and to share and diffuse them as geographic information.

1. INTRODUCTION

1.1 Main targets and innovations

This work focuses on three main targets, corresponding to three different approaches.

Firstly, from the point of view of the architectural heritage, our main contribution to the knowledge of the Monastery of San Lorenzo of El Escorial is the produced georreferenced documentation of the underground vaults of the external quarter that is known as *Galería de Convalecientes* (Gallery for Convalescents) (Figure 1). This part of the Monastery was never surveyed before. Our work produced a set of reliable geometric spatial information, and an accurate georeferenced survey composed by traditional maps and plans, transverse and longitudinal sections, and 3D models of the cellars. Traditional multiview ortographic projection allows to determine high precision measurements, while the latter permit a visual approach of the whole complex set of inrerrelated spaces, and show the geometry and stereotomy of the 16th century stonework. In addition, all this products can be used by many researchers of different fields.

Secondly, from a methodological point of view, the integration of different geomatic survey methods was needed. Due to the lack of connectivity within the inner and the outer coordinate systems, the methodology required the use of traditional topography, and laser scanning (Grussenmeyer et al, 2010), but we also applied some existing methodologies from the field of the Civil Engineering and tunnel surveying (Seedahmed, 2006; Varela, 2015). All of them deal with the problem of georreferencing by including a procedure that is termed correlation.

Figure 1. Tomás López Enguídanos 1800, *Corredor inmediato a la Botica en el Real Monasterio de S. Lorenzo (Corridor next to the Chemist's Building in the Royal Monastery of S. Lorenzo)*. Biblioteca Nacional de España, Madrid. View from the Friars' Garden (*Jardín de los frailes*). The surveyed cellars are under the L-shaped open galleries.

Finally, from the perspective of the diffusion processes, the adaptation of the spatial datasets related to Cultural Heritage to the INSPIRE Directive, implies an outstanding contribution to

* Corresponding author

standardisation and diffusion of datasets related to cultural heritage, according to the norms and standards of the European Infrastructures of spatial data.

1.2 Precedents

Precedents must consider the three main focuses of the research.

From the perspective of the architectural heritage preservation and diffusion, there is an exhaustive study of both the Gallery and the Chemist's buildings (Chías, 2015), but there were still no accurate surveys of the Gallery's cellars. However, there are precedents in surveying the cellars of the main building of the Monastery (Martín Gómez 1985; López Mozo, 2000) showing some interesting stereotomic solutions, to be compared with the proposed case study.

From the methodological point of view, there are different preceeding methodologies to be applied in surveying and georeferencing of underground spaces. Some of them have been successfully developed in Civil Engineering, infrastructure networks, and mining (Davis, 1981; Schofield and Breach, 2007). Survey and 3D modelling of vaulted spaces by means of scanner laser are consolidated methodologies with abundant precedent applications and references. The works developed in urban cavities survey in Cagliari (Deidda and Sanna, 2013) must be stressed because they dealt with similar problems.

About the INSPIRE Directive and its application in Spain through the LISIGE Law, the works developed by Del Bosque and Vicent (2011), Parcero-Oubiña (2012), and Chías and Abad (2015; 2016), are pioneer. These works were produced within the *Grupo de Trabajo de Infraestructuras de Datos Espaciales de España* or IDEES (Spanish Spatial Data Infrastructures Working Group), and the Working Group of IDEES applied to Cultural Heritage, which is promoted by the Instituto del Patrimonio Cultural de España.

1.3 Case study: the cellars of the Gallery of Convalescents in the Monastery of El Escorial

The Gallery for Convalescents was built at the second half of 16th century, as an autonomous annexed building close to the Monastery. Old or sick friars used to enjoy the sun and open air benefits in the Gallery's corridors, being protected from the north cold winds. These corridors are open to the Friars' Garden (*Jardín de los Frailes*), where medicinal plants once grew. It was worth enjoying the different species, and collecting and storing them in the cellars. They compose a set of fresh ventilated spaces provided with an abundant water supply and drainage (Chías 2015).

Though its construction was contemporary to the Monastery, there is no connection between its cellars and the Chemist's Bulding (*Botica*) cellars, to those of the Gallery. The connection with the main building is possible through the Friars' Garden (*Jardín de los Frail*es), but also along an open air corridor that encircles the Tower of the Infirmary (*Torre de la Enfermería o de la Botica*).

Thus, when the original uses of the Gallery were lost, its cellars fell into oblivion. It is still difficult to visit them, because the stairs leading to the underground vaulted rooms are hidden. And as a consequence, this part of the Monastery was never surveyed before.

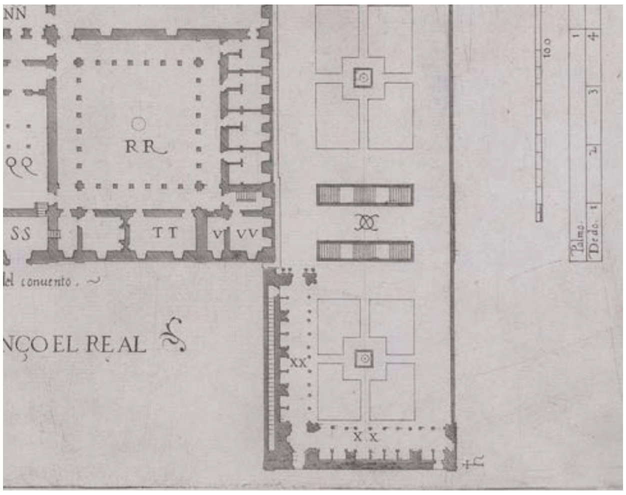

Figure 2. Juan de Herrera and Pedro Perret 1587-1589, *Primer diseño* (*First Drawing*) (detail). Biblioteca Nacional de España, Madrid. Ground floor plan. The L-shape at the bottom represents the Gallery. The Infirmary Tower is lettered as VV, being the exterior angle one of the external control points. North is located at the left side.

Ancient 16th century documents by Herrera and Perret (Figure 2), as well as later drawings produced along the 20th century, lack of precision and show major contradictions. For instance, the stairs are wrongly placed in all of them (Lorente, 1944; Zuazo, 1964), while the underground vaults are absolutely ignored. The aisle's dimensions are also wrong. As a consequence, the comparison with the historical drawings was not useful to our research, as they were neither accurate nor reliable (Fiorillo et al, 2013).

Figure 3. The upper cellar runs from east to west. On the right side, the stair leading to the Friars' Garden can be seen.

The only access to the upper level cellar is a hidden stair at the ground floor that is embedded in the retaining wall of the *Lonja*'s West esplanade. As a consequence, the underground spaces remained isolated from the main building of the Monastery and from the neighbouring Chemist's Building, while connections were only established through the lower gate of the Tower of the Infirmary.

On the other hand, the cellars compose a set of complex interrelated series of main and secondary underground areas. Main spaces are built at different levels and with different heights. They are covered with barrel vaults and connected with a conic vault over an inner stony stair, whose width is similar to the one of the upper space.

The addition of a set of various niches and smokestacks at both the northern and western walls must be stressed. They were originally used to store and process the medicinal plants.

Both cellars have some small skylights that are placed at the level of the Friars' Garden. Although they admit daylight, they can not be used to get accurate measuring from inside the cellars, because of their height and their geometrical complexity, that make them inaccessible.

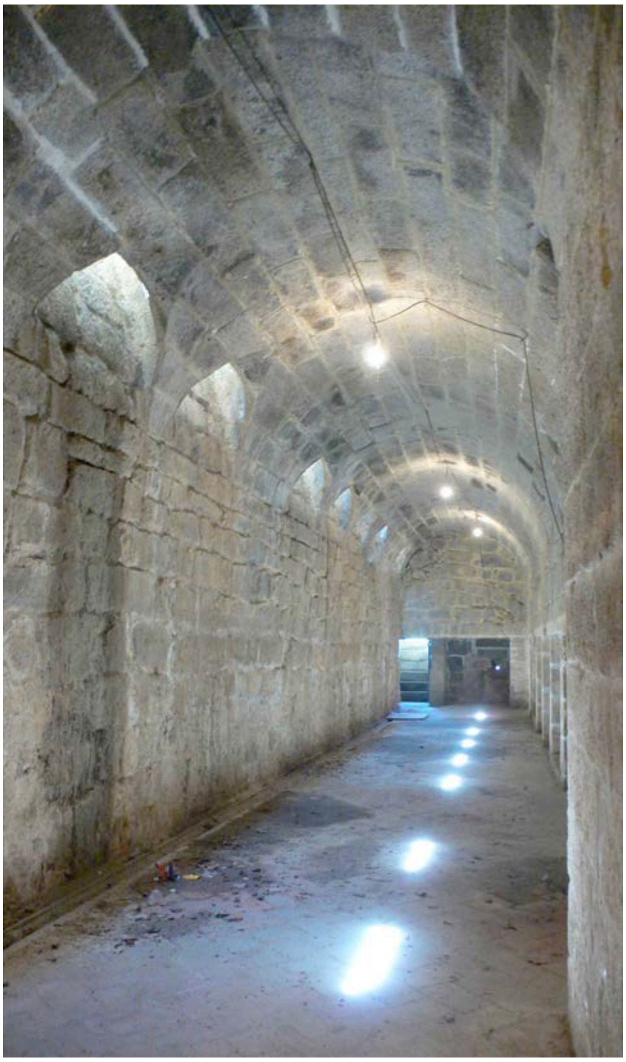

Figure 4. The lower level cellar whose longitudinal axis runs north to south.

2. METHODOLOGY

2.1 A combined methodology

The main problem in this underground surveying is to correlate the coordinates of the control points inside the cellars with the external georeferenced network. To do so, at least the coordinates of one of the inner control points, and the bearing of at least one alignment, must be transferred to the corresponding ones at the surface (Schofield and Breach, 2007). Due to the characteristics of the case study, we decided to use a combined methodology of traditional topographic methods, GPS, and laser scanning.

Prior to the survey operations, the cellars were inspected and sketched, in order to get a first approach to the elements and geometry of the spaces, and to design accordingly the surveying strategies, and the number and location of the topographic and laser scanning standpoints. The targets for recognizing the homologous points of the laser scanner point clouds were selected from the most significant elements in the stonework.

The survey operations took four days. On the fisrt one the detailed topographic measures inside the cellars were carried out according to the defined inner traverse. On the second and third days, the laser scanning survey was developed, paying special attention to those elements to be surveyed in detail. On the fourth day, the correlation was completed by means of the GPS located in the external control points and the defined outer traverse.

2.2 Topographic surveying network

2.2.1 Surveying the local topographic network: As the only access to the cellars is descending a stair of granite, we measured the vertical and horizontal angles to get the elevation of the internal control points (trig levelling), and to establish the correlation of heights. Traversing method was then applied.

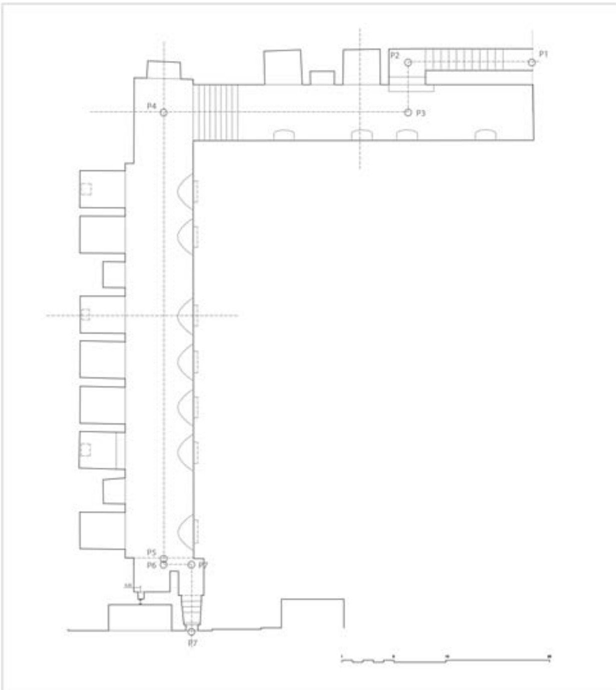

Figure 5. Control points in the cellars used in the traversing method.

The starting control point of the inner traverse was set at the midpoint of the edge of the higher step of the stair, while the terminal one was set at the intersection of the axis of the lower vaulted space with the internal face of the *Muro de los Nichos* (Wall of the Niches) at the ground level of the upper vaulted space, which is +0.90 m high. Intermediate surveying points are shown in Figure 5. Problems appeared when we began the correlation process with the total station, because the initial and the final points of the traverse, were not intervisible. The same happened to the main external reference point in the edge of the Tower of the Infirmary (PA), and point (P1), that was located 0,20 m under the Friars' Garden level. Some added difficulties were due to the sloped south wall of the Monastery, that interfered with measurements. This problem was solved with the definition of an external traverse, where staring point was located in point (PA). Two intermediate station points were defined, one in the axis of the eastern portico at the garden's level (PB), and the other one at the intersection of the edge of the southern wall of the Gallery with the parapet of the Wall of the Niches (PC). The final point (PD) was located at the orchards' level, at the edge of the small window, close to the terminal point of the interior traverse, and visible from there. Outer and inner traverses closed within the margins of tolerance previously established.

As the height differences between the exterior points were small (see Table 1 and Figure 6), they were measured using the traditional measuring tape.

No corrections were needed because the temperature gradients were negligible. We also used a PLS 180 Palm Laser level, and a laser distance measurer Leica DISTO. As the work scale was 1:50, the tolerances were always under 0.01 m in the horizontal and 0.005 in the vertical component.

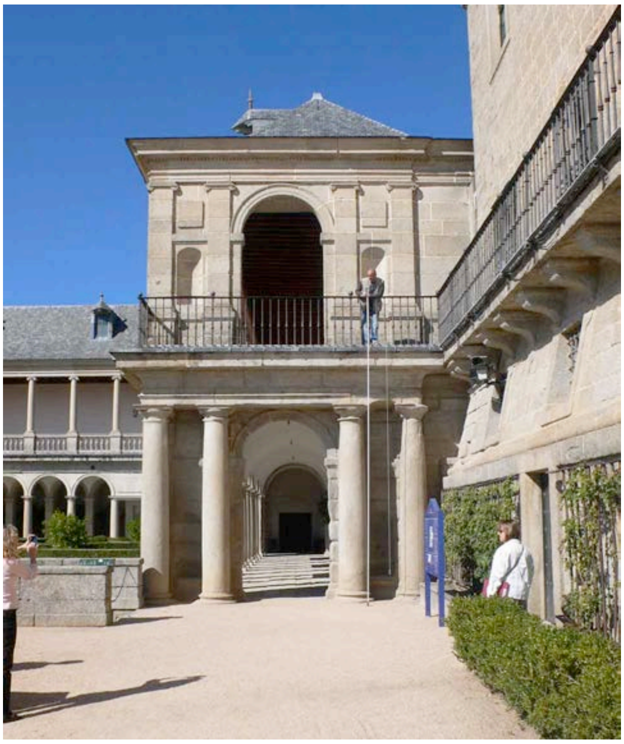

Figure 6. Differences of height between the external station points were directly measured with tape and plumb. Increases lately added were taken into account, as well as the difficulties introduced of the sloped wall of the Monastery's south façade.

Point designation	**Station Point Coordinates**		**Differences in height**	
			Old Castilian Feet (1 feet = 0,2786 m)	**Meters**
External Station Points				
PA	40º 35' 17,90"N	4º 08' 57,06"O	0,00	0,00 (1,028 m o.s.l.)
PB	40º 35' 17,75"N	4º 08' 58,08"O	- 15,00	- 4,18 (1,023.82)
PC	40º 35' 17,21"N	4º 08' 58,07"O	- 15,00	- 4,18 (1,023,82)
PD	40º 35' 58,06"N	4º 08' 58,26"O	- 34,33	- 9,56 (1,018,44)
Internal Station Points				
P1	40º 35' 18,00"N	4º 08' 57,32"O	- 15,20	- 4,23 (1,023.77)
P2	40º 35' 18,05"N	4º 08' 57,38"O	- 24,20	- 6,74 (1,021.26)
P3	40º 35' 17,98"N	4º 08' 57,62"O	- 25,00	- 6,96 (1,021,04)
P4	40º 35' 18,06"N	4º 08' 58,00 O	- 32,01	- 8,92 (1,019.08)
P5	40º 35' 17,26"N	4º 08' 58,28"O	- 32,01	- 8,92 (1,019,08)
P6	40º 35' 17,25"N	4º 08' 58,28"O	- 32,00	- 8,91 (1,019.09)
P7	40º 35' 17,24"N	4º 08' 58,13"O	- 32,00	- 8,91 (1,019.09)
P8	40º 35' 17,19"N	4º 08' 58,16 O	- 32,90	- 9,16 (1,018,84)

Table 1. Coordinates of each control point after correlation process. The origin of heights is 1,028 m over the sea level in Alicante, according to the Spanish High Precision Levelling Network (*Red Española de Nivelación de Alta Precisión*).

2.2.2 Georreferencing in the Spanish National Geodetic Framework: Considering that cellars are positioned in the local reference system, the coordinates must be converted to the Spanish National Geodetic Framework. In spite of using the official utility provided by the IGN, we preferred to use the measurements surveyed with our GPS in order to correlate the local reference network to the trig points of the official Spanish geodesic reference system, which is the European Terrestrial Reference System 1989 (ETRS89).

We used a total station LEICA Viva TS11 with GNSS function that was placed along the previously defined external traverse. As main reference external points we chose as the starting control point the south-western edge of the Tower of the Infirmary, at the ground plan level of the Monastery. This point is included in the official Spanish High Precision Levelling Network (*Red Española de Nivelación de Alta Precisión*), being their coordinates perfectly defined (see Table 1). Other intermediate control points are shown in Figure 7, including the edges of both the eastern and southern porticos of the Gallery of Convalescents at the level of the Friar's Garden (Figure 7). The final control point was set at the orchards level, in the edge of the small window in the soutern façade of the cellar. Data consistency and tolerance were checked along each stage.

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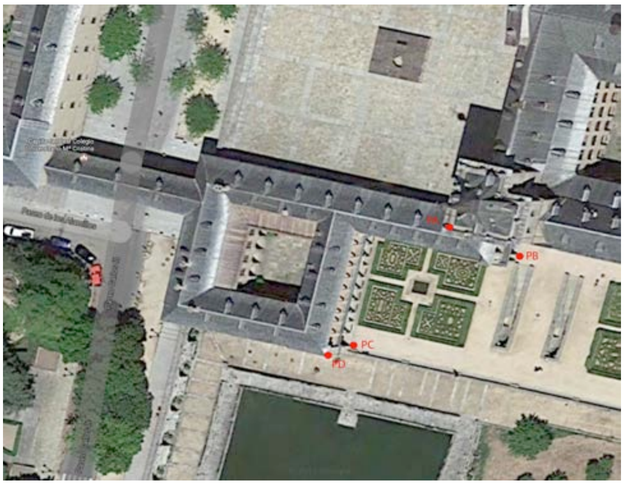

Figure 7. Location of the external control points.

Correlation was easy considering that the external control points were mutually visible, keeping also the intervisibility with the two extreme internal control points. The internal and the external traverses were closed with an error of 0,02 m.

2.3 Laser scanner survey

The laser scanner survey was performed using a pulsed scanner Leica ScanStation 2, with an integrated high-resolution digital camera, and a PC user interface provided by the software Cyclone-SCAN. We made our choice for several reasons, as the improved produtivity related to its very-high speed scanning – with a 50.000 points/sec maximum instantaneous scan rate-, its survey-grade accuracy, excellent range, full field of view, and high sensitivity to different surface reflectivity levels. Its main characteristics are summarised in Table 2.

For general horizontal scans we adopted a work resolution of 3,000 points, while for vertical scans was of 1,200 points (total scan 3,600,000 points).

According to the average accuracy of single measurement, scanning works were planned in order to get at least one point to define each lineal centimeter at every tangent at the measured surface. Thus, proportion between the point size and the minimal distance between points, was optimal.

The average distance between the set of scanning positions was 2 m to 4 m maximum. Because of it, the amount of points in many overlaped areas was highly over the established minimum. Figure 9 shows the position of every scan.

The height of the scanner position depended on the geometry of the various elements to be studied. We used a tripod that placed the scanner station 1,0 m high over the floor level, but in niches and smokestacks it was necessary to place the scan directly on the pavement of the corresponding level. It these cases wee planned the fieldwork in order to avoid a previos levelling. On the stairs we set various scan positions to ensure the definition of every surface, preventing the apparition of blind areas.

Some elements required a higher definition, such as vault intersections, and lunettes. In these cases, we found better to set the scan closer to the element and centered along its axis, than to perform two successive scannings. Scans were also performed at the maximum sphere permited by the station.

System Performance	
Accuracy of single measurement	
Position (at 1 m-50 m range, one sigma)	6 mm
Distance (at 1 m-50 m range, one sigma)	4 mm
Angle	Horizontal 60 µrad / Vertical 60 µrad, one sigma
Modelled surface precision / noise	2 mm, one sigma
Target acquisition	2 mm std. deviation
Resolution	1”, dynamic range +/- 5’
Laser Scanning System	
Laser Class	3R (IEC 60825-1)
Range	300 m @ 90%; 134 m @ 18% albedo
Scan rate	Up to 50,000 points/sec, maximum instantaneous rate Average: dependent on specific scan density and fiel-of-view
Scan resolution	
Spot size	From 0–50 m: 4 mm (FWHH-based)
	6 mm (Gaussian-based)
Point spacing	Fully selectable horizontal and vertical < 1 mm minimum spacing
Maximum sample density	< 1 mm
Field-of-view (per scan)	
Horizontal / Vertical	360º maximum / 270º maximum

Table 2. Main characteristics of the laser scanner.

Figure 8. The laser scanner surveying the upper spaces.

An interesting advantage is the fact that the global 3D model does not need that every scan position must be levelled, as it is automatically corrected by the provided scan software. According to this, we levelled once at the beginnig of each session, and in each change of allignment in the cellar spaces. From the total of 37 positions, seven of them were previously levelled.

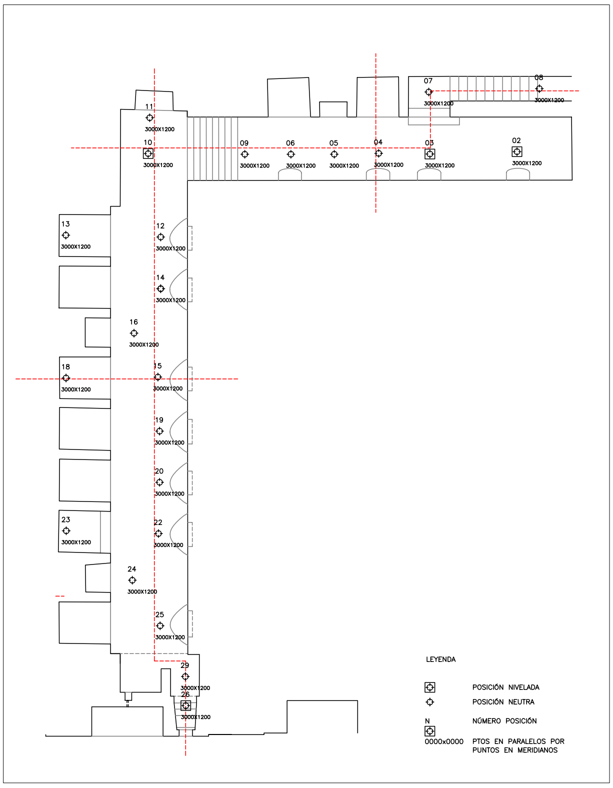

Figure 9. Location of the scanner-laser inside the cellars.

Finally, sensitivity to different ranges of reflectivities showed to be highly interesting to our research, because sometimes mortar joints between the ashlars are blurred, due to sealing plasters, and also to a washed out stonework. Reflectivity allows to detect the different materials, and to find hidden joints. This characteristic became an essential tool to study the stereotomy of vaults, walls, and other stonework or masonry elements in the cellars.

Although scan speed was not essential, it reduced significantly the time taken for fieldwork.

2.4 The 3D Model

Cyclone-SCAN brings many possibilities of visualisation, but also of exchange and export of file and image formats from the scan software to other CAD software. We used AutoCAD and Revit as main drawing and modelling tools, because there are direct export of point datasets ASCII format.

Software permits the connection of the successive scans as it it seen in a 3D visor, allowing the operator to couple each pair of scanned sections, by fitting at least three points on the defined surfaces. The enchainment of these connected sections produces the global 3D model of the cellars' complex spaces.

The produced global 3D model allowed us to produce orthoimages, sections, maps, segmented representations and other digital deliverables useful for researchers, conservators or communicators.

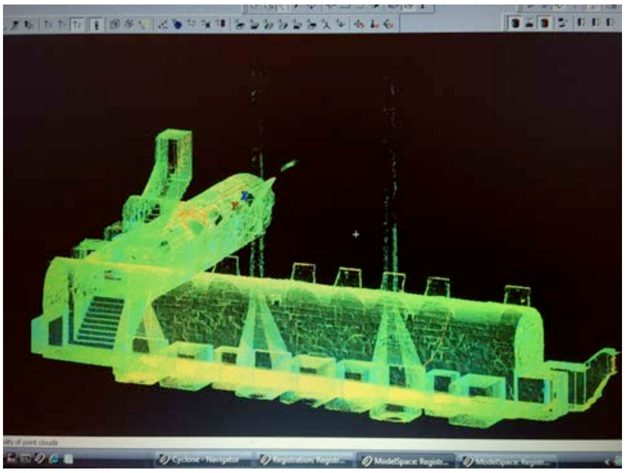

Figure 10. Three-dimensional model of the vault complex. The model was built by composing the sets of data collected with the scanner laser along the field work. Upper and lower main spaces can be clearly seen, as well as the inner stair and the wall-embedded access stair.

Some elements required a deeper knowledge, that was achieved by means of a higher density scanning. This possibility permited to produce some models of elements that are particularly interesting as smokestacks and lunettes, that could not be surveyed using only the traditional methods.

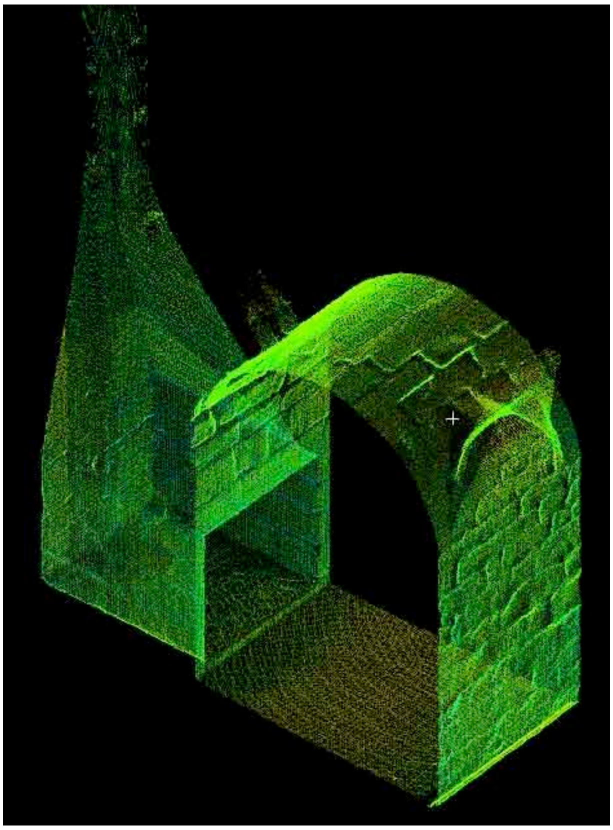

Figure 11. Detail of a smokestack and a section of the vault in the lower cellar.

The 3D model allowed also to develop further interpretations and analyses of the stonework. The stereotomy of the vaults and the walls inside the cellar has proved to be particularly interesting. A deep analyse will permit to put forward some interesting hypothesis about dates and construction periods.

As our aim was neither to check the accuracy of a photogrammetric model, nor to produce great impact images, but to study the stereotomy and the geometry of the diferente elements, we did not superpose the digital photographic images to the 3D models.

Figure 12. The geometry and stereotomy of the inner vaults and their intersections evidence a construction with a varied repertoire of solutions and techniques.

3. PROSPECTIVE: ADAPTATION TO THE INSPIRE DIRECTIVE

The INSPIRE Directive established an *Infrastructure for Spatial Information in the European Community*, aiming to enable the interoperability and harmonization of spatial datasets and services across Europe. There are two main data specifications inside INSPIRE that might concern cultural heritage data: the Data Specification on Protected Sites, and the Data Specification on Area management/restriction/regulation zones and reporting units. These data specifications include the technical documentation of the application schema that defines the content and structure of the data required by one or more applications. Cultural heritage also overlaps the Data Specification on Buildings, for architectural heritage is to be taken as constructed buildings under that data specification (Chías and Abad, 2015).

The simplest application schema is called *ProtectedSite* Table 3). It includes the same stereotypes included on the *INSPIRE Data Specification on Protected Sites* (European Commission 2014), which holds information on various types of attributes as legal issues, geographical and cultural features, and documental aspects, being the minimum information identifier -the only *InspireID*- and *geometry*, as required by the *INSPIRE Data Specification on Protected Sites*. The *inspireID* is the identifier of the protected heritage place within INSPIRE as specified in its generic conceptual model (Drafting Team 2010, 94-98), while *geometry* defines the location and refers to the spatial boundaries defined by the administration responsible for its protection and management; it must be filled in following the ISO 19107:2005.

«featureType» **ProtectedSite**
+ geometry: GM_Object
+ inspireID: Identifier
«voidable»
+ legalFoundationDate: DateTime
+ legalFoundationDocument: CI_Citation
+ siteDesignation: DesignationType [1..*]
+ siteName: GeographicalName [0..*]
+ siteProtectionClassification: ProtectionClassificationValue [1..*]

Table 3. IDEE Working Group 2013, the *ProtectedSite* application schema according to INSPIRE.

This stage of the research is being prepared currently, and it is just presented here as a part of the prospective planning.

4. CONCLUSIONS

Conclusions deal with each different aspect of the research.

In this case the historical drawings were useless, because they were produced from an aesthetical and artistical point of view, lacking of the necessary accuracy and reliability. According to the hand made drafts and sketches that we drew along the successive field work campaigns, and also to the point cloud that was transferred to an AutoCad file, a new accurate 1:50 surveying was produced. It includes some interesting sections of each space.

For this reason orthoimages, sections, maps, segmented representations and other digital deliverables of the building that were produced along the research, are particularly interesting and opportune, becoming an useful material for researchers, conservators or communicators.

The ability that the 3D model has to evidence the stereotomy of the cellars is impressive. It allows to tackle further analysis of the solutions that were sought along the construction period, and also to propose new hipothesis about dates and stages of construction of each element that composes de cellars. To deal with the study of the pathologies of materials and structures is also possible.

On the other hand, both the cultural heritage values and the historical involvements are accurately documented, and a deep research on ancient uses and building techniques is included. An accurate description of the surveying techniques to be applied in GPS disconnected underground areas is also provided. Finally, other remarks related to standardised spatial datasets are discussed.

Elements as the smokestacks or the lunettes can only be surveyed using a laser scanner. The former because of their lenght and narrowness, and the latter due to their complex composed geometry. In both cases some of their sections are inaccesible. Thus, the composed methodology evidenced that traditional method are still useful when surveying historical buildings, and specially if combined with modern digital technologies. In these cases geomatic techniques are not sufficient in order to obtain the required products.

Finally, the spatial component of heritage elements is an essential part of their characterization and value as cultural goods, and the INSPIRE Directive becomes an opportunity to integrate cultural heritage datasets into an interoperable framework, and to share and diffuse them as geographic information. As a prospective task, the web page -that is still under construction-, is taking into account such an important challenge.

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