DIGITAL SURVEY IN BRAMANTE'S MASTERPIECES

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ABSTRACT:

This paper is part of a current of researches that deal with the survey of Cultural Heritage as the first tool of knowledge and dissemination of the memory and value of ancient architecture. The progress of survey techniques and the spread of new tools and measurements instruments obliges frequents update in our project; the survey also compares itself with progression over the time, especially when the context of interest is broad as in the case here described. Here the complex of Santa Maria delle Grazie has been surveyed starting from the Chiostro delle Rane and Old Sacristy, including the room of the Candle man, by Donato Bramante, the Chiostro del Priore, built through the years with the aid of Beltrami and Portaluppi, and the New Sacristy. The cathedral survey and the Last supper room together with The Chiostro dei Morti has not yet been included; this first part has been considered as a first cross section enough to present first problems, techniques and aims. In addition, the destination of the survey in progress has been evaluated on a broad spectrum: from comparison with other Bramante's masterpieces to the map rendering of some of its decorated parts to the construction of simple meshes for the reconstruction of virtual environments. This is the reason why some part of the complex has been surveyed with more attention and high-detail while other with more simplicity and low-detail, not only to spare time.

1. INTRODUCTION

The relationship between the survey and digital modelling of Cultural Heritage has changed over the years to significantly modify research expectations, opening up the field to extremely promising outputs both in the field of metrological accuracy and iconographic completeness. A deep knowledge of a building starts from a measured object, sets of points shaping surfaces which are the first raw outputs of a survey. Accuracy of the measurements, speed of data acquisition, eventually high detailed reconstruction are the main advantages of a digital survey. This paper deals with the most recent experiences of comprehension of architecture starting from a 3D survey with the integration of different techniques and technologies.

The case study is the basilica and sanctuary of Santa Maria delle Grazie in Milan, very famous for the presence of Leonardo's painting the Last Supper host in what was once the old refectory of the Dominican monastery. The digital survey idea and interest started from the desire to give more results to a different part of the monastery, not the celebrated painting nor the cathedral but: the Renaissance Chiostro delle Rane (Figure 1) with the small room of the Candles man, both of Donato Bramante; the Old Sacristy and the New Sacristy (subject to several interesting transformation) as a connection between the main part of the convent and the Cathedral; the more recent cloister - Chiostro del Priore - untouched by second world war bombing but changed and re-planned by some important architects such as Luca Beltrami, Alessandro Pica, Piero Portaluppi. It must be said that however interesting the architectural complex is, it is not very well known because the Last Supper focuses the whole attention on itself and the Cathedral with its Tiburio and vaults as well. Nevertheless, the complex stories of a part of the convent linked to the Renaissance time with the duchy of Ludovico il Moro as well as the reconstruction of the monument after the 1943 bombing deserve a specific narration both from the side of architecture and historical events.

As the monument was subjected to various structural modifications, demolitions, and reconstructions in the centuries an archive and digital 3D survey campaign can be a very helpful instrument to interpret and understand the history of its transformations. For this reason final aims of the survey are to (i) extract each kind of metric and geometrical information. (ii) elaborate classic 2D drawing (floor plans, sections, elevations, ortho-images) and actualize the existing ones. (iii) develop a metrological study comparing historical information and maps. (iv) realize 3D reconstruction of each historical construction phase. (v) use all data for dissemination and promotion purposes also taking advantage of Virtual and Augmented Reality applications.

An integrated approach of range and image-based 3D survey techniques is mandatory because of the complex shape of the structures and the various purposes listed (Menna et al., 2016; Fassi et al., 2011). In these cases, perhaps one of the first and more common problem is the colour information of the 3D data, very important for dissemination and valorisation purposes (Cipriani, Fantini, 2017). In order to have a mesh model with a good resolution texture and above all a metric correspondence (pixel-to-point) between the geometric detail and the radiometric data, the most suitable approach is a photogrammetric acquisition. The laser scanner allows having coloured point clouds but the quality of the images obtained both in terms of resolution but also chromatic quality does not satisfy the needs of a quality texture. Thanks to the constant technological developments over the past few years, laser scanner instruments are now equipped with integrated cameras that allow the acquisition of HDR images (3-5 bracketing).

However, the integrated cameras never guarantee the same flexibility and freedom of setting management of a reflex camera that, on the other hand, allows not only to provide an

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incomparable resolution but also to manage, for example, a correct white-balance, colour dominants, exposure, etc.
Moreover, a photogrammetry approach, can easily reach to capture the undercuts of column and capital also, that could not be physically reached with a less manageable laser scanner. On the other hand photogrammetry can have problems with the white surface of the cloister that is poor of features for the matching algorithms, and no many markers can be attached on the monument. So a TLS survey was chosen to a have a whole geometry of vaults colonnades etc. (e.g. for the cloisters) and the photogrammetry was used only to add some colour information in some cases such as in the Old Sacristy.
The paper presents only the first phase of the studies: various topics - still under development - are presented to better understand the choice of survey methods and instruments. The interest of this article is focused on the description of the workflow used for the data processing from the raw point cloud to final 2D and 3D graphic representations to better understand the sequence of transformations of the complex.

Figure 1. The Chiostro delle Rane and a view of the Lantern of the Cathedral

2. RELATED WORKS

The use of an interdisciplinary approach of direct survey, terrestrial laser scanning, photogrammetry, 3D modelling for BIM or virtual construction crosses the research field with different purposes according not only to the destination of the survey but also to the scientific interests of the authors (Russo, Guidi et al., 2011). The aim to test the best workflow for Cultural Heritage 3D reconstruction (Remondino, 2011) analyzing their complexity and the specific case studies has been faced to test general workflows (Camagni, Colaceci et al, 2019) and there are several attempts to systematize it (Brusaporci, 2015). Many studies have been developed with specific attention to unusual geometries such as vaulted ceiling, decorated and painted also (Adami, Scala et al. 2017), complex curved surfaces, unusual geometries (Clini, Nespeca et al. 2019) and many ornamental details.
After the first studies for 3D acquisition and modelling now the comparison deals with different technique and workflows regarding data acquisition, pre and post processing, modelling, (Balzani, Maietti, 2016) looking at different interoperability problems coming from data integrating from one tool and software to another one. After technical problems of data integration between photogrammetry and laser scanner have been solved, the main researchers focus now on the relationships between meshes modelling and the texturization of the model for different needs: from diagnostic analysis to the virtual reality and serious games. Three-dimensional survey methods give many advantages to architectural, archaeological, and cultural heritage studies giving the possibility to produce virtual reproductions of the investigated object to be experienced in VR and AR applications (Palma, Spallone et al., 2019) for didactic and touristic purposes (Dhanda, Rehina et al., 2019).

3. THE CASE STUDY AND ITS HISTORY

3.1 The beginning and Renaissance

The history of the convent starts in the middle of 1400 where the church was realized from 1466 to 1490 by Guiniforte Solari with the assistance of the Dominican friars for the general guidelines. The convent was finished before the church to allow the friars to live in with respect to all the need of the confraternity (AAVV 1937).
The list of the convent's program is simple: church, internal cemetery, chapter room, refectory, dormitory. Other cloisters will follow the program just to organize daily life in the convent, as a vegetable garden included for self-autonomy of the fraternity. At the beginning of the design some constrains gave the peculiar structure of actual morphology: a pre-existing military camp located in the area, but mostly the pre-existing chapel of the Madonna determined the unusual relationship between the apse of the cathedral and the Chapel itself. The refectory was completed in 1488 and frescoed close to 1500. Before the new century the whole main structure was completed.
During the full Renaissance who saw Ludovico il Moro as duke of Milan he decided to allocate in the church the monumental tombs for himself and his family as his first loved wife Beatrice d'Este had already dead. It is in the attempt to modernize the whole complex according to the dictates of the Renaissance that he called Donato Bramante to add the Chiostro delle Rane and the Old Sacristy completed of a long and narrow underground passage to reach the Castle. A small gap between the apse of the church and the Chiostro delle Rane, vaulted and decorated with similar features of the Old Sacristy was probably conceived by Bramante himself. The famous lantern was probably conceived by himself but then given to other workers.

3.2 After the 1943 bombs

After May the 7th 1799 the suppression of the convent took place. Some minor works happened during the first years of 1900, Luca Beltrami was involved in them, while previously several documents regarding the opening of new roads around the Church made necessary to intervene to clean old and fainting buildings that over the centuries had been built near or adherent to the complex. New view to the monument were opened. A part from those years a second important transformation of the complex took place through the reconstruction due to the bombers in August 15th1943. We have two documents that give us a precise representation of the situation before and after the bombs: a complete survey of the complex by Agnoldomenico Pica and Piero Portaluppi in 1937, due to a request for renovation of the monument and a complete map related to a description of Friar Gattico with the destroyed parts of the convent highlighted. The Chiostro dei Morti, the library, the refectory and the left side of the church were completely destroyed; all the attention was focused on the saved Cenacle.

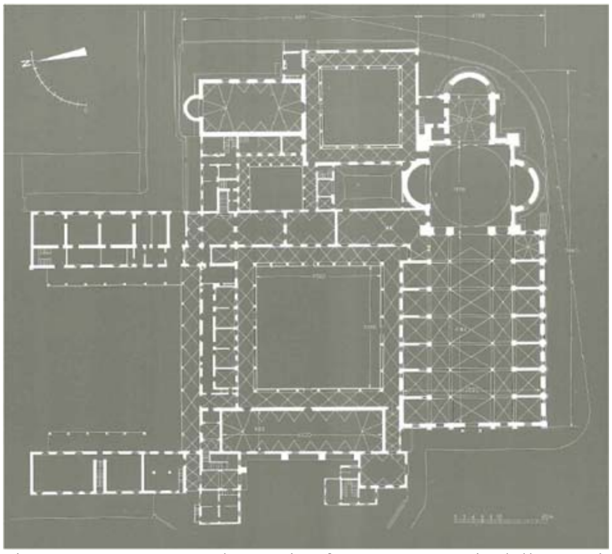

Figure 2. 1937 Survey by A.Pica from Santa Maria delle Grazie in Milano, Milano, 1983.

Figure 3. The devastation of Santa Maria delle Grazie after the 1943 bombs seen from the Last Supper wall.

Figure 4. The Cloister of Priore, after the II World war, partially demolished even if not touched by bombs to develop a new entrance of the convent.

The friars had prepared a special reinforce before the bombs with sand bags. The post-war reconstruction was only partial and told with suffering in the archive documents: a long dialogue between the Dominicans, the Offices and the Architects. Main efforts were concentrated on the demolished parts to be completely rebuilt following historical documents. In spite of this the different levels of via Sassi with respect to the cloisters ground level, the presence of the Old Sacristy that had remained undamaged during the war, the opening of new perspectives on the Bramante's lantern were the cornerstones for launching a strong debate starting at the end of the 40s till the end of 50s. What appears to be still partially known concerns the reconstructions of what was known as the Chiostro del Priore and which had not been affected by the war events but more than once designated as a possible location for a new entrance to the convent. Different architects were involved in its definition: Frisia, Pica, Portaluppi, Bernasconi. The work went on between partial demolitions requested for funds and partial reconstructions up to a project signed by Portaluppi and Bernasconi which in 1959 designed the cloister in fake Renaissance features, opposing a closure to Via Sassi but at the same time freeing the volume of the old Sacristy. These transformations through the centuries can be easily described through successive representations that can simulate virtual construction of existing and no existing parts focusing on comparison of historical documents and drawings and on the definition of the monument's real geometrical reliability. For this initial stage of the research the 3D survey of the Chiostro delle Rane, Old and New Sacristy, and the Chiostro del Rettore that are the areas subjected to more transformation was performed.

4. THE WORKFLOW

This research aims at testing a complete and integrated workflow used for the study project of the Santa Maria delle Grazie sanctuary. The main steps of the 3D survey management were: (i) acquisition of historical data (documents, photos, paper drawing, and maps) helpful to understand the architectonic evolution and the current condition of the heritage. (ii) 3D survey applying range and image-based systems. (iii) elaboration of the raw digital data. (iv) optimization of 3D point cloud reconstruction (points cleaning and filtering; point-to-point space regularization above all there are many overlapped areas; eventual decimation, etc.) that represents the complete geometrical shape of the measured building.
A following step consists of the following sub-points of the standard well-known image-based workflow based on the combination of photogrammetric principles and computer vision algorithms: (a) Photos alignment (internal camera self-calibration and external cameras orientation). (b) Encoded markers recognition to optimize the parameters calibration (passage strongly recommended but not mandatory). (c) 3D points reconstruction (in general sparse cloud) scaling. (d) Dense matching to generate a high-detailed 3D point cloud (Remondino et al., 2014).
The process of sparse cloud and dense cloud generation is based on procedures (Structure-from-Motion – SfM e Multi-View Stereo – MVS) that have become completely automated and that are able to process a large number of images (Remondino et al., 2017). The 3D scene reconstruction (estimation of the 3D coordinates of the sparse cloud from 2D images – step a) is a process simultaneous to the external orientation of the cameras.
Instead, the third step for Terrestrial Laser Scanner - TLS approach consists of point clouds (a) scans alignment in the same coordinate system; (b) single point cloud filtering and removing poor points and (c) merging of the scan in a single and complete cloud. The typical TLS errors and noise that affect the points are

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due to: (i) dark surfaces that absorb a large part of the emitted laser so that it returns with a week intensity. (ii) orientation of the laser beam direction (incidence angle) too tangent to surface. (iii) surface roughness. (iv) edge effect when the beam hits a corner and a part of it is reflected while the rest continues its path until it meets another obstacle. The more common scans registration method can be target based or target-less using Iterative Closest Point algorithm (ICP). The first approach requires more time during the on-site survey for the organization of the targets placement and consequent stations positioning (it has to be ensured a minimum of three target between two consecutive scans). Instead, on-office the alignment process is fast (with encoded target automatically recognized from the software) and it can be possible to check the registration error on the single target. The employ of targets is absolutely recommended for a georeferencing. Using the second method the planning time of the relative positions of targets and stations is recovered but a higher number of scans is required because of a good overlap (50%) among the scans is mandatory; in addition, the registration process may need more time. The choice depends on the instrument speed of point acquisition but also on the site practical characteristic, for example, how much time is possible to stay on-site? Is it possible to attach planar markers and leave them for several days? Is it possible to close the working area (tourists can cover the markers and move spherical or cylindrical targets)? Split the survey many times is more complicated than to manage one target survey in a historical site.
The final point cloud, after the optimization process, is the starting point of any kind of other elaborations. Directly from the 3D point model is possible to develop metrological analysis, extract 2D technical drawings, and compare the current geometry with the historical phases and structural transformations.
The polygonal model generation and its eventual texturization are useful for VR and AR application. Moreover, the mesh model can be used for the rendering of the 3D reconstructed scene and/or to create a promotional video. It is also possible a cad modeling based on historical data to reconstruct the different building structure hypothesis during the centuries. These models can be used to compare the current state with the building past and to understand its evolution.
Finally, another way of heritage promotion and enhancement is the possibility of publishing all these collected and elaborated data - so different from each other- online on web platforms, e.g. 3D HOP (Visual Computing Laboratory, 2018) and BIM3DSG system (Rechichi et al., 2016; Fassi, Parri, 2012). These systems allow visualizing, study, and interacting with 3D models and 2D sources (textual, photos, documents, etc.). The possibilities offered by 3D and web sharing for cultural heritage dissemination are endless.

5. SANTA MARIA DELLE GRAZIE SURVEY

TLS survey was performed of five main spaces of the Santa Maria delle Grazie convent: 1) the Chiostro delle Rane and 2) the Old Sacristy and 3) the very small room of the Candle Man built by Donato Bramante; 4) the more recent smaller cloister by Luca Beltrami - Chiostro del Rettore; 5) and the New Sacristy. In Figure 5 the scan stations performed for the TLS survey of Santa Maria delle Grazie listed areas of interest of are shown.

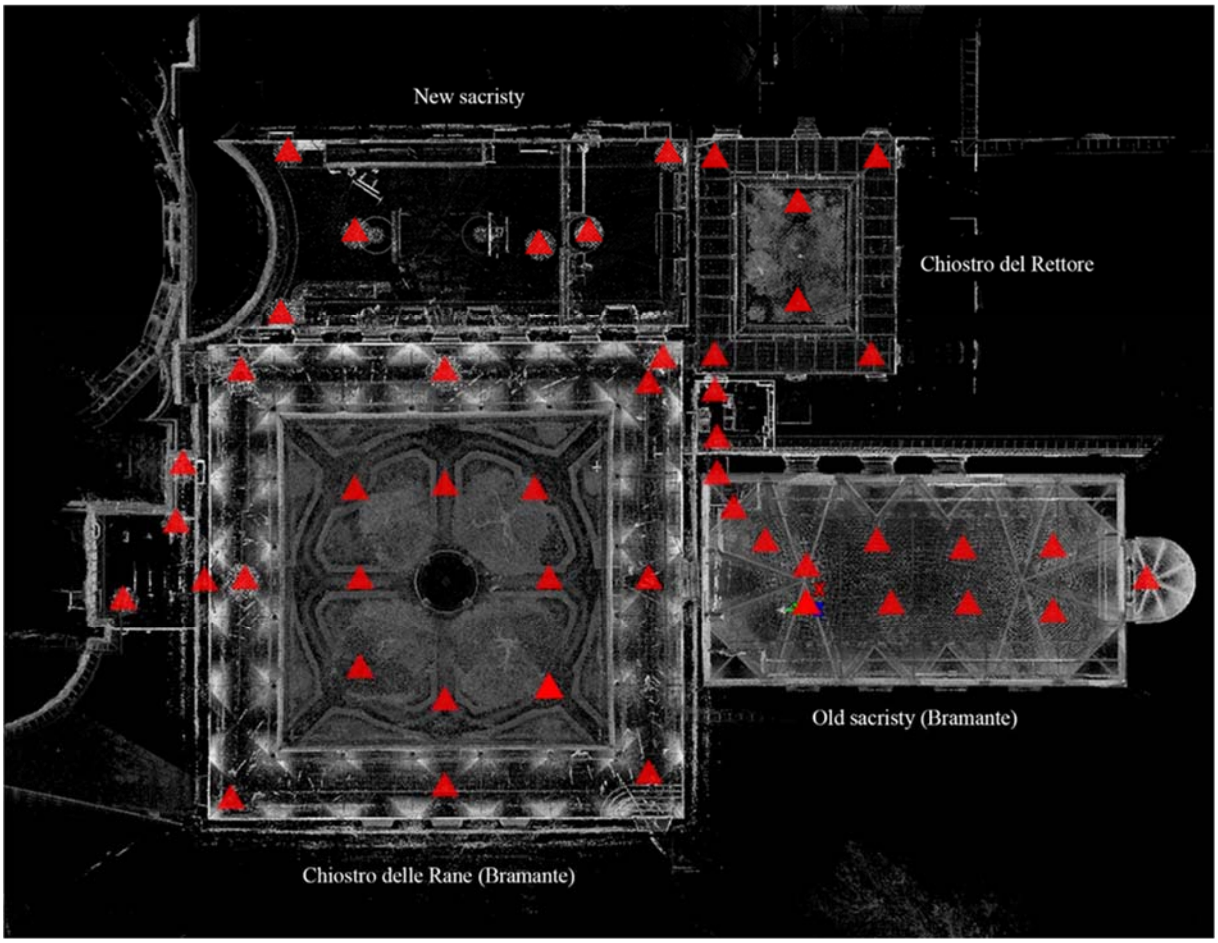

Figure 5. The scan stations performed for the TLS survey of areas of interest of Santa Maria delle Grazie

	Historical photos/ document	TLS	Photogramm.
Chiostro delle Rane (Bramante)	Ancient maps of Milano, Drawings from 1800 Pictures of the 1900	Leica HDS 7000 16 scans (8 vaulted colonnade and 8 cloister) 6mm@10m	CanonEOS 70D 18 mm
Old Sacristy (Bramante)	Ancient maps of Milano, Drawings from 1800 Pictures of the 1900	Leica P30 10 scans (8 - 6mm@10m 2 - 3mm@10m) and panoramic image acquisition	
Room of Candle Man (Bramante)	First survey from Pica	Leica P30 3 scans 6mm@10m	
Chiostro del Rettore	Survey before the II world war, images before and after it, plans, picures	Leica P30 6 scans 6mm@10m	CanonEOS 70D 440 photos with a fish-eye lens (8 mm) 185 photos with a rectilinear lens (18 mm)
New Sacristy	Reports regarding its renovation from Dominican	Leica P30 6 scans 6mm@10m	

Table 1. The different type of acquisition performed to date for the case study

A close range photogrammetric acquisitions were used to integrate the TLS survey. In Table 1 are synthesized the different type of acquisition performed to date for the case study: historical documents and drawing, mapping, historical photos, TLS, and photogrammetric measurements.
Due to practical constraints related to the days available for access with the instruments in the areas of the convent and the social events in the historical site, the surveys were carried out in two days and with two different Leica laser scanners.
A target-less alignment for the scan registration was chosen not to be possible to leave any type of targets in the building and impossible to complete the survey in one day. Therefore, due the impossibility to leave a fixed reference to link the survey of the second day, a cloud-to-cloud registration was preferred for the whole project. In this way, the work time on site has been reduced since it is not necessary to put the targets. The choice of scan stations has been simplified but obviously, the number of necessary scans has increased. In fact, in order to have a good target-less registration, a considerable overlap (50%) is required among subsequent scans. The redundancy of points in overlapped areas guarantees a good accuracy of the alignment process (Wujanz et al., 2019).
The registration was performed dividing the process for blocks. First for each main areas (the 2 cloisters and the 2 sacristies), a cloud-to-cloud alignment was processed and optimized. Then using connecting scans these 4 blocks were aligned together in the same coordinate system. In Figure 6 it is possible to see horizontal and vertical slices of the aligned scans, represented with different colors. It is a very useful representation to perform a visual check of the good registration. In the figure, no misalignments are seen and in the zoom detailed the circular shape of the column is correctly aligned.

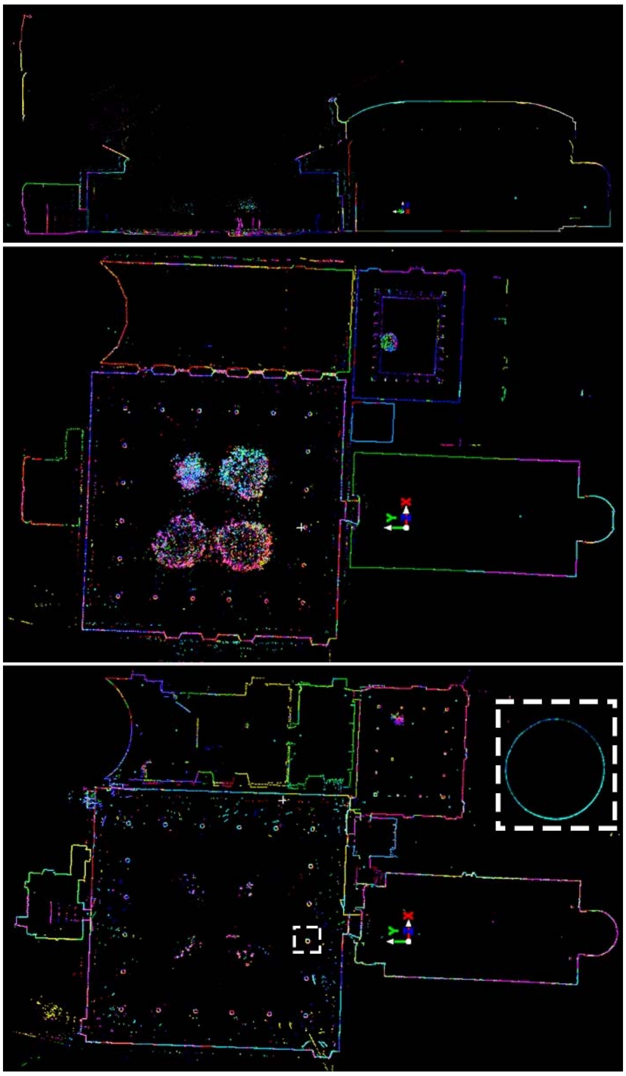

Figure 6. Horizontal and vertical slices of the aligned scans, represented with different colors: no misalignments are seen and in the zoom detailed the circular shape of the column is correctly aligned

The HDS 7000 was used to survey Chiostro delle Rane with 16 scans (8 to capture the vaulted colonnade and 8 to the inner cloister) and a scan resolution of 6mm at 10m distance. The Chiostro del Rettore, Old Sacristy and New Sacristy were measured with a Leica P30. For the Old Sacristy was needed 10 scans (6mm@10m resolution) of which two at higher position and with higher resolution (3mm@10m) in order to have more detailed of the vaulted roof. Moreover in the same time of the geometric acquisition was also captured panoramic images with the scanner-integrated camera to have colored point cloud. A low point-to-point density was set (about 12mm@10m) for the 4-connection scans between the Old Sacristy and the Chiostro del Rettore. This space was surveyed with 6 scans and a resolution 6mm@10m. Moreover, two photogrammetric acquisition was performed with a Canon Eos 70D: 440 captures with a fish-eye lens of 8 mm and 185 with a rectilinear lens of 18 mm. An image-based approach was chosen in order to add colour information to the digital survey and obtain final a textured mesh. Also for the Chiostro delle Rane, some partial photogrammetric acquisitions have been made on some details (an altar, a fresco, a capital, a column, an epigraph, a bas-relief, etc.).

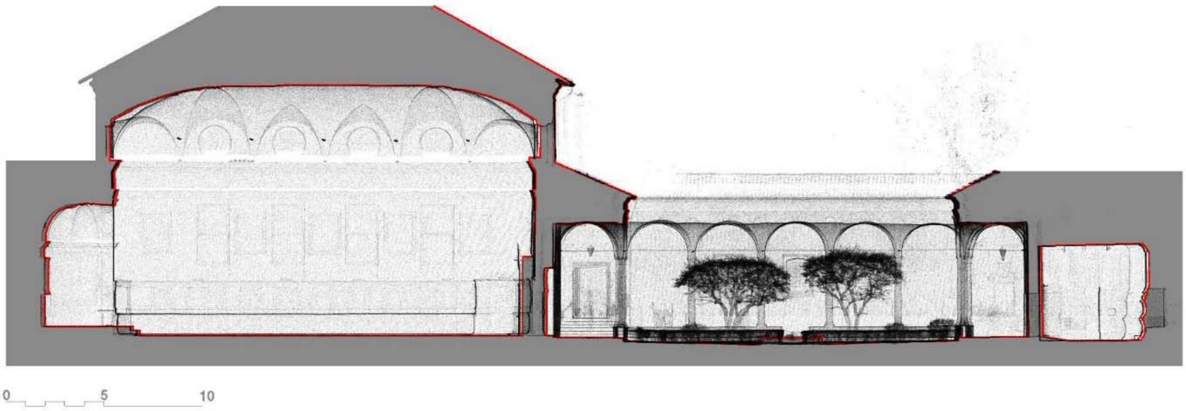

Figure 8. A longitudinal section on the Old Sacristy (left), the Chiostro delle Rane (center) y the room of Candle Man (right)

Figure 9. A detail of the longitudinal section at 1:100 scale

In Figure 8 there is a typical example of 2D technical drawing that can be extracted from the final point cloud. It is a longitudinal section on the Old Sacristy, the Chiostro delle Rane y the room of Candle Man. Figure 9 shows a zoom of the drawing at 1:100 scale where it is possible to observe the geometrical detail of the point model.
In Figure 10 there is a simple comparison between the TLS survey output (top view of the point model) and a historical drawing of the Complex: the evident difference is between the dimensions of the Chiostro del Priore that in the old floorplan is larger and with different morphology.
Finally, (Figure 11) there is a visual compare between two perspective view: the 3d point cloud and the sketch of the lantern in a historical drawing around 1959.

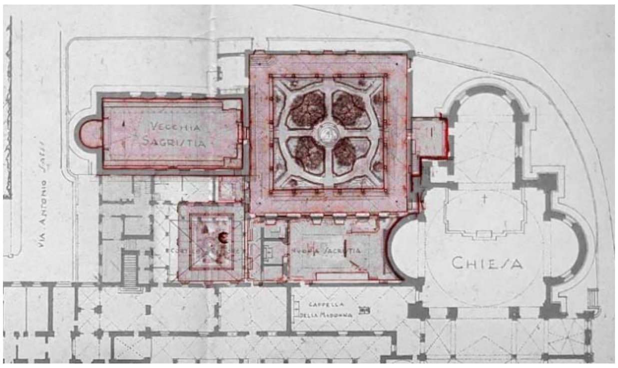

Figure 10. A comparison between the current survey (red) and the drawing of a survey before the second world war: the Chiostro del Priore in the old floorplan is larger and morphologically different.

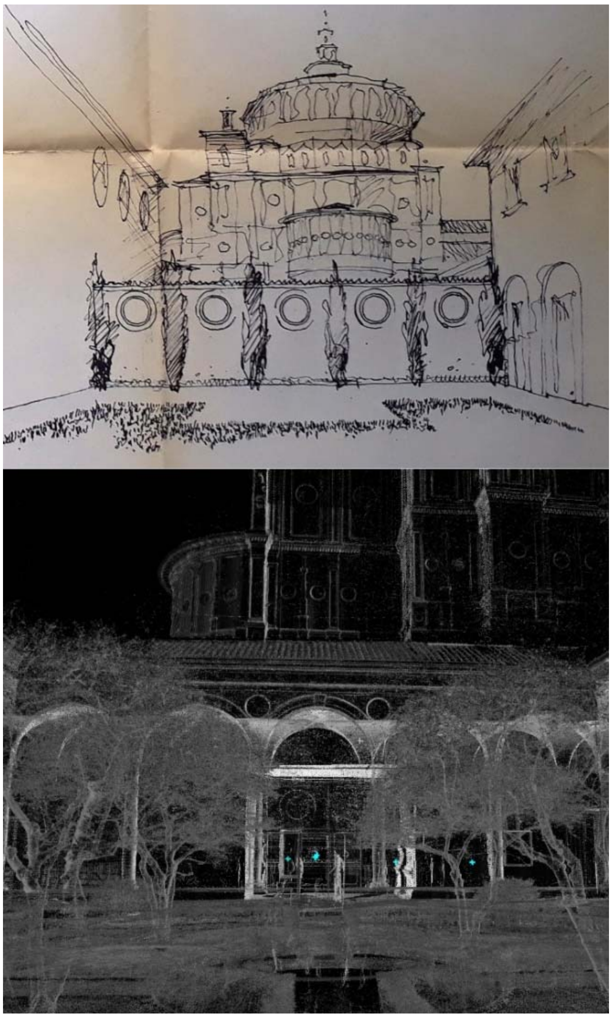

Figure 11. A visual compare between two perspective view: the 3D point cloud and a sketch from a proposed solution of the 50th from via Sassi with a view on the Lantern.

6 CONCLUSION

It is the first time that the Convent of Santa Maria delle Grazie is surveyed with technical instruments and integrated multi-scale 3D acquisition. The methodology of survey acquisition between TLS and photogrammetry is consolidated and considered as a reverse modelling starting from architecture where the final model is a complex workflow of shape simplification. This first step here described has considered more average internal errors than real comparison between actual and the precedent survey campaign; all the average errors can actually be really compared in terms of alignment of walls and morphology of spaces and not in terms of metrical accuracy among this survey and the historical ones. In facts, the whole documents examined in the archives of the Municipality are generally printed maps of ancient drawings, scale far lower to the detail obtained from the actual digital survey, and represent a low scale of detail, with a description mainly close to 1: 200. The meaning of our detailed survey can’t be definitely considered for the global distance between our model and the historical ones. The 3D model itself is a master that has only one reference point, the Monument itself; for this reason it becomes a benchmark for all the hypothesis linked to the previous growing and demolition of the convent; it is the only possibility we have to build a real history of this Monument. The 3D model obtained in fact can allow morphological and structural analysis and many other researches, contributing to the debate on the process from acquisition of metric data to the 3D modelling. Considering the richness of data acquisition, their semantic meaning despite different methodologies and tools, any interpretation phase is possible; nevertheless, data elaboration phase is quite time consuming and must be finalized to precise objectives every time. This can be considered the highest value of a digital survey for the knowledge and dissemination of Cultural Heritage.

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