MOBILE MAPPING FOR CULTURAL HERITAGE: THE SURVEY OF THE COMPLEX OF ST. JOHN OF THE HERMITS IN PALERMO (ITALY)

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ABSTRACT:

During the 11th and 12th century, the Arab-Norman architectural style characterized the most beautiful and important Cultural Heritage buildings in Sicily, and especially in Palermo (Italy). The relevance of these monuments is highlighted by their inclusion in the UNESCO World Heritage Sites List in 2015. For many years, the University of Palermo has been studying and documenting several Arab-Norman cultural assets, and in particular, the complex of St. John of the Hermits in Palermo (Italy). A first detailed 3D survey of the main structures of this complex was carried out using a terrestrial laser scanner while the 3D survey of the entire complex was made using a Mobile Mapping System (MMS). The paper describes the workflow and the results of the mobile mapping survey undertaken with a Handheld Mobile Laser Scanner (HMLS) based on Simultaneous Localisation and Mapping (SLAM) technologies. The work allowed surveying the entire site with an extremely fast acquisition and obtaining the geometric information useful for historical architectural evaluations. In addition, due to the characteristics of the site, the work enabled the assessment of the HMLS data processing testing different automatic algorithms for point cloud filtering.

1. INTRODUCTION

Cultural Heritage (CH) sites are often characterised by complex conditions which make 3D survey operations particularly difficult; these conditions may be due to the morphology of the site, the presence of architectural/archaeological elements overimposed and stratified over the centuries, with different monumental buildings, possible ruins to be preserved, new archaeological findings (Auteliano et al., 2022; Ebolese et al., 2019; Scianna and La Guardia, 2019). Due to this variability, technologies for 3D digitisation of large-scale sites must be versatile, reliable, and efficient (Zlot et al., 2014). Recent advances in Geomatics enabled the use of a wide range of sensors for point clouds acquisitions in CH sites, to be adopted from case to case according to several factors, such as the scope of the investigations, the complexity, and the dimensions of the environment to be digitised and the optimisation of the process (Pepe et al., 2022). Imaging or ranging measurement systems not only must be apt to the survey purposes but must be balanced as well against the desired accuracy, the time of acquisition, the consumption of resources and the limitations which affect each capture methodology (Lo Brutto and Spera, 2011; Masiero et al., 2018).

As it is well known Terrestrial Laser Scanning (TLS) is a static-capture method according to which the device performs a scan at a time from one fixed location (Wu et al., 2022). The process is reiterated until the whole area has been covered moving the laser scanner in different placements until the desired final point cloud resolution has been achieved. Mobile Mapping Systems (MMSs) provide instead a continuous laser scanner acquisition in place of few discrete scanning positions required by TLS thanks to the capability of calculating the trajectory of the device (Gollob et al., 2020). In this case, acquisitions are made while the operator moves the laser scanner, fixed on non-stationary platforms, along one or more paths in the environment to be captured (Sammartano and Spanò, 2018). These devices can be vehicles, backpacks or handheld systems. The first two are based on a Global Navigation Satellite System (GNSS) receiver and an Inertial Measurement Unit (IMU) to determine the positioning and orientation of the laser scanner. This configuration, based on the number of satellites reachable by the GNSS receiver, limits their use to environments with relatively open visibility (Del Perugia et al., 2019). The greatest concern in the use of these MMSs is whenever the GNSS signals become weak or missing at all, which makes these systems unsuitable. In order to overcome this issue, nowadays the latest devices, especially Handheld Mobile Laser Scanners (HMLSs), are capable of digitising complex 3D scenarios on the move without recurring to satellite positioning (Bauwens et al., 2016). Indeed, thanks to the Simultaneous Localization and Mapping (SLAM) algorithms, HMLS can acquire data with simultaneous point cloud registration and map extraction (Alsadik and Karam, 2021). Beyond their being the least expensive among the MMSs, HLMS are portable and compact devices, advantageous to measure narrow spaces with occlusions, extensive areas with the presence of dense vegetation and uneven terrains, where geometric references are scarce (Sammartano and Spanò, 2018). They are very useful to capture outdoor or indoor environments whenever they are difficult to be reached, as experimented in a wide range of applications not only for CH sites but including, i.e., forest inventories and narrow places, such as canyons and pits as well (Akpinar, 2021; Ryding et al., 2015; Xin et al., 2022). Comparing TLS and HLMS technologies, HLMS offer more uniform coverage with less occlusion, helping to reduce the time on-site for data acquisition and their successive elaboration (Nikooehmat

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et al., 2017). During an HLMS survey, the points' measurement is much faster than TLS and acquisition time is no longer considered a problem except for the autonomy of the devices (Frias et al., 2022). HMLS systems usually offer a centimetre-level accuracy whilst the resolution of captured data depends on the acquisition speed and the distance to the object at each moment (Cabo et al., 2018). Point clouds resulting from HMLS are often less precise and noisier than TLS ones, due to the propagation of positioning errors within the SLAM algorithms (Del Duca and Machado, 2023). These errors could be evaluated against geometric primitives on simple constructive elements, such as horizontal and vertical planes and cylindrical items. Usually, the accuracy of HMLS data is benchmarked against TLS data of the same captured scene, with different methods (Kalvoda et al., 2021). After taking all these circumstances into consideration, HMLS represent an advantageous solution for the digitisation of complex and extended CH sites.
The work aimed at documenting and surveying a whole architectural complex with the use of a HMLS. In particular, the study was focused on the Arab-Norman complex of St. John of the Hermits in Palermo (Italy). The Arab-Norman architecture represents a paradigmatic case developed thanks to the peaceful relations of different cultures; these successions and mixtures are a tangible evidence in CH artefacts of that time.. This activity is motivated by the relevance of the site since the complex and other famous coeval monuments were included in the UNESCO World Heritage Sites list in 2015. Various activities were already undertaken by the University of Palermo for the 3D survey and documentation of these sites (Allegra et al, 2020, Aricò and Lo Brutto, 2022).
This knowledge is aimed at supporting design proposals which, considering both the architectural and technological aspects for in-depth analysis at many different scales, interpret the history and the spirit of the monument. In this case study, the coexistence of two different cultures (the Arab and Norman) are peculiar features of the cultural asset, defining its architectural style. Besides, the monument also shows the themes of continuity, stratification, and innovation over the centuries. For this reason, a detailed 3D survey was needed in order to obtain a complete knowledge of the site.
Actually, part of the complex (the homonymous church and the so-called "Islamic Hall") has been surveyed in a previous TLS acquisition, aimed at obtaining a Heritage Building Information Model (HBIM) of the two buildings alone (Aricò et al., 2023).
The mobile survey captured the remaining parts of the complex which were excluded from previous activities since it has a complicated logistical situation (a garden with dense vegetation, confined interior spaces, etc.).
The research has also allowed to compare different solutions for mobile point cloud processing. To remove inconsistent information (mainly the vegetation) from the ground data, some automatic filtering algorithms (from commercial and open-source software) were tested. The results were evaluated in comparison to a not-automatic filtering operation.
The mobile point cloud processing allowed to model the ground surface of the entire monumental complex and to provide a useful product for evaluating the stratigraphy of the site.

2. THE COMPLEX OF ST. JOHN OF THE HERMITS

The complex of St. John of the Hermits covers an area of approximately 2500 square metres in the historical centre of Palermo (Italy) and is a result of human and cultural stratification over the centuries. The monumental complex was named after the Gregorian monastery of St. Hermes built in 581, replaced in 842 by a mosque whose ruins are still partially visible today. Together with the main homonymous church, built on those ruins, it includes a rectangular room (the Islamic Hall), a huge hanging garden with dense vegetation, a cloister and the abbot's residence (Figure 1). There were also a dormitory and a refectory, which no longer exist, whilst an Islamic burial ground was partially discovered under the church in 2016. Traces of the destroyed Benedictine monastery are still visible on the perimeter walls.

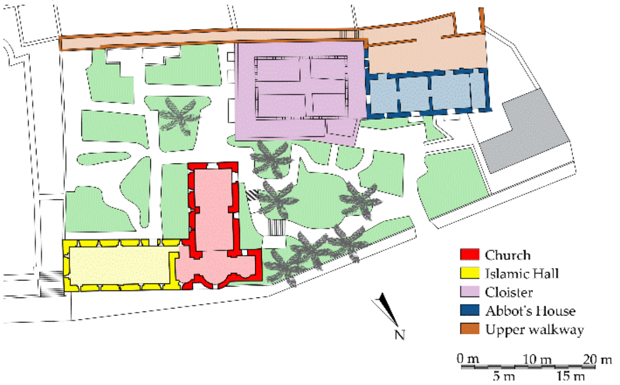

Figure 1. Plan of the whole complex.

The church was built in 1132, heavily altered during the 16th century and restored to its harsh original appearance in 1880. Its plan is made of five different-dimensioned cubic spans, running orthogonally to shape a commissary cross with a single nave and a protruding transept divided in a central chancel and two lateral rooms, a *diaconicon* on the left and a *prosthesis* on the right. The walls are made of bare sandstone ashlars with a row of lancet arched windows which, together with the five hemispherical domes on top of each span and the bell tower, are typical elements of the Arab-Norman architectural style and one of the most iconic images of Palermo. The Islamic Hall, adjacent to the north-eastern side of the church, is the only part of the previous mosque still standing. It has been embedded to the main building and re-used for liturgical purposes as well, proved by traces of frescoes representing the Madonna between two saints. The cloister has a rectangular plan with open-air walkways running on the perimeter with lancet arches supported by slim double columns and an entrance in the middle of each side (Figure 2).

Figure 2. The interior of the complex: the cloister.

In the garden, there is a lowered arched domed well, slightly out of the centre of the crossroad. The abbot's house is accessible from the northern side of the cloister; this is a two-storey building with four rooms covered by false vaulted ceilings, typical of the 17th century. The Benedictine monastery was built in the western side of the area, in correspondence with the current homonymous street, along the façade of the church. It was destroyed in 1876 (Bellafiore, 2018). A verdant garden on different levels covers the walkable areas among all these buildings (Figure 3).

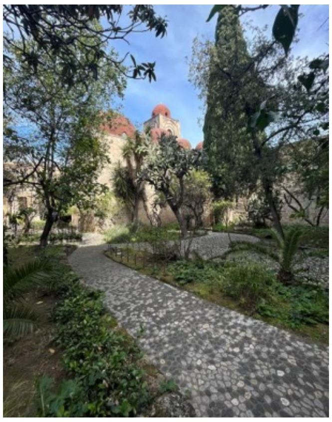

Figure 3. The interior of the complex: the surrounding garden.

3. DATA ACQUISITION

As previously reported, the church and the Islamic Hall have been already surveyed with a TLS to manage these buildings in a HBIM environment (Aricò et al., 2023). A total of 40 scans was necessary to acquire all the relevant surfaces of these two buildings. The survey of the entire complex with TLS techniques was too difficult to perform due to the presence of the dense vegetation of the garden and the particularly confined spaces. To overcome these issues a HMLS survey was planned. HMLS devices are the most convenient for acquiring extensive areas quickly, without recurring to dozens of scans and burdensome multi-cloud registrations.

Prior to starting with the HMLS survey a preliminary step has been carried out to assess any potential issue during acquisition. This inspection revealed few critical spots for the data capture, such as the dense vegetation, as previously reported, which partially covers the ground and part of the vertical surfaces of the complex; moreover, some problems were related to the presence of visitors, whilst some areas (such as the extrados of the domes or the upper parts of the buildings) would have been very difficult to be measured by the HMLS.

3.1 HMLS survey

The use of HMLS is not completely straightforward and preliminary scan planning is beneficial at all times, especially for large and various CH sites, to ensure data completeness and avoid repetitiveness. The preliminary design of scan trajectories enables faster HMLS non-stop acquisitions, optimizing survey operation on-site (Frias et al., 2022). During acquisitions, the device must be handled at a constant level to avoid any loss in overall accuracy. Walking paths must be traced at a short distance from each other to avoid overlapping issues on scene acquisition. Indeed, the registration accuracy is usually improved if the walking paths have a good percentage of overlap; whenever the distance between scan locations is large, the algorithm risks missing the correct point clouds registration (Shao et al., 2020). Moreover, for a correct overlapping, walking paths must not be placed near building walls, to maintain the best instrumental inclination between the laser and the vertical surface.

Taking in consideration all these requirements the acquisition planning was aimed to optimize the number of walking paths and their coverage to be considered in the HMLS survey, according to the desired level of detail of the final point cloud. All the assessments have been done related to the HMLS characteristics, the built environment and the site conditions.

The device chosen for this operation was the HMLS Stonex XH 120, which can acquire 655360 points per second with a maximum range of 120 m, a ranging accuracy up to 1 cm and an angular sampling accuracy of ±0.01° in vertical and horizontal directions (Figure 4). This device is based on SLAM technology and can obtain in real-time processing high-precision point clouds without lighting and GPS. The device doesn't have an RGB sensor and is unable to produce colour point clouds.

Figure 4. The Stonex HX 120 used for the survey.

The survey can be monitored via a tablet which shows in real-time the point cloud acquisition. The data are stored in 500 GB memory. The previous definition of the survey path is necessary to avoid oversizing issues on point cloud acquisition. Furthermore, to ensure trajectory control, it is advisable to identify ground reference points to start and stop the acquisition. The start and stop points will coincide whenever closed paths are necessary. Reference points can also be used to align the different paths in the same reference system.

In the case study, after prearranging two reference points (one inside the church and the other inside the abbot's house), data acquisition was performed according to six different walking paths, in order to capture the most significant indoor and outdoor environments in an exhaustive way. These paths, partially overlapped, started and stopped in one of the ground reference points (the same for each path) to allow the automatic correction of the point cloud acquisitions. Four paths were planned starting and stopping from the ground reference point inside the church; the last two paths instead were calculated on the ground reference point inside the abbot's house. The six paths have passed around the cloister and the garden in front of the church, along the hanging garden towards the main street, inside the abbot's house, along the upper walkway on the perimeter walls of the complex, inside the Islamic Hall and inside and around the church and toward the garden (Figure 5).

The path inside the church and the Islamic Hall was executed to acquire additional geometric information of the monumental parts in common with the TLS survey previously performed.

During acquisition, each set of data was appropriately managed by the Stonex Cube-Slam software, which processed the real-time acquisition showing the results in a tablet.

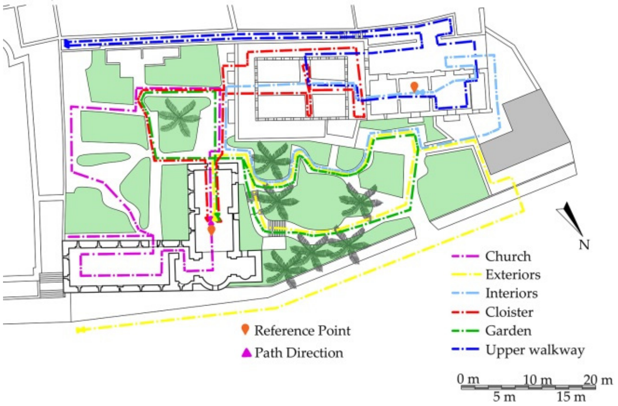

Figure 5. Scheme of the six walking paths inside the complex.

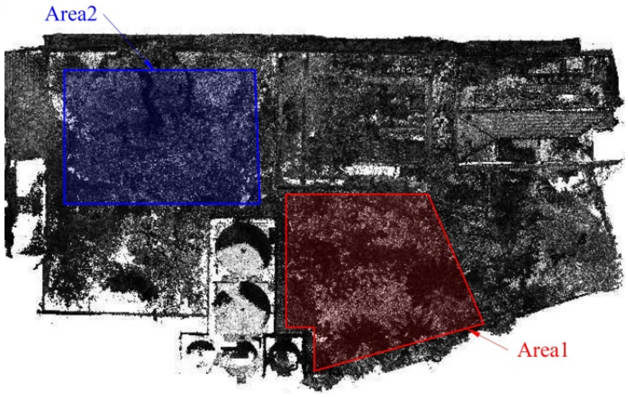

Figure 6. Areas selected for testing automatic filters.

4. DATA PROCESSING

Albeit the data were processed in real-time by the HMLS processor, the results were optimized through a necessary additional step. First of all, the six point clouds were aligned on the basis of the ground reference points. The point clouds were then converted into the .e57 format and the alignment was improved with an automatic registration based on Iterative Closest Point (ICP) algorithm. This last operation was managed by the Stonex Reconstructor software.
In order to produce data useful for the documentation and knowledge of the site, the obtained raw data needed to be processed with an appropriate workflow.
The six point clouds acquired by the HMLS survey were managed using Cloud Compare open-source software. They were first merged to obtain a unique dataset; in this step, the overall number of points consisted of about 500 million, with a storage size of about 15 GB. Since the HMLS device was not comprehensive of an RGB sensor, the resulting dataset was monochrome. The acquisition of monochromatic information complicated the identification of redundant, inconsistent or unwanted data present in the scene. The acquired dataset was comprehensive of terrain, built environment and vegetation.
In order to identify the exact shape of the terrain in the point cloud, it was necessary to strip the ground information from the built environment and the dense vegetation. The first aim was pursued through a manual segmentation of the buildings (the church, the Islamic Hall, the Abbot's House, the cloister and the upper walkway perimeter walls) since they presented a clear shape and were easily clusterised from the main point cloud. The second purpose was the removal of the vegetation; this process was more difficult to be achieved, considering the strong presence of plants and trees inside the monumental site. In this case, the analysis of two different automatic procedures was carried out. In particular, the Automatic Ground Classification (AGC) algorithm available in the commercial software Autodesk ReCap and the Cloth Simulation Filter (CSF) plugin developed in the open-source Cloud Compare software were used. But even after the separation of the built environment, the overall point cloud still resulted oversized for being processed by these tools.
In order to test them, two restricted areas (Area1 and Area2) were chosen as samples (Figure 6). In this way, the different outcomes of both algorithms were compared. Area1 is located in the hanging garden; it is characterised by everchanging levels of the terrain, connected through terraces, where the vegetation is most impenetrable than anywhere else in the monumental complex.
Area2 is located fronting the Islamic Hall façade and it has a flatter surface with less vegetation. The trimmed cluster for Area1 was made by about 58 million points, whilst Area2 counted about 54 million points.

4.1 Automatic filtering of point clouds

The Automatic Ground Classification (*AGC*) – The last release of Autodesk ReCap 2024 offers a new tool for automatic ground classification. This filter processes the point clouds to classify scan data into "ground" and "off-ground" points. Four quality settings (less details, more details, optimum and custom) could be chosen for filtering. Theoretically, within the "less detail" settings, smoother ground surfaces should be achieved, whilst, within the "more detail" settings, the ground surface should be more detailed. However, very few information is given from Autodesk about this tool. The first three settings are completely automatic with no possibility of intervention from the operator, the latter one is customisable and enables other two parameters, the "ground details", which is the value of the grid size for processing ground surface points (any feature larger than this value will be maintained in the surface), and the "processing window size", which determines the area of processing (this value should be large enough to include the largest object on the ground).
After some preliminary tests, it was decided to filter the point cloud using the "custom" settings to customise the parameters. In order to optimise the tool, the points of vegetation remotest to the ground (such as foliage and high branches) were previously eliminated. In this way, the tree trunks were more easily recognised. The final processing was carried out by setting the "ground details" parameter to 0.10 m and the "processing window size" parameter to 0.5 m.
Considering the results obtained in Area 1 and Area 2, it is possible to affirm that the algorithm works better where the terrain is flat and regular (Figures 7 and 8). In fact, in Area 1, where the slope was significant, the tree trunks were not deleted. Instead, in Area 2, where the terrain shape was almost plain, the algorithm worked fine. A remarkable hole was created by the filter in place of a man-dug pit in Area2, being the tool unable to process all the points under the terrain surface. The tree trunks were not filtered as expected, but the point clouds showed some irregular spikes, especially in Area1 where trees were very close to each other.
After removing the vegetation points, Area1 consisted of about 10 million points whilst Area2 counted about 13 million points, with a respective average reduction rate of 83.4% and 74.6%.

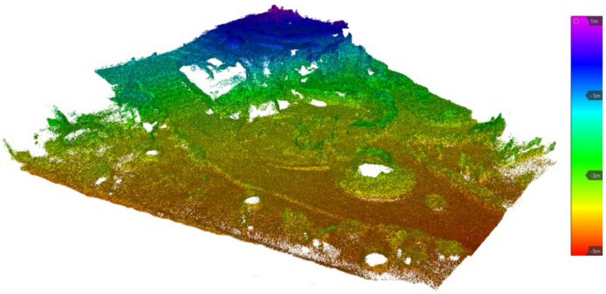

Figure 7. Area1 after the AGC filtering.

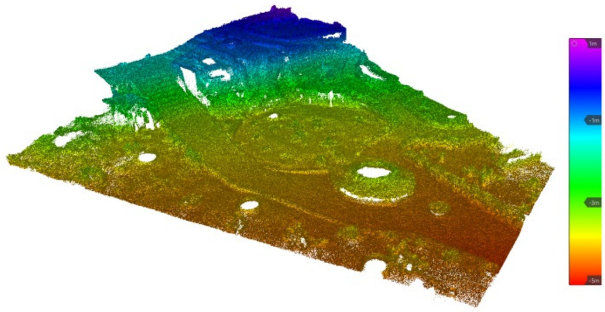

Figure 9. Area1 after the CSF filtering.

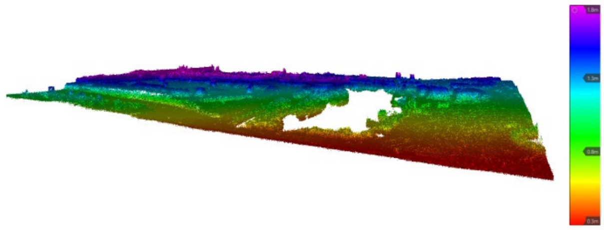

Figure 8. Area2 after the AGC filtering, showing the hole in correspondence of the man-dug pit.

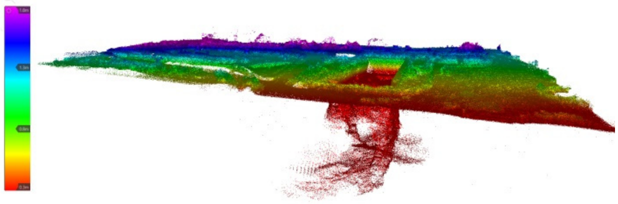

Figure 10. Area2 after the CSF filtering, including the man-dug pit.

The Cloth Simulation Filter (*CSF*) - The plugin available in Cloud Compare is based on an algorithm implemented by Zhang et al., (2016) which simulates the behaviour of a cloth dropping and covering the surface to be stripped. This tool was developed to extract ground points in discrete return airborne LiDAR (Light Detection and Ranging) data but could be also used for filtering terrestrial point clouds. The advantage of this tool is the simple user-friendly interface, requiring only the setting of a few parameters. In the first step, the altimetry of the terrain (as "Steep slope", "Relief" and "Flat") can be set; in the second step, advanced parameters can be chosen to optimize the processing: "Cloth resolution", "Max iterations" and "Classification" threshold. The first refers to the grid size of the virtual cloth used to cover the terrain, the second to the maximum iteration times of terrain simulation and the last to a threshold for dividing the point clouds into ground and off-ground parts. The threshold was calculated considering the distances between points and the simulated terrain.
Some preliminary tests on the whole dataset were carried out setting a "Steep slope" terrain and a "Cloth resolution" of 0.3 m, a "Max iterations" of 1000 and a "Classification threshold" of 0.3 m. Afterwards, the two test areas were processed after a "Flat" terrain, a "Cloth resolution" of 0.3 m, a "Max iterations" of 1000 and a "Classification threshold" of 0.1 m have been set. After this filtering, Area1 consisted of about 19 million points whilst Area2 counted about 18 million points. Both processes achieved an average reduction rate of 66% (Figures 9, 10). Using this algorithm, the filtered point clouds showed more holes, whilst the tree trunks were correctly deleted. The results obtained in Area 1 and Area 2 were similar, highlighting that the algorithm works fine independently from the shape of the terrain. This overview pointed up the pros and cons of each approach in consideration of the main purpose these tests have been done for; both the solutions didn't suit the prerequisite expectations, because the AGC algorithm works fine only on regular and plan surfaces, instead, the CSF solution leaves too many holes in the elaborated point cloud. Probably, these solutions work better in simpler datasets and not in contexts with overgrown vegetation.

4.2 Ground surface and complex reconstruction

In order to obtain an "as-is" model of the ground, not-automatic filtering was performed on the whole garden considering the automatic processing limitations.
In order to achieve a more refined result and to simplify the work, filtering was provided separately for each point cloud at a time; this approach certainly increased the elaboration time but avoided the generation of further errors.
Once all the vegetation has been removed, the six point clouds were merged and subsampled to obtain a more manageable dataset. The subsample was carried out with Cloud Compare using the "spatial mode" and setting a minimum distance of 8mm between two contiguous points.
For recreating the morphology of the ground, the point cloud was turned into mesh surfaces using the plugin Poisson Surface Reconstruction of Cloud Compare (Kazhdan et al., 2006). After testing different parameters aimed at obtaining the best results, the "octree depth" parameter was set to 11 (thus preferring a more precise reconstruction rather than a faster processing time). In this way, meshes were better calculated.
The point cloud obtained from not-automatic processing was more advantageous allowing to minimize the generation of holes and to obtain a higher reduction rate of noise and uniform coverage of points.
After the meshing process, which allowed the ground surface reconstruction of the entire complex, the point clouds of the buildings and structures, which were previously segmented, were repositioned on the mesh.
The HMLS dataset was hence aligned to the point cloud detected by the TLS survey. The alignment process was carried out considering the common geometries present on the two point clouds (the church and the Islamic Hall). A manual procedure was firstly performed by choosing several pairs of homologous points between the two point clouds; an automatic alignment with ICP algorithm was then carried out in order to refine the previous results. At the end of the process, the built environment of the church and the Islamic Hall in the HMLS point cloud has been replaced with the corresponding parts of the TLS point cloud (Figure 11).

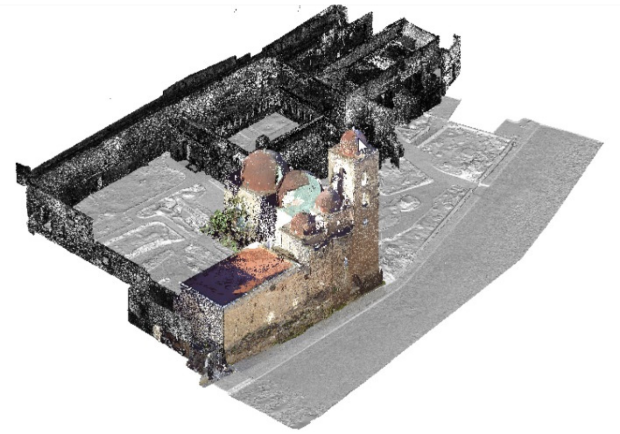

Figure 11. The mesh surface in relationship to the remaining built environment.

5. HISTORICAL AND STRATIGRAPHIC ANALYSIS

The complex of St. John of the Hermits shows the typical characters of the multicultural western Islamic-Byzantine syncretism which flourished during the Norman kingdom in Sicily across the 12th century. During this period, architectural and artistic features (i.e. tile mosaics and floors, carved structural details, such as windows grills and column capitals, etc.) and their styles were conspicuously influenced and renewed thanks to the several ethnic groups (Muslims, Jews, people from northern Europe) different by origins and religious beliefs, which lived together in peace in the same place and at the same time.
In the case study, the exhaustive dataset given by the integration of the HLMS point cloud with the TLS acquisition enabled the extraction of section planes for stratigraphic analysis inside the monumental area. The latter, regarding in parallel the ground/sub-ground and elevated buildings, empowered for the first time the cognition of the area where the monumental complex of St. John of the Hermits stands as a unicum.
In particular, the HLMS filtered point cloud was integrated with the TLS acquisition comprehensive of the geometric information about the church and the Islamic Hall.
From this cluster several sections were extracted through the Cloud Compare software, as a basis for the stratigraphic analysis to be consolidated by the historical, philological, and typological information acquired on the monumental site.
Considering the vertical section shown in Figure 12, it is possible to observe the same level between the cloister pavement and the second stair of the abbot's residence. Besides, the terrain of the complex is extended in a regular planned shape. These factors, considering also the still visible traces of the perimeter walls, can confirm the presence of the Gregorian monastery of St. Hermes.

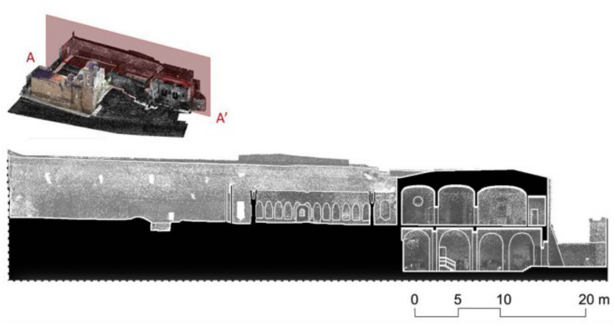

Figure 12. Section across the abbot's house and the cloister.

The vertical section shown in Figure 13 brings to light the geological substratum placed 2.50 m below the ground floor of the church. This section also shows the shaft of the pit dug at 4.20 m below the ground floor of the church. The possibility to analyse the relationship between the geological substratum and the built environment offers a better knowledge of the historical stratifications of the monumental complex.

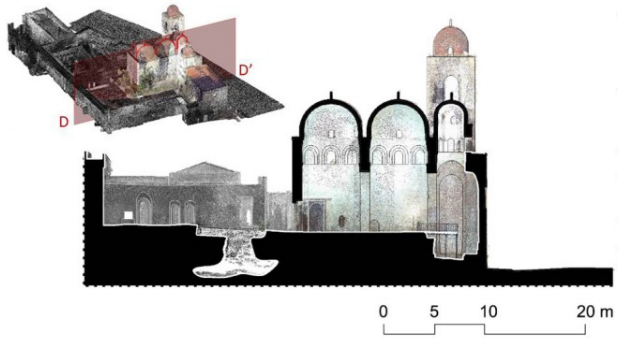

Figure 13. Section across the church and the garden in correspondence of the man-dug pit.

The considerations arising from this study constitute an important contribution to the awareness about how the Norman culture interacted and integrated with the Arab one by enhancing the pre-existing buildings - as is commonly believed - or whether it more likely replaced, obliterating, the traces of a recent past. This is still a very controversial topic in the historical cultural debate. In addition, the identification of certain parts where the rocky bank is outcropping has enabled the exact positioning of certain areas - such as inside the church - where there are evident traces of stone quarrying activities, dated back previously than the Arab domination in Sicily (which lasted about 250 years). This evidence proves that this site, located outside the defensive walls of the historical city of Palermo, was already used several centuries before the construction of the church in the 10th century.

6. CONCLUSIONS

The increased popularity of HLMSs suggested alternative acquisition methods for large-scale CH site documentation. This paper focused on an example of HLMS survey carried out at the complex of St. John of the Hermits in Palermo (Italy) and on the related outcomes which this methodology can have.
In such an extensive area where the main problems were the dense vegetation and the complex distribution of ground levels across the entire area, MMS technology enabled a very accurate result in capturing the entire scene, helping to correlate the different environments of the complex and extracting useful information with minimal consumption of resources. Compared to the TLS acquisition time, HMLS operations were indisputably faster.
The main challenge of HMLS acquisition remains the elimination of vegetation from the dataset. In fact, HMLS survey tends to acquire redundant point cloud information in presence of vegetation. The automatic tools, tested in this application to solve this problem, did not give the desired results. The specific morphological condition of the site and the presence of very dense vegetation were obstacles to the adequate removal of all the off-ground points. To worsen the process, the used HMLS device didn't detect the radiometric component of the scanned points as it doesn't come with an RGB sensor, and the resulting monochrome point cloud was less clear to be enquired.

The HMLS systems are advantageous in terms of portability, usability and acquisition time, and the resulting point clouds have good reliability. However, it has been demonstrated that the precision and range limitations of HMLS can be refined by integration with other imaging or ranging methodologies. Wherever a higher-resolution detail is required and given a sufficient overlap among them, the overall HMLS point cloud can be combined with other more traditional point clouds (Zlot et al, 2014). In our research, matching the HMLS point cloud with the previous TLS one, helped to understand better the captured data and partially enrich the final 3D model with radiometric information.
At the end of the process, the 3D model describes the "as-is" site, and it can be exploited for extracting all the sections relevant to the overall description and comprehension of the complex, where the distinct parts are all related to each other.
The comparison and the integration of two different methodologies guaranteed extra-mile documentation of the complex, where the available information can be retrieved, shared, manipulated, extracted and updated at all times for addressing several purposes for the valorisation of the site.
The studies carried out confirm the importance of this site for the study of relations between Arab-Norman culture and may be useful in framing the complex in an even broader temporal panorama.

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REFERENCES

Akpinar, B., 2021: Performance of Different SLAM Algorithms for Indoor and Outdoor Mapping Applications. *Applied System Innovations*, 4, 101, 1-11. https://doi.org/10.3390/asi4040101

Alsadik, B., Karam, S., 2021: The simultaneous localization and mapping (SLAM): An overview. *Surveying and Geospatial Engineering Journal*, 1(2), 1-12. https://doi.org/10.38094/sgej1027

Allegra, V., Di Paola, F., Lo Brutto, M., Vinci, C., 2020: Scan-to-BIM for the management of Heritage Buildings: The case study of the Castle of Maredolce (Palermo, Italy). *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLIII-B2-2020, 1355–1362. https://doi.org/10.5194/isprs-archives-XLIII-B2-2020-1355-2020

Aricò, M., and Lo Brutto, M., 2022: From Scan-to-BIM to Heritage Building Information Modelling for an ancient Arab-Norman church. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLIII-B2-2022, 761–768. https://doi.org/10.5194/isprs-archives-XLIII-B2-2022-761-2022.

Aricò, M., Lo Brutto, M., Maltese, A., 2023: A Scan-to-BIM Approach for The Management of Two Arab-Norman Churches in Palermo (Italy). *Heritage, 6*, 1622-1644. https://doi.org/10.3390/heritage6020087

Autelitano, F., Bruno, N., Martinelli, R., Calvanese, V., Garilli, E., Biancardo, S.A., Dell'Acqua, G., Veropalumbo, Zerbi, R.A., Roncella, R., Giuliani, F, 2022: The construction of a street never opened to traffic. The extraordinary discovery of pavement engineering in vicolo dei Balconi of Pompeii. *Journal of Cultural Heritage*, Volume 54, 108-117, https://doi.org/10.1016/j.culher.2022.01.012.

Bauwens, S., Bartholomeus, H., Calders, K., Lejeune, P., 2016: Forest Inventory with Terrestrial LiDAR: A Comparison of Static and Hand-Held Mobile Laser Scanning. *Forests, 7(6)*, 127. https://doi.org/10.3390/f7060127

Bellafiore, G., 2018: *Palermo. Guida Della città e dei Dintorni*. Edizioni Bellafiore, Palermo, Italy.

Cabo, C., Del Pozo, S., Rodríguez-Gonzálvez, P., Ordóñez, C., González-Aguilera, D., 2018: Comparing terrestrial laser scanning (TLS) and wearable laser scanning (WLS) for individual tree modeling at plot level. *Remote Sens*., 10(4), 540. https://doi.org/10.3390/rs10040540

Del Duca, G., Machado, C., 2023: Assessing the Quality of the Leica BLK2GO Mobile Laser Scanner versus the Focus 3D S120 Static Terrestrial Laser Scanner for a Preliminary Study of Garden Digital Surveying. *Heritage,* 6, 1007-1027. https://doi.org/10.3390/heritage6020057

Del Perugia, B., Giannetti, F., Chirici, G., Travaglini, D., 2019: Influence of Scan Density on the Estimation of Single-Tree Attributes by Hand-Held Mobile Laser Scanning. *Forests, 10,* 1-13. https://doi.org/10.3390/f10030277

Ebolese, D., Lo Brutto, M., Dardanelli, G., 2019: The integrated 3D survey for underground archaeological environment. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci*., XLII-2/W9, 311–317, https://doi.org/10.5194/isprs-archives-XLII-2-W9-311-2019.

Frías, E., Previtali, M., Díaz-Vilariño, L., Scaioni, M., Lorenzo, E., 2022: Optimal scan planning for surveying large sites with static and mobile mapping systems. *ISPRS Journal*, 192, 13-32. https://doi.org/10.1016/j.isprsjprs.2022.07.025

Gollob, C., Ritter, T., Nothdurft, A., 2020: Forest Inventory with Long Range and High-Speed Personal Laser Scanning (PLS) and Simultaneous Localization and Mapping (SLAM) Technology. *Remote Sens., 12*(9), 1509. https://doi.org/10.3390/rs12091509

Kalvoda, P., Nosek, J., Kalvodova, P., 2021: Influence of Control Points Configuration on the Mobile Laser Scanning Accuracy. *IOP Conf. Series: Earth and Environmental Science*, 906, 012091. https://doi.org10.1088/1755-1315/906/1/012091

Kazhdan, M, Bolitho, M, Hoppe, H, 2006: Poisson surface reconstruction. *Proceedings of the fourth Eurographics symposium on Geometry Processing*, The Eurographics Association, 06, 61-70, http://dx.doi.org/10.2312/SGP/SGP06/061-070

Lo Brutto, M., Spera, M. G., 2011: Image-based and range-based 3D modelling of archaeological Cultural Heritage: the Telamon of the Temple of Olympian Zeus in Agrigento (Italy). *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XXXVIII-5/W16, 515–522, https://doi.org/10.5194/isprsarchives-XXXVIII-5-W16-515-2011.

Masiero, A., Fissore, F., Guarnieri, A., Pirotti, F., Visintini, D., Vettore, A., 2018: Performance Evaluation of Two Indoor

Mapping Systems: Low-Cost UWB-Aided Photogrammetry and Backpack Laser Scanning. *Appl. Sci.*, 8, 416. https://doi.org/10.3390/app8030416

Nikoohemat, S., Peter, M., Oude Elberink, S., Vosselman, G., 2017: Exploiting Indoor Mobile Laser Scanner Trajectories for Semantic Interpretation of Point Clouds. *Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, IV-2/W4, 355–362, https://doi.org/10.5194/isprs-annals-IV-2-W4-355-2017, 2017.

Pepe, M., Alfio, V.S., Costantino, D., Herban S., 2022: Rapid and Accurate Production of 3D Point Cloud via Latest-Generation Sensors in the Field of Cultural Heritage: A Comparison between SLAM and Spherical Videogrammetry. *Heritage*, 5(3), 1910-1928. https://doi.org/10.3390/heritage5030099

Sammartano, G., Spanò, A., 2018: Point clouds by SLAM-based mobile mapping systems: accuracy and geometric content validation in multisensor survey and stand-alone acquisition. *Applied Geomatics*, 10, 317-339. https://doi.org/10.1007/s12518-018-0221-7

Scianna, A, La Guardia, M., 2019: Survey and Photogrammetric Restitution of Monumental Complexes: Issues and Solutions - The Case of the Manfredonic Castle of Mussomeli. *Heritage*, 2(1), 774-786. https://doi.org/10.3390/heritage2010050

Shao, J., Zhang, W., Mellado, N., Wang, N., Jin, S., Cai, S., Luo, L., Lejemble, T., Yan, G., 2020: SLAM-aided forest plot mapping combining terrestrial and mobile laser scanning. *ISPRS Journal*, 163, 214-230. https://doi.org/10.1016/j.isprsjprs.2020.03.008

Williams, E., Smith, M., Eichhorn, M., 2015: Assessing handheld mobile laser scanners for forest surveys. Remote Sens., 7, 1095-1111. https://doi.org/10.3390/rs70101095

Wu, C., Yuan, Y., Tang, Y., 2022: Tian B. Application of Terrestrial Laser Scanning (TLS) in the Architecture, Engineering and Construction (AEC) Industry. *Sensors*, 22(1):265. https://doi.org/10.3390/s22010265

Xin, Y., Wang, R., Wang, X., Xiao, Z., Lin, J., 2022: High-Resolution Terrain Reconstruction of Slot Canyon Using Backpack Mobile Laser Scanning and UAV Photogrammetry. *Drones*, *6*, 429, 1-23. https://doi.org/10.3390/drones6120429

Zhang, W., Qi, J., Wan, P., Wang, H., Xie, D., Wang, X., Yan, G., 2016: An Easy-to-Use Airborne LiDAR Data Filtering Method Based on Cloth Simulation. *Remote Sensing*, 8, 501. https://doi.org/10.3390/rs8060501

Zlot, R., Bosse, M., Greenop, K., Jarzab, Z., Juckes, E., Roberts, J., 2014: Efficiently capturing large, complex cultural heritage sites with a handheld mobile 3D laser mapping system. *Journal of Cultural Heritage, 15,* 670–678. https://doi.org/10.1016/j.culher.2013.11.009