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Innovative Approaches through 3D Survey and Virtual Technologies for the Geometric and Semantic Fruition of Built Heritage Sites on the Web

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Abstract

Nowadays recent advances in Geomatics and Computer Science led specialists to explore new methodologies for the preservation and valorization of Built Heritage (BH). In fact, if on one hand the preservation of monumental complexes needs to remotely manage virtual representations of the real environments to be preserved, on the other hand the valorization allows visitors to virtually explore BH sites in remote, thanks to the spread of web technologies. The main challenges about the virtual fruition of BH sites are related to the management of 3D big data digitized geometries and the requirement for property software-based solutions. This work explores a possible strategy, based on open-source technologies for the web fruition of 3D geometric and semantic information of BH sites from 3D digitization. The first results of this research are related to the cloister of the Cathedral of Cefalù (Italy), which represents a classic example of a BH site that, for its extraordinary importance and its state of preservation, could benefit from the application of virtual technologies for conservation and fruition purposes. The work describes the acquisition of the 3D geometric dataset through laser scanner and photogrammetric surveys, its optimisation, and the design of a web-based platform for the fruition online of 3D geometric and semantic information. The web navigation system was developed through Three.js JavaScript WebGL libraries, inside a HTML5 compliant environment, connected in real-time to Postgres Relational Database Management System through the activation of a Python module in an Anaconda platform. In this way, the geometric information, hosted by the WebGL environment, was connected in real-time to the semantic information stored in the database. This system represents a prototypical structure for the future development of a full platform for the web exploration and management of BH sites developed with low-cost technologies and useful for a large variety of stakeholders (from municipalities to private companies) who manage BH sites.

CCS Concepts
• **Geomatics methodologies** → TLS; Computer graphics; Database Management System; Virtual Reality, WebGL

1.Introduction

In recent times, the spread of new survey technologies in Geomatics has revolutionized the digitization of Built Heritage (BH) sites both for fruition and conservation purposes [ALL23; PCC*19]. Range-based technologies allow nowadays to obtain 3D point cloud reconstructions of indoor and outdoor environments of monumental complexes, employing static [TBC*17] and mobile laser scanning solutions [ALL23]. At the same time, the image-based 3D reconstruction methodologies enabled by photogrammetric processes based on Structure from Motion (SfM) algorithms, diffused the use of terrestrial and on-flight image acquisitions for obtaining the 3D digitization of BH sites. Due to their non-invasive nature, these technologies are considered very useful for the analysis of BH sites, guaranteeing their maintenance and, at the same time, allowing accurate and detailed 3D reconstructions. Moreover, the application of a Scan-to-BIM approach also allowed geometric information to be transferred to 3D parametric models based on families of architectural objects, to obtain the Heritage Building Information Modelling (HBIM) models.

In the last decades, the possibility of obtaining a 3D digitization of monumental complexes led specialists to employ these datasets for Virtual Reality (VR) and Augmented Reality (AR) applications too [LFF24]. In fact, the technological advances in gaming technologies (the so-called serious games) have opened new scenarios for the virtual fruition of BH sites using different devices such as projectors, totem installations, Oculus [DHD18]. These tools were first considered for improving the quality of exploration inside museums and in the archaeological sites. This concept has been further improved with the diffusion of fast web internet connections, enabling the download of proper VR or AR applications in situ [SGG*20], or the direct remote exploration on the web [GBF24]. This last solution, based on WebGL open-source JavaScript libraries, employs the capabilities of the web browsers, ensuring simple and fast experience on the client side. The first experiments in this field allowed experts to employ web browsers for 3D virtual navigation inside an archaeological or monumental complex [SLS16]. The main challenges of this kind of application are the limited size of 3D dataset to be loaded, the limited controls of navigation and the limited formats to be integrated inside the web browser visualization. In order to address these challenges, several web-based solutions which support the management of 3D heritage datasets and online visualization were developed. Among the open-source alternatives there is "Potree" [GBF*24], a free 3D visualization tool developed in JavaScript designed to optimize large point clouds. Alternatively, a WebGL-based platform widely used in the BH field, Sketchfab, offers an intuitive user interface and compatibility with VR environments.

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However, its commercial nature presents some restrictions in the free version. Another interesting solution is Atis.cloud, a platform dedicated to management, visualization and sharing of point clouds and 3D models, but limited due to its licensing model and limited interactivity with the public. Recent advances in this field included several control configurations, the visualization of different 3D mesh and point cloud formats, and the possibility to optimize the 3D visualization of the loaded dataset [FBG*24; ADL24]. In this scenario, our choice considered a more tailored solution using Three.js and PostgreSQL, allowing greater control over both the visualization and semantic management of the data. This work presents the first results for the development of a 3D virtual navigation system of a BH site on the web, comprehensive of geometric and semantic information of single architectural elements. The work was tested on a dataset acquired during a 3D survey campaign in the Cathedral of Cefalù (Italy), which considered the digitization of the cloister and the architectural elements of the columns in detail. The cathedral and its cloister represent one of the main Arab-Norman monumental complexes in Sicily; in particular, the cloister contains precious unique column configurations to be preserved. For this reason, the development of a 3D virtual navigation system offering the possibility to visualize and manage geometric and semantic information associated with the cloister represents an important step for the valorization process of the site. The web navigation system was developed inside an Apache webserver containing different .html pages integrating Three.js open-source JavaScript libraries. Compared to previous experimentations in this field [ALL23; ADL*24], this solution considered popup linked information which integrated the geometric details of single elements, and the associated semantic information stored in Postgres open-source database management system. In this way, through a direct connection to the database, it is possible to manage and edit the semantic description visualized on the web related to the architectural elements. This kind of approach can be useful for municipalities and private companies for the management and web fruition of BH 3D digitalized datasets, aimed at the conservation and the fruition of monumental complexes with low-cost open-source solutions.

2. The cloister of the Cathedral of Cefalù

The Cathedral of Cefalù, on the northern coast of Sicily (Italy), is a prominent example of Norman architecture in the Mediterranean region. Commissioned by King Roger II in 1131, the cathedral was a symbol of the consolidated Norman authority and an expression of the cultural synthesis of Arab, Byzantine, and Latin traditions over the centuries. Since 2015, the cathedral was inscribed within the UNESCO World Heritage Site list as a part of the "*Arab-Norman Palermo and the Cathedral Churches of Cefalù and Monreale"* itinerary, underlining its historical and architectural significance. Adjacent to the Cathedral, the cloister is a rare and well-preserved example of Romanesque monastic architecture in Sicily. Completed in 1166 by William I as part of the original ecclesiastical complex, the cloister (Figure 1) used to serve as a space for reflection and religious life for the community of canons. Based on a strong theological medieval symbolism, the cloister was meant to represent Paradise on earth. It features a rectangular layout with arcades supported by paired columns, many of which are adorned with intricately carved capitals depicting biblical scenes of the New and Old Testaments, vegetal motifs, and fantastical creatures. These sculptural elements not only reflect the artistic influences of the period, combining Norman, Arab, and Byzantine styles, but also serve as valuable sources for the study of medieval iconography and cross-cultural exchange in Norman Sicily. The southern and western sides only have been preserved in their original configuration: the eastern aisle of the cloister was destroyed by a fire in 1809, whilst the northern one was dismantled for restoration in 1952, but it hasn't ever been reassembled.

Figure 1: The cloister of the Cathedral of Cefalù (Italy).

3. Materials and Methods

The structure of the workflow which has been followed for the 3D virtual fruition of the cloister of the Cathedral of Cefalù, considered a process of different steps, as shown in the preliminary scheme below (Figure 2). First, survey operations enabled the acquisition of the 3D detailed point clouds of the area. Then the digitization process enabled the optimization of the acquired datasets to be suitable for web fruition. Finally, the construction of the web navigation model, integrating 3D web visualization and Database Management System, enabled to define the final structure of the 3D web navigation system.

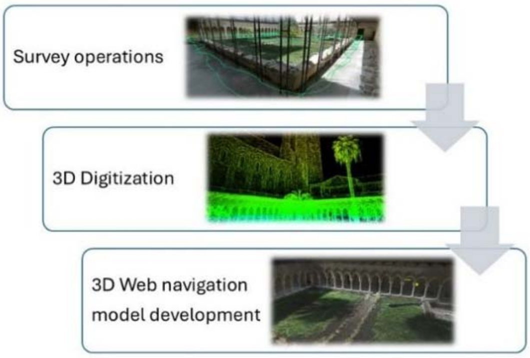

Figure 2: *Scheme of the workflow.*

3.1. 3D Survey and data processing

The 3D survey was carried out to obtain a first dataset covering the entire cloister and a second dataset with a higher level of detail focused on a limited test area only. In fact, in this initial phase of the project, the experimentation was conducted on the south-eastern corner of the cloister to simplify data management and highlight the main critical issues. This corner is characterized by a section where the original structure of the cloister's porch is still present, and another one where it is no longer standing. A third dataset has been added for the acquisition of a pair columns to be visualised at the highest level of realistic detail.

The first 3D survey aimed to produce an initial comprehensive point cloud of the entire cloister using a Lixel L2-32 mobile laser scanner by xGrids. This device falls on the category of Handheld Mobile Laser Scanners (HMLS) equipped with Simultaneous Localization and Mapping (SLAM) technology for sensor positioning and trajectory tracking. The scanner has a range of 120 meters, an acquisition speed of 320,000 points per second, a relative accuracy of ±1.2 cm, and an absolute accuracy of ≤3 cm. The acquisition of the entire cloister was carried out along a single closed path, which was followed in each direction (forward and backward) to ensure visibility of all architectural elements. The data collected were then processed using the proprietary LixelStudio software by xGrids: the spherical images captured during the scan enabled the delivery of a coloured overall point cloud, which was further edited and filtered to remove outliers and point cloud noise. This process resulted in an initial dataset of the entire area, used as a reference for subsequent processing (Figure 3).

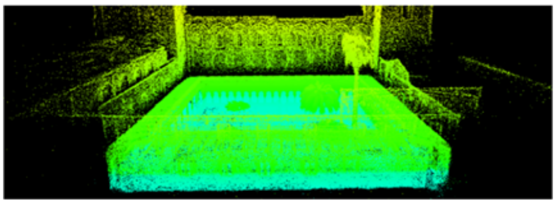

Figure 3: *The point cloud acquisition visualized in Lixel Studio.*

A second, more detailed and higher-resolution point cloud was obtained for the south-eastern corner of the cloister chosen as a sample, to detect a reduced dataset regarding the colonnade and the arcades. The survey was carried out using a static terrestrial laser scanner (TLS) Faro Focus 3D S120 characterized by a distance accuracy up to ±2 mm, a range from 0.6 m up to 120 m, a measurement speed of 976.000 points/second, a vertical and horizontal field of view of 305° and 360°. A total of 9 scans were taken: 4 on the corridor, with full-dome settings, and 5 on the garden, with a reduced field of view. All the scans were configured with an acquisition resolution of 6 mm at 10 meters, with a generous overlap to ensure maximum reliability of the registration process. Eleven plain targets were also uniformly distributed on the involved surfaces to improve the registration.

These laser scanning acquisitions were also supplemented by a detailed photogrammetric survey of a pair of columns located in the south-eastern corner of the cloister. Specifically, a series of close-range images (from distances varying between 50 and 100 cm) were taken for one of the two original columns still in place. The images were captured using a Nikon D3300 camera with a focal length of 18 mm following a typical convergent image acquisition scheme.

The overall point cloud coming from the HMLS acquisition was further subsampled for file size optimization purposes, setting an average point spacing of 10 cm which reduced it to 98 Mb to be contained in the file limits of the system (100 MB only). The TLS scans were then processed in an automated way through the Autodesk Recap software, starting from the ones on the porch. At the end of the process, after stripping the unnecessary information (due to inconsistencies such as vegetation, the garden flowerbed and the capture of other scattered bits of the cloister) and manual segmenting, the scans were merged and resampled to create a unique point cloud made of about 23 million points, which was used to build two different products of digitization. The first product was based on an optimized version of the point cloud, subsampled with a point spacing of 1.5 cm, reducing the initial dataset to about 1.5 million points sized 45 MB in a .pcd format. The second product was a surface model obtained from a HBIM parametric digitization, which has been made starting from the same dataset but for different purposes. Once obtained the parametric model of this section of the cloister, it has been exported as a simplified 3D point cloud, small-sized to be more manageable within a remote web-based system.

The images from the photogrammetric survey were processed using Agisoft Metashape software, using the coordinates of several points extracted from the TLS point cloud as Ground Control Points (GCPs). Although this method employed a local reference system, it enabled us to scale and align the photogrammetric reconstruction to the static point cloud acquisition. This approach was considered acceptable given that at the current stage, the 3D digitization was finalized for web fruition only. The photogrammetric processing delivered a 3D model of the columns and capital with photorealistic textured meshes: the detailed quality of texture was kept high and set to 4048x4048 pixels, but the number of polygons has been reduced to be sized less than 30 MB in .obj format. The other two models were optimized as well within Agisoft Metashape software to be implemented in the web navigation model.

3.2. Development of the 3D web navigation system

The 3D web navigation system was conceived as a low-cost multiscale visualization platform, developed with open-source solutions, able to combine geometric and semantic data, with real-time customization possibilities. The framework adopted for the construction of geometric and semantic 3D web navigation system (Figure 4) consists of 3 interconnected parts: the webserver, the database and the python platform. The webserver (in our case an Apache open-source server) hosts the .html pages, the Three.js JavaScript open-source libraries and the 3D models to be visualized. In this way, the webserver runs the online visualization system of the 3D environments, enabling the navigation of the subsampled overall point cloud, the detailed visualization of the corner and the detailed textured mesh of the columns.

The database (in our case Postgres open-source database management system) contains the tables associated with the architectural elements with the text information describing the objects. The connection between the database and the .html visualization of the semantic description is granted by a Python script running in Anaconda open-source python platform. This script employs Flask web micro-framework and psycopg2 Python open-source libraries, ensuring the real-time connection between the text information inside the database table and the web visualization inside the .html file. Overall architecture enables the development of a multiscale web visualization model, combining different levels of information.

Figure 4: *The connections between the different parts of the framework.*

4. Results

The strategy adopted in this work considered different steps such as survey operations, 3D data processing and design of the web navigation system, finalized to the conservation and the web fruition of the monumental complex. The structure of the web navigation system starts with a general view of the point cloud of the cloister with the presence of popup elements which enable a more detailed visualization of specific parts (as i.e. the point cloud of the of the south-eastern corner) and specific architectural elements (i.e., the columns). Clicking on each pop-up element, a new window can display the detailed 3D visualization with the semantic description of the modules (Figure 5). The content of the semantic description is hosted in the database and can be updated in real-time employing the connection to the server. In this way the system allows users the web fruition of geometric and semantic content at different scales of visualization. The optimized size of 3D data guaranteed good quality in web navigation using the most common web browsers (Chrome, Firefox, Safari). The interface is basic at this stage, because the focus of the work was firstly to generate and test the efficiency of the system, but future improvements of the impact on web navigation are not excluded.

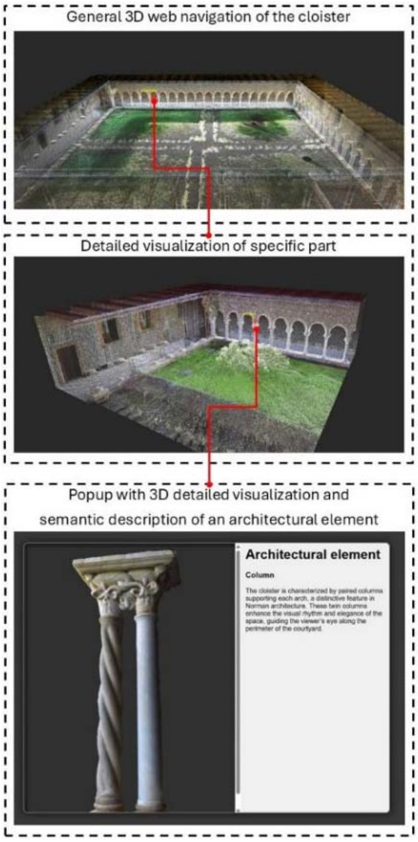

Figure 5: *The structure of the web navigation system.*

5. Conclusions

This experiment represents the first step for the implementation of a low-cost process for the 3D digitalization of BH sites on the web with geometric and semantic integration. The case study of the cloister of the Cathedral of Cefalù represents a clear example of a monumental complex which strongly benefits the application of 3D digitization techniques for conservation and fruition purposes. The possibility of semantic and geometric fruition of the environment, developed with the connection between the database management system and the 3D web visualization, is a precious tool for specialists who work in the maintenance of the monument and for visitors who can explore the cloister on the web as a preview of a possible real visiting experience. In the future, the system will be improved in interface and implemented with further modules to enhance the possibility of real-time web management in terms of 3D geometric information (improving the quality and the variety of 3D formats to integrate) and semantic information.

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