

Medieval cultural heritage, from 3D survey to data management: the castle of Canossa

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Abstract – In the cultural heritage knowledge path, the survey process assumes a primary role as a tool to analyze and interpret through bibliographic and iconographic analysis and the study of reality. The case study analyzed in the article is the Castle of Canossa, the epicenter of some critical events in medieval times. The authors describe the first part of the research, mainly focused on the integrated survey process between active and passive techniques at architectural and territorial scales. Several geometrical validation steps have been introduced to verify the reliability of the 3D acquisition and historical reconstruction. The paper highlighted the crucial relationship between territorial heritage and buildings, laying the groundwork for a more articulated analysis of the entire architectural complex. The final aim is to realize a 3D BIM model that represent the current and the original architectures in the same type of environment.

I. INTRODUCTION

Castles are an admirable example of layered and complex structures with a substantial scale variability. The dimension can range from the territorial scale, such as city walls or military outposts, to the individual building (tower, palace, gate) or portion of walls. They are composed of multiple interconnected defensive systems and architectural superstructures. Besides, fortified castles build a relationship and dependence with the surrounding influence area, defining its development. The territory becomes a filter of access, especially in the case of fortified castles positioned in dominant positions. Therefore, the analysis of these buildings cannot be limited to the architecture study. It is essential to interpret the internal and external ecosystem development. The case study reported in the paper is the Castle of Canossa (Fig. 1), a complex fortified building close to Reggio Emilia, Italy. The Castle's history overlaps with Matilda of Canossa, an emblematic female figure in the medieval era. Today, the Castle has vestiges of its original shape, but most masonry portions have been lost during



Fig. 1. Location of Canossa in northern Italy and image of the remains of the castle from East.

millennial history. The research project aims to study the entire building system in-depth from a historical, geometric, and material point of view, building a valuable information system to represent its original architecture. In the paper, the authors show the first part of the project, the multiscale acquisition phase, and the first restitution of the Castle and its context. These steps are useful to prepare the knowledge conditions for future interpretation, such as the realization of a BIM model that represent the current and the original architectures. Though the use of BIM for existing buildings is

nowadays a consolidated practice, called hBIM (historic Building Information Modeling) [1], less are the works that focused on the use of three-dimensional models to represent archaeological artefacts. The works referred to concern the use of open-source Cloud-Based HBIM platforms [2, 3] trying with different approaches to modeling such as the use of meshes and NURBS geometries [4]. The cloud-BIM platforms have a great influence on data transparency and accessibility, not only for IFC (Industry Foundation Classes) files but also for external semantic data linked to the objects. The implementation of the BIM model intends to be achieved with reference to other similar works proposed in literature [5] and consists of two main aspects: i) virtual reconstruction of the castle based on the 3D survey and archival documentation, for the realization of virtual/augmented reality applications (VR/AR technologies), which concerns a dissemination and fruition aspects [6, 7]; ii) use of shared platforms for the collaboration and data management in the field of cultural heritage conservation. Although the use of GIS (Geographic Information System) in archeology has always been, and still is contentious at the theoretical level [8, 9], the use of GIS technology is nowadays almost taken for granted. This work, while focusing more on the two aspects previously described, does not neglect the implementation of the BIM model with GIS systems.

II. CASE STUDY

Canossa Castle is located in the Reggio Emilia Apennines on a white sandstone hill (Fig. 1). The Castle is known for the famous "Walk to Canossa," an event involving Emperor Henry IV, Pope Gregory VII, and Countess Matilda di Canossa. The building is part of an articulated system of fortifications in the Reggio Emilia Apennine territory. To this day, little remains of the Matildic-era fortress, leaving a trace of a past imposing fortress. These ruins primarily date from the late Middle Ages to later centuries; only part of the foundations seem to refer to the original time of Matilda. The ruins include the remains of a monastery and some palace walls, built by Ruggeri in the late 16th century. Part of an apse and ruins have survived in the southern area. The foundations of the tower-gate, located south of the building are still visible. At the same time, a raised section of the eastern tower is visible. The National Museum of Canossa is located in the centre of the archaeological area, containing many remains and a valuable historical reconstruction of the Castle. This latter was created by the Reggiana Society of Archaeology suggesting the original appearance of the fortress in Matilda's time. Starting from the plan of the excavations carried out by Gaetano Chierici in 1880 [10], the model is the result of archival and on-site research. For this reason, this model has been analysed in the research, evaluating its reliability concerning the existing system.

A. The History

The Castle foundation traces back to the 10th century [11]: Donizone reports that Adalberto Atto prepared, on the hill of the Reggio Emilia Apennines, a new fortified system [12]. The presence of a pre-existing settlement is not reported, even if recent research refers to a Roman settlement [13]. The Castle faced the first two sieges in 953 and 957 by Berengar II of Ivrea and Adalbert, Berengar's son. It was still a little fortification composed of a tower with walls but already proved its impregnability.

In 1077, there was a meeting between Gregory VII and Henry IV. The Castle had been enlarged to host an important event and accommodate Gregory VII's court by that date. In 1092, Henry IV attacked the Castle, losing the battle. A few years later, in 1106, the Castle underwent further expansion by Matilda di Canossa. Upon her death, the Canossian property in 1116 came into the possession of Emperor Henry IV, opening new claims from the Church [11, 14]. In 1255, Reggiani people led by Albert of Canossa besieged the fortress reducing it to ruin [14]. Few years later, the Canossa family rebuilt it. Between the 13th and 14th centuries, a landslide reduced the hill on the southern side, probably due to anthropic reasons. Thus, the northern access would later be strengthened in defense [11].

In 1409 all the Canossian castles were part of the plan to strengthen the fortified structures by the Estensi [11]. However, three years later (1412), there was a new siege by the Reggiani, with the help of the Parmensi, which probably caused a second landslide, this time on the western slope [15]. Very few damages have been caused by this last siege in the architectonic system. Only the walls have been seriously damaged. In 1512, the Castles passed to the Papal State, and in 1523 the Este reoccupied Canossa Castle, carrying on military interventions [11].

In 1557/58, the most destructive event was the cannonades by Ottavio Farnese, who caused a landslide in the northern area, destroying the entrance structure on the north-eastern corner [14, 15, 16]. From 1570, the Castle changed hands several times, starting with the Ruggeri, who turned the Castle into a stately home and ending in 1642 with the Valentini of Modena, who held it until 1796.

After this date, the fortress remains neglected and falls into ruin. Finally, in 1878, the Italian state purchased the hill, declaring it a national monument. On the fortress site, the National Museum of Canossa, named Naborre Campanini, opened in 1893 and was reorganized in 2002. Since 2017, the Matilda of Canossa Cultural Association has managed the area.

III. DATA ACQUISITION

An integrated survey campaign based on active and passive 3D data acquisition methodologies has been planned to understand the Canossa system. The survey

planning has foreseen three different one-day acquisition campaigns. A data set suitable for multi-scale analysis and representation has been acquired, adapting the survey process to the different external conditions. Data redundancy made it possible to perform metric validation on the quality of the acquired data, controlling the global and local accuracy. Thus, the project pipeline, described below, included progressive validation steps to use the data at increasingly larger scales.

A. Territorial survey

The Canossa hill presents a peculiar morphology, composed of rocky (south and north-east sides) and vegetation-covered areas: It has a high variation of .ca 60 m between the base and the summit. The entrance to the Castle is a narrow-paved road that climbs among the trees of the southwest side. The territorial survey was carried out by integrating a GNSS system with RPAS (Remotely Piloted Aircraft System) photogrammetry. Initially, 20 ground targets with A3 and A2 dimensions were distributed in the whole area with a higher density on the top of the hill. These targets (GCPs, Ground Control Points) defined the absolute reference network of points acquired by GNSS and the photogrammetric system.

Most GNSS stations showed a sufficient satellite coverage but low or non-existent data signal. For that reason, the Network Real Time Kinematic (NRTK) configuration (by Sokkia GCX3) was initially substituted with GNSS in static mode (by Topcon GR3). The master station was placed in the center of the survey area with a minimum acquisition time of 10 minutes (1 epoch per second) for each GCP. Afterwards NRTK acquisition problem was solved, turning the receiver on and off for each point, gaining priority access to the data band, and acquiring points with fewer epochs (5-10 epochs) and lower accuracy. This mode was adopted for surveying natural points along the ascent to the Castle, acquiring three points for each hairpin bend of the paved way, bounding any change of staircase direction. This arrangement made it possible to contain the global alignment error within the 10 cm error highlighted at some points at the hill base. The absolute coordinates of the master GNSS were first determined by downloading data from two permanent GNSS stations of the private TOPCON TopNet network. Then, the coordinates acquired from the rover system were processed with short baselines (static mode with post-processing differential correction) and integrated with NRTK coordinates. All elevations were transformed from ellipsoid to geoid elevations with national ITALGEO2005 geoid model, obtaining the final list of coordinates framed in ETRF2000(2008.0) - UTM32 and elevations in the national elevation system (Genova 1942). The standard deviation of the GNSS static points considered in the project was less than 3 cm, while an error within 10 cm was accepted for the NRTK coordinates.

The RPAS photogrammetric acquisition campaign was planned to use a DJI Mavic mini 2, equipped with a camera set up of 4.49 mm (nominal value), of focal length, f/2.8, ISO 100, and 1/1250 sec of exposition. As a result of the acquisition step, a calibrated focal length value of 4.85 mm was fixed. The flying distance was 90 meters from the hill base. Two flights were scheduled with 13 to 15 waypoints with perpendicular flight directions, using the camera in the nadiral set-up. A third manual flight with the oblique axe to acquire the hillsides and the external walls of the Castle was integrated at the end. The first two flights presented an average altitude of 605 m, the third 620 m. The ground elevations, which varied between 510 and 578 m, resulted in a GSD varying between 4 cm and 1 cm. The ortho-image extracted within the Agisoft Metashape program provided an average GSD of 2.24 cm. The final photogrammetric block was composed by 286 images with a mean GSD of about 3.2 cm at the bottom of the hill.

B. Architectonic survey

In the first stage, a photogrammetric campaign related to the archaeological area (remains of the castle) and the Museum was carried out. It divided and coded the different areas, preparing a database structure to identify and optimize data management.

The integration of 3D terrestrial laser scanning and RPAS photogrammetry allowed facing the multi-resolution required. The ground survey was carried out with a Focus M70 (Faro). Its reduced dimension and lightness helped face different levels and slopes. The first scan was positioned in a barycentric position. A resolution of 3 mm@10m was set, acquiring a vast archaeological volume. The acquisition project foresaw 154 scans, ranging a resolution of 6 to 24 mm@10m, concerning the environmental conditions and the level of architectural details. The high number of scans came up from the aim to avoid shadows in all the archaeological area, which present several terrain variations many hidden surfaces. The range-based campaign included also the whole internal part of the Museum. The range-based approach allowed sampling of all the surfaces except the high part of the wall, the museum roof, and the external wall of the Castle. The range-based clouds were aligned in JRC Reconstructor (Gexcel), alternating a cloud-to-cloud ICP alignment with bundle adjustments to optimize some intervisible blocks. Each scan was filtered at 30 meters distance, eliminating all outliers by reducing the measurement uncertainty. The global alignment error is only a few millimeters, consistent with the instrument's standard deviation (1 sigma). The entire system was then roto-translated in the absolute reference network with an average and distributed orientation error of 3.7 cm.

The photogrammetric RPAS survey was carried out with a manual flight devoted to acquire detailed part of the archaeological area. The acquired images were

integrated with the territorial flights and processed within the Agisoft Metashape program. The final photogrammetric block has been composed by 356 images obtaining a ground GSD of 7-10 mm (Fig. 2).

In an integrated survey project, it is critical to plan local and global data validation to identify the degree of data reliability. This step was made identifying possible deviations between the photogrammetric point cloud and the range-based one was planned. To make the two clouds more consistent, they were resampled with a 1 cm step to have two systems with similar resolutions. Then they were brought into both CloudCompare and JRC software, identifying the deviation map between the two clouds. The analysis showed an average deviation of less than 1 cm and the values obtained show how the most significant variations are related to vegetation. This is due to the acquisition methodologies (active and passive) that detected tree geometries from two different viewpoints, not having the same overlap with archaeological surfaces. The acceptable deviation values demonstrate the successful absolute orientation process between the different point clouds and their level of reliability.



Fig. 2. Complete and integrated point cloud of the entire Castle-Hill system.

IV. DATA PROCESS

The data acquired with the procedures described in the previous chapters were initially processed by segmenting the point cloud through the division of the points that belong to one of the following categories: vegetation, architecture and ground. Afterwards, the points representing the ground were used to create the polygonal mesh model that represented the topography.

The segmentation of the point cloud was made using the CloudCompare open software. The first part of the process was made using the CANUPO algorithm integrated into the software. This algorithm uses an automated construction of a classifier that finds the best combination of scales (i.e. all scales contribute to the final classification but with different weights) that maximizes the separability of two categories that the user has previously manually defined (i.e. samples of vegetation and samples of ground segmented from the point cloud) [17]. This algorithm proves effective in the

classification of 3-dimensional point cloud data [18, 19]. Subsequently, manual operations were carried out to refine the procedure by manually removing the points not recognized by the automatic procedures. This aspect is very important to return an error-free topographic surface. The result is made up of three different point clouds representing the vegetation, the architecture and the ground (Fig. 3). In particular, the classification algorithm recognized about 94% of the points while the remaining 6% are manually selected. They mainly concern the removal of points of objects (cars, road signs, etc.) that do not belong to the three main categories (terrain, vegetation, and architecture).



Fig. 3. Segmentation of point cloud. Above: point cloud of the Vegetation and Architecture. Below: point cloud of the Ground.

The points of the terrain were reduced from an initial number of 42,567,000 to a final number of 4,804,310 and then used for the construction of the topographic surface. The surface was created using the PoissonRecon plugin which allowed to generate the polygonal mesh model (Fig. 4).

The point cloud of the architecture is instead used to create the 3D BIM (Building Information Modeling) model. The intent is to use the polygonal mesh model to represent the topographical context and to use a BIM authoring software to model the architectures on the top the hill (museum and remains of the castle) using a typical Scan-to-BIM process [20, 21] starting from the point cloud. This activity is going to be carried out in the coming months. By reading the data from the survey combined with archival documents, it is intended to produce, the pre-existing architectures (no longer present is the represented form). In the hBIM (historic Building Information Modeling), the information consist mainly of historical resources such as historical images, historical

documents, existing reliefs, literary works, and archival documentation. Starting from the construction of a modeling environment, which contains the three-dimensional semantic model (hBIM), it is essential to integrate different representation methods within the same space. Photographic, pictorial images and engravings obtained by a mathematical or optical process could include information and notes necessary for a complete understanding of the transformation. This means that it is necessary to link the model with primary sources such as images and iconographic images [22].

V. CONCLUSIONS

Castles and their territory represent complex but closely interconnected systems. Adopting a knowledge process based on historical, geometric, material, and technological analysis is the basis for fully understanding the origin and development of these complex architectures. Besides, this pipeline must be adapted to the different scale levels contained in the fortified systems. The research regards Canossa Castle, a complex system located in the Reggio Emilia territory.

The research aims to gather the geometrical information to start an interpretation step and suggest some reconstructive hypotheses about the Castle at the time of Matilda of Canossa [23]. So, the article suggests a consolidated survey methodology based on active and passive multi-resolution techniques integrated with source analysis. An integrated survey campaign is applied using the GNSS system, photogrammetry from RPAS, and a 3D laser scanner. In particular, RPAS plays a crucial role in the different surveying techniques as the only one that can solve the problem of scale variation and limited accessibility of the site.

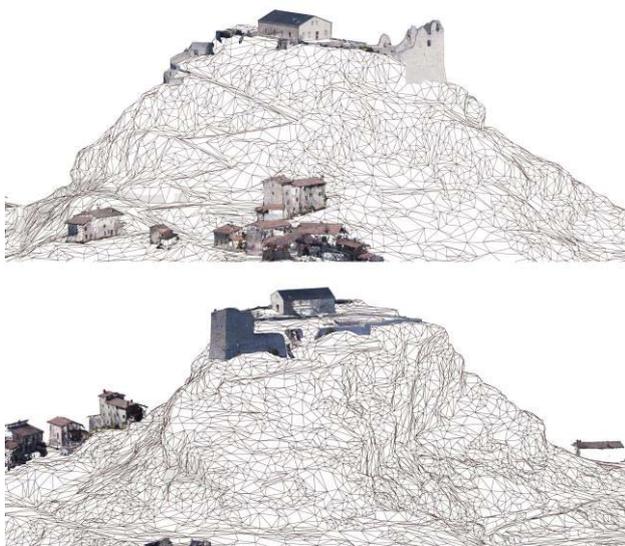


Fig. 4. The polygonal mesh model of the ground and first operations of 3D modeling.

The use of the different techniques highlighted different bottlenecks concerning the specificities of the area. In the pipeline, several validation step has been planned in order to obtain a reliable integrated model. Data extracted represents a substantial base to start the 2D representation and 3D reconstruction. This will result in a three-dimensional BIM model capable of providing a reliable decision-making basis for the conservation and enhancement of the architectural and cultural heritage represented by the Castle of Canossa. The BIM model will have a dual purpose, ensure professional collaborations between project members and stakeholders through a digital platform and develop virtual systems in order to improve tourist-cultural use of the Canossa site.

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