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New discoveries at the Castello Sforzesco in Milan: an integrated approach through 3D modelling and GPR survey.

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***Abstract* – The research on Castello Sforzesco in Milan developed an integrated 3D information model combining historical sources and contemporary survey technologies. A digital twin was structured through multiple layers of geometric data, organized by attributes and accuracy of the original information. The model quickly proved useful in analyzing theories on hidden underground routes. This potential led to collaboration between the Politecnico and Codevintec Italiana s.r.l., resulting in a wide survey with stepped frequency ground-penetrating radar. The data revealed numerous original structures and others only hypothesized. One example is the second counterscarp gallery, drawn by Leonardo da Vinci and now located a few centimeters from the currently accessible one. Other results suggest the debated gallery leading to Santa Maria delle Grazie. The study shows how integrating historical analysis with conventional and modern survey techniques, enriched by geophysical investigations, can yield valuable insights and enhance understanding of architectural heritage.**

I. INTRODUCTION

Nowadays, the management of buildings and the related information relies increasingly on the use of digital technologies, techniques, and solutions. This is now an unavoidable path, no longer limited to newly constructed buildings typically associated with BIM systems. Digitalization has, in fact, become an integral part of the architectural heritage and built environment sectors as well.

Given the changing habits of the population, this pairing has rapidly gained ground in the large-scale dissemination of information, drawing from the ICT (Information and Communication Technology) domain and giving rise to numerous experiments involving VR (Virtual Reality), AR (Augmented Reality), and MR (Mixed Reality) [1].

Even more significant developments have occurred within the professional domain, where the focus has increasingly shifted toward the concept of digital twins. In this framework, non-invasive diagnostic tools such as Ground Penetrating Radar (GPR) based on stepped frequency technique can play a fundamental role. GPR enables the investigation of subsurface and inner structural features of buildings, providing crucial geometric and material data that are often inaccessible through traditional survey methods. When integrated into a digital twin, these high-resolution datasets enrich the model with detailed information about the hidden or embedded components of the built environment, such as voids, reinforcements, or degradation patterns, thus enhancing its accuracy, reliability, and predictive capabilities. The ability to perform repeated surveys also supports the temporal dimension of digital twins, allowing for condition monitoring and lifecycle management of structures over time [2]. The current landscape remains highly fragmented across a wide array of sub-themes, resulting in multiple research directions. Consequently, there exists a broad variety of digital twins that, each in its own way, interprets reality by generating a tailored replica of a building based on the information available and processed. These digital twins address different requirements and serve diverse functional objectives, such as accessibility, knowledge, management, and conservation. This plurality of purposes inevitably influences the internal structure and development process of each model, which can vary considerably depending on the intended final use, even though they often originate from the same data source, namely a point cloud acquired via laser scanning or photogrammetry [3]. This remains particularly true when the digital twin is used to represent an existing physical object. However, these tools are also frequently employed for reconstructing the historical layers of a building, serving as the platform where lost geometries can be digitally brought back to life [4, 5]. A digital twin may also be defined as a digital counterpart of an object or system that simulates its processes and dynamics. It should therefore provide the necessary information aligned with the specific function for which it was conceived and developed. While this concept is already well established within the BIM domain and new building models, it still represents an open field of investigation when applied to the existing built heritage. This has led to a growing body of experimentation and research [6, 7, 8] aimed at exploring how to best exploit such datasets and examine their integration with the components of the digital building.

The present study positions itself within this context, developing a novel approach to the knowledge and management of architectural heritage, supported by contemporary surveying techniques and technologies for the study and digital transposition of information. The proposed framework is capable of representing existing structures, lost elements, and hypothetical reconstructions within a unified model, combining information from diverse sources that vary in both nature and accuracy. The goal has consistently been to produce a working model able not only to organize the knowledge related to a heritage asset and facilitate its interpretation, but also to serve as a dynamic tool, capable of evolving over time and fostering new investigations and research insights. This latter aspect, namely the ability to stimulate the advancement of studies and the deepening of knowledge of the built heritage, constitutes the core of the present contribution, which shows how the study of the 3D model has led to new and valuable analyses and discoveries concerning the heritage asset.

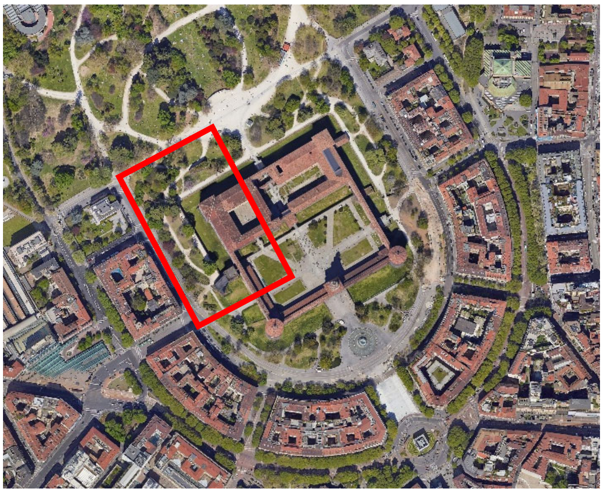

Fig. 1. Zenithal view of the Castello Sforzesco (Google Earth) with the study area highlighted.

The activities were carried out at the Castello Sforzesco in Milan (Figure 1) [9, 10], with a particular focus on the underground and above-ground spaces of the north-eastern area of the fortress complex (Figure 2), as well as the Ghirlanda infrastructure, a defensive system located outside the castle's main core, which was partially demolished in the late 19th century. The Milanese stronghold immediately proved to be an ideal case study for these tests, due to its complexity and stratification, as well as being a strong catalyst for the subsequent geophysical investigations and GPR surveys, considered necessary following the study of the model. Indeed, Ground Penetrating Radar Ground Penetrating Radar (GPR) immediately played a key role in investigating hidden structures [11] and potential underground passages within the castle complex. The use of a 3D step-frequency GPR system enabled extended-area mapping with high resolution and improved depth penetration, making it possible to identify inaccessible or lost elements with greater accuracy. These data were integrated into the digital twin, supporting archaeological interpretation and enriching the model beyond the visible layers.

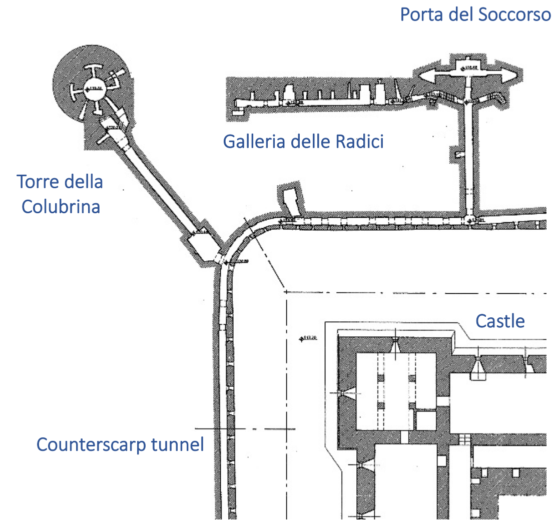

Fig. 2. Underground infrastructure of the Ghirlanda (well-known and accessible spaces).

II. 3D INFORMATION MODEL

The work carried out on the Castello Sforzesco enabled the development and testing of a new approach to the digitisation of architectural heritage. The fundamental idea is that the digital twin should be capable of collecting data from a variety of sources and representing both existing structures and those that have been lost. This stems from the belief that only such a tool can provide a comprehensive description of a historic building and the processes that have shaped it and are still ongoing [12]. Typically, this type of architecture is associated with a vast body of documents, written works and information accumulated throughout its existence. These are supplemented by more recent sources, such as photographic material, both traditional and modern surveys, etc. All these sources yield geometric information with varying levels of accuracy. The system devised aims to arrange together all geometric data available on an architectural asset, including that which will be produced or updated in subsequent phases. The goal is to provide a tool that supports and facilitates the understanding of complex structures and is capable of both incorporating future data and, above all, stimulating new studies and questions about the architectural heritage.

The proposed structure is based on the notion of LOGI [13]: Level of Geometric Information. The digitisation method is structured around a three-tier classification of data, into which the different elements of the building are then catalogued and modelled. The definition of these modelling levels draws inspiration from the LODs (Levels of Development) associated with BIM processes, as well as from other research initiatives that have developed classification systems for levels of detail in modelling [14].

The classification system of sources, and of the resulting 3D elements derived from the information they contain, is currently composed of the following three levels. Within each of these levels, the modelled volumes display a consistent degree of accuracy, determined by the nature of the information and the sources considered.

Fig. 3. Views of part of the point cloud implemented for the development of the 3D model.

LOGI 1. This first level concerns the 3D modelling of hypotheses derived from historical documentation (iconographic material, ancient texts, historical cartography, etc…) and thus produces simple three-dimensional elements representing structures that are no longer visible but were likely once present.

LOGI 2. This level includes documents produced using traditional surveying methods, such as classical geometric surveys and trilateration.

LOGI 3. This represents the highest level in terms of detail and precision; information and materials from modern geomatic surveys fall within this category. Examples include point clouds and surveys with a precision of a few millimetres (Figure 3). In LOGI 3 the 3D modelling of architectural elements involves a simplification factor with respect to the accuracy of the survey. Since the objective is to develop a tool to support the understanding and management of assets, this approach was deemed acceptable, even though the outcome still provides a reliable and accurate model capable of conveying the necessary information.

It is important to highlight that, despite the manipulation of information and its potential simplification, during the exploration of the model, it is always possible to access the original reference information, allowing consultation of the original data and sources. The 3D model is in fact paired with an information management system [15]. The system requires that all modelled elements within the 3D environment be linked to attribute tables (likewise the structure of the national Topographic Database) that describe them and contain the essential data for identifying each object and its connections to the source documents. Indeed, each attribute table always contains a link to the original resource used, whether it is a document or the survey output, located in a specially created online repository.

The result is an organic yet heterogeneous collection encompassing all elements of the building, from those still accessible to those hypothesised, no longer visible or no longer extant. Moreover, by developing the digital twin in multiple blocks and employing a rigorous georeferencing strategy, each element of the 3D model can be continually updated with new data.

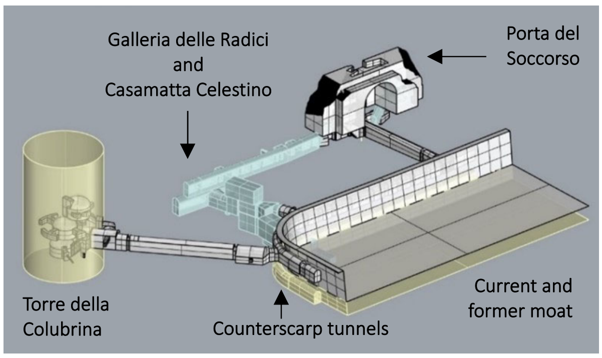

Fig. 4. Portion of the 3D information model of the Castello Sforzesco showing elements pertaining to all three LOGI.

Based on this structure, the 3D information model of the studied section of the Castello Sforzesco, the north-eastern corner of the Ghirlanda complex, was developed. This area includes above-ground elements as well as a considerable underground infrastructure composed of tunnels and small- to medium-sized rooms, the result of the modelling phase is shown in Figure 4. The elements of LOGI 1, based on historical documents, are shown in yellow. These are the Torre della Colubrina, the original plan of the moat and the second counterscarp tunnel. The Casamatta Celestino and the Galleria delle Radici are shown in blue, obtained from the drawings of a previous traditional survey and pertaining to LOGI 2. Finally, in grey, the elements of LOGI 3, surveyed using photogrammetric and laser scanning methods; these are the current moat, the casemates of the Colubrina Tower (underground), the Porta del Soccorso and the accessible infrastructure of the counterscarp tunnel.

From the outset, the developed tool proved highly valuable not only for understanding the architecture, but also, perhaps more importantly, for raising thought-provoking issues and providing avenues for further study and research. This highlights the intrinsic potential of such a digital object to enable continuous improvement and enrichment, as exemplified by the GPR survey carried out.

Numerous questions emerged from the study of the model and its data, but two directed and paved the way for the subsequent extensive ground-penetrating radar (GPR) survey, which led to the major discoveries presented in the following chapter. The first concerned the Spanish Bastions (Figure 5), which no longer exist, or perhaps are simply no longer visible. By examining the model and comparing that area with the Topographic Database (DBT), the question arose as to how much of these structures might still be present beneath the ground level of Parco Sempione or the adjacent streets, an issue that could be addressed through non-invasive geophysical investigation. The second issue relates to theories concerning a second counterscarp gallery, which some have posited lies just below the floor level of the currently accessible gallery. However, this hypothesis appears to conflict with what can be visualised in the model.

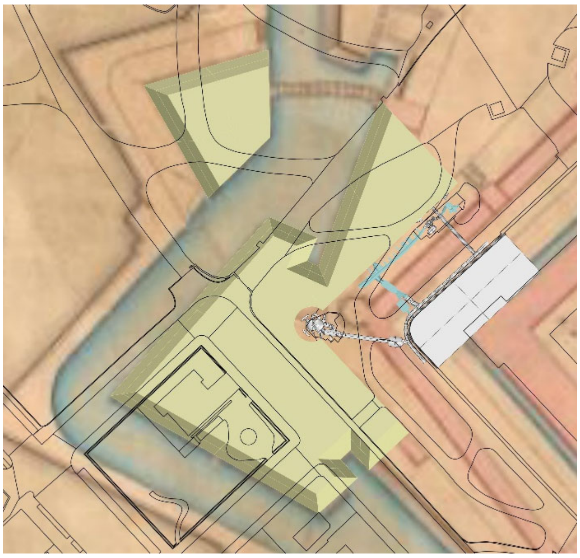

Fig. 5. Comparison between the 3D model of the Bastions, the Theresian Cadastre and today's DTB.

These and other questions formed the foundation for the continuation of research at the Milanese fortress, which led to unexpected discoveries and new data with which to test the model and its structure.

III. GPR SURVEY AND NEW DISCOVERIES AT THE CASTLE

The primary geophysical investigation was conducted using different GPR systems: the Kontur array and single-channel GSSI systems. The primary large-coverage survey was conducted with the Kontur, a stepped-frequency system featuring a 1.80m wide antenna array with 20 channels operating in the 200-3000 MHz frequency range. For smaller or more constricted areas, the single-channel GSSI Flex NX, UtilityScan 350 MHz and 200 MHz systems were employed. The data were acquired along a high-density grid and georeferenced with an RTK GNSS receiver. GPR data processing, performed using the Examiner and RADAN software, included gain correction, filtering, and 3D migration.

Fig. 6. The red lines indicate all underground structures identified through GPR surveys. The grey traces represent the areas covered by the GPR survey.

The GPR survey conducted at Castello Sforzesco has unveiled a more extensive and intricate underground network than previously documented (Figure 6), bringing to light numerous anomalies suggestive of buried structures and unrecorded tunnels. Several of these anomalies present regular geometries and alignments consistent with known elements of the site, particularly with the counterscarp gallery, indicating the possible existence of parallel or connected underground pathways. To validate this interpretation, a comparative analysis was performed between the GPR response of the known gallery and a newly discovered anomaly. As shown in Figure 7, the remarkable similarity in the geophysical signatures provides strong evidence that the anomaly corresponds to a second, previously unknown gallery running parallel to the accessible one.

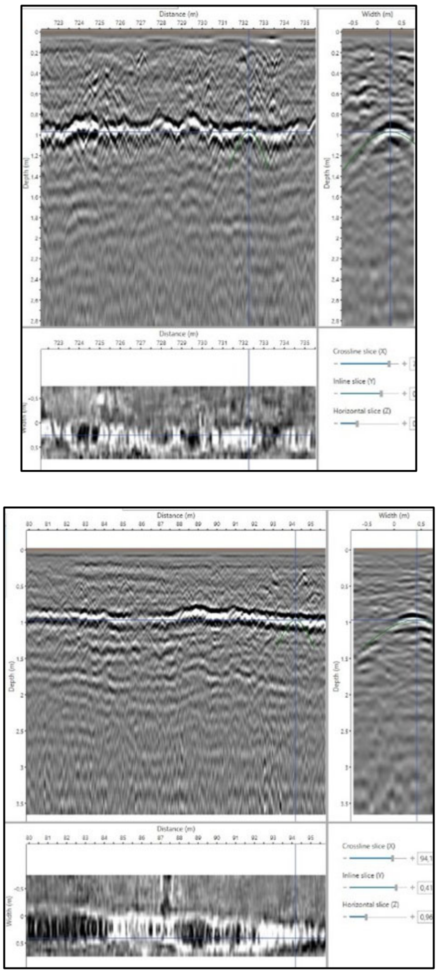

Fig. 7. The GPR profile of the newly discovered anomaly (above) presents a hyperbolic signature nearly identical to that of the known counterscarp gallery (below), confirming its nature as a parallel, man-made structure.

In specific areas, visual inspections of sealed or partially obstructed corridors directly corresponded with GPR signals that showed clear continuations of these passages beyond the visible blockages. The interpretation of these results was greatly enhanced by integrating the GPR data with visual evidence gathered during site visits and with 3D model geometries derived from the information dataset (historical documents, traditional surveys and modern geomatics) previously assembled and organised in LOGI.

Among the most significant findings, the survey identified a clear, continuous anomaly consistent with the passage frequently mentioned in historical records and local legends-most notably, the hypothesized underground connection between the Castle and the church of Santa Maria delle Grazie. This provides the first substantial physical evidence supporting the existence of the tunnel said to have been used by Ludovico Sforza to secretly visit the tomb of his wife, Beatrice d'Este. The compelling evidence for this discovery is presented in Figure 8, which integrates the historical photograph of the tunnel with the corresponding GPR data that scientifically validates its presence.

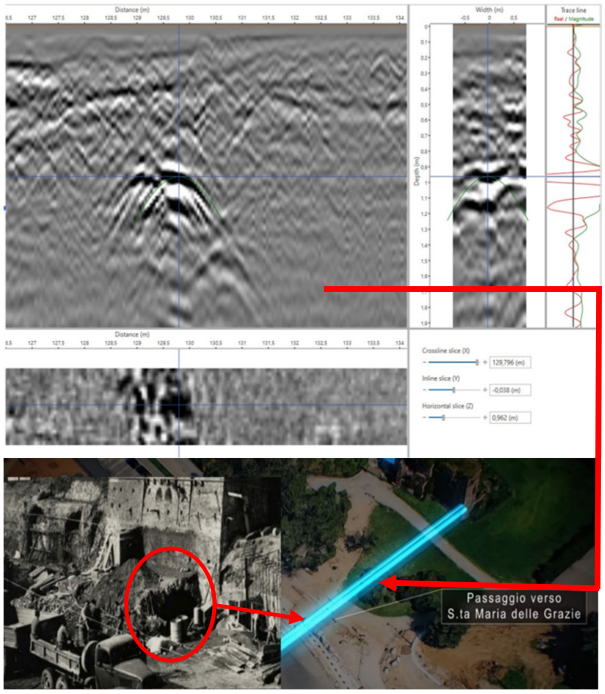

Fig. 8. The GPR data (above) provides scientific validation for the historical evidence (below). The GPR profile reveals a clear hyperbola confirming a structure. The historical photo shows the tunnel entrance during past excavations.

IV. CONCLUSIONS

The work carried out has clearly reaffirmed the usefulness of geophysical investigations, specifically GPR (Ground Penetrating Radar) surveys, for the non-invasive exploration of the subsurface. Moreover, the activities conducted on the Milanese case study enabled the validation of the effectiveness of the proposed and tested framework for the development of the 3D information model. The survey successfully identified various defensive tunnels, many of which show clear geometric and spatial connections to structures already known within the castle complex. These include multiple parallel galleries and interconnecting corridors, which suggest a highly organized and extensive underground defense system. Notably, the investigations also brought to light strong evidence of the tunnel connecting the Castello Sforzesco to Santa Maria delle Grazie. Although further confirmation of the tunnel's layout will require additional studies and surveys, the extensive investigation using the Kontur and GSSI GPR has enabled a broad and high-resolution mapping with improved signal penetration. The integration of 3D GPR data with the 3D model and its heterogeneous sources (from historical documents to point clouds), as well as with direct observations, marks a significant step toward validating long-standing hypotheses and expanding our understanding of the site's hidden architectural features.

However, the most significant issue highlighted once again by this experience is the essential need for an integrated, multidisciplinary approach in the knowledge, understanding, and management of the built heritage. This approach must encompass disciplines ranging from historical and archival research to modern geomatic surveying and geophysical investigations. The complex stratification that characterizes many of our architectural assets makes it indispensable to adopt complementary interpretative methods, which together contribute to forming a comprehensive and exhaustive body of information. Only through the integration of diverse sources and analytical tools can a deep understanding of architectural heritage be achieved along with insights into the historical dynamics that have shaped it and may still be detectable today. Ultimately, only a multidisciplinary strategy can efficiently address the growing demands for information, as well as its organization and dissemination.

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