Historical building floor characterization thanks to GPR and LiDAR integration

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Introduction

The conservation and the preservation of cultural heritage historic buildings necessitate interventions that safeguard their authenticity and structural integrity. Thus, the creation of digital models, often referred to as digital twins, has become a central focus in geomatic surveying, particularly in the fields of architecture and cultural heritage, driven by the development of the Heritage Building Information Modelling (HBIM). The latter refers to the generation and management of digital representations of an historical building's physical and functional characteristics throughout its lifecycle. This approach enables professionals across various sectors (e.g., architecture, engineering, construction, and geology) to collaborate and share information from the design through the construction, and the building's operational phase, enhancing the management and preservation of both contemporary and historical structures (Tucci et al. 2017; Gspurning et al. 2022; Sulzer et al. 2023). LiDAR systems, often coupled with digital photogrammetry, has emerged as a key remote sensing technology for creating accurate digital models consisting of point clouds composed of millions of points. These techniques are widely used in fields such as civil engineering, architecture, urban planning, geology, and archaeology, allowing for the creation of reliable 3D models useful for documentation, analysis, and conservation purposes (Gigli et al. 2014; Telling et al. 2017; Beni et al. 2023). Recently, advancements in SLAM (Simultaneous Localization and Mapping) laser scanning technology (see Section Methods for more details) have opened the possibility for fast and detailed documentation of architectural spaces, offering a complementary dataset for deeper structural analysis.

To characterize the conservation state of historical buildings, non-invasive (or minimally invasive) and non-destructive methods have become indispensable, and among these geophysical surveys are employed for the diagnosis, conservation, and monitoring (Coli et al. 2022; Coli et al 2023; Napoli et al. 2024). When applied to cultural heritage buildings, they are used to locate targets ranging in size from a few centimetres to a few meters (Pazzi et al. 2016; Morelli et al. 2020; Pazzi et al. 2020). Among all the geophysical techniques, Ground Penetrating Radar (GPR) has become a prominent tool. It allows to evaluate the structural integrity and preservation state by detecting variations in material properties, moisture content, and structural voids. GPR's capability to deliver high-resolution data through very close 1D profiles and/or 2D grids (Daniels 2004) makes it a cost-effectively method for buildings diagnostics.

This study focuses on the coupled application of GPR and SLAM laser scanning techniques to detect anomalies within the floor of the Galileo Tribune. It is a room located inside Palazzo Torrigiani in Florence, and it is part of the La Specola Museum itinerary. It was designed by the Florentine architect Giuseppe Martelli at the behest of Grand Duke Leopold II of Lorraine, and it was inaugurated in 1841 during the Third Congress of Italian Scientists. The Galileo Tribune's floor consists of a marble mosaic, characterized by slabs of different and unknown thicknesses. Unfortunately, the floor structure is unknown. Verisimilarly the marble mosaic rests on a slab, of unknown thickness, above the cross vaults of the cloister surrounding the inner courtyard. The space between the vaults and the slab is likely filled with lightweight material (an example of filling with ceramic material can be found in Perez-Gracia et al. 2019). Recently, it has been noticed that part of the marble floor in the vestibule has suffered differential subsidence. Thus, the overall objective of the present study is to investigate the structure below the marble pavement using GPR and to identify possible causes of the subsidence (such as the presence of voids or a degradation of the supporting structure), as well as other possible areas of attention. Given the absence of an updated planimetry of the Galileo Tribune, which was necessary for precise GPR survey localization and spatial interpretation, a detailed point cloud was generated through a mobile laser scanning survey. This survey encompassed the Galileo Tribune, the underlying cloister, the access staircase, and the mezzanine rooms beneath the Tribune. This 3D dataset reveals itself to be of fundamental importance in interpreting the GPR anomalies.

Methods

As well known, the GPR technique is based on the propagation of electromagnetic waves in the subsurface (Butnor et al., 2001), which are emitted by a transmitting antenna and are received by a receiving antenna after undergoing reflection from the target. By analysing the amplitudes and travel times of the recorded signals, it is possible to obtain qualitative and quantitative information about the materials and structures through which the transmitted signal propagated (Dossi et al., 2021). To optimize the resolution and the survey depth at the study area, two antennas with different frequencies were selected: specifically, a C-Thrue GPR antenna and a RIS-ONE antenna, both manufactured by IDS Georadar s.r.l.. The first one is a small and extremely handy instrument, equipped with two pairs of antennas with orthogonal polarity and a peak frequency of 1500 MHz, allowing high detail (1.0-2.0 cm resolution) but limited investigable depth (70.0-80.0 cm). Both linear and gridded profiles were acquired. The second one is equipped with a 400 MHz antenna and allows investigation, in masonry, of depthsup to 3.0-5.0 m with a resolution along the propagation direction of 6.0-7.0 cm. Only linear profiles were acquired. A total of 133 GPR profiles were acquired with the two GPR antennas, subdivided into seven separate projects (Fig. 1a) distributed as to cover the entire Galileo Tribune (the distance between two parallel profiles was 50.0 cm) and to obtain a higher resolution (the distance between two parallel profiles was 10.0 cm) in the area where the pavement subsidence was reported. Data processing was done using GRED HD software. It allows specific signal processing (e.g., spatial and temporal filtering, removal of offset and background noise, calculation and assignment of the electromagnetic wave propagation velocity for the conversion of radargrams from time to thickness/depth), and the combination of radargrams for tomographic analysis and the 3D reconstruction of any reflectors.

To achieve the digital model of the Galileo Tribune and its surroundings the GeoSLAM ZEB-HORIZON RT mobile laser scanner (MLS) was employed (Fig. 1b). The latter system works by combining the time of Flight (TOF) with Simultaneous Localization and Mapping (SLAM) techniques. This approach enables a mobile mapping system to build a map of its surroundings while simultaneously localizing itself within that space. This dual functionality helps overcome the limitations of traditional point cloud data acquisition using terrestrial laser scanner positions by integrating motion data (e.g., from an Inertial Measurement Unit, IMU) to refine the systems position within the surveyed environment. Real-time reconstruction algorithms continuously compare new data with existing maps to adjust for any positional errors, ensuring that the digital model remains accurate during the scan.

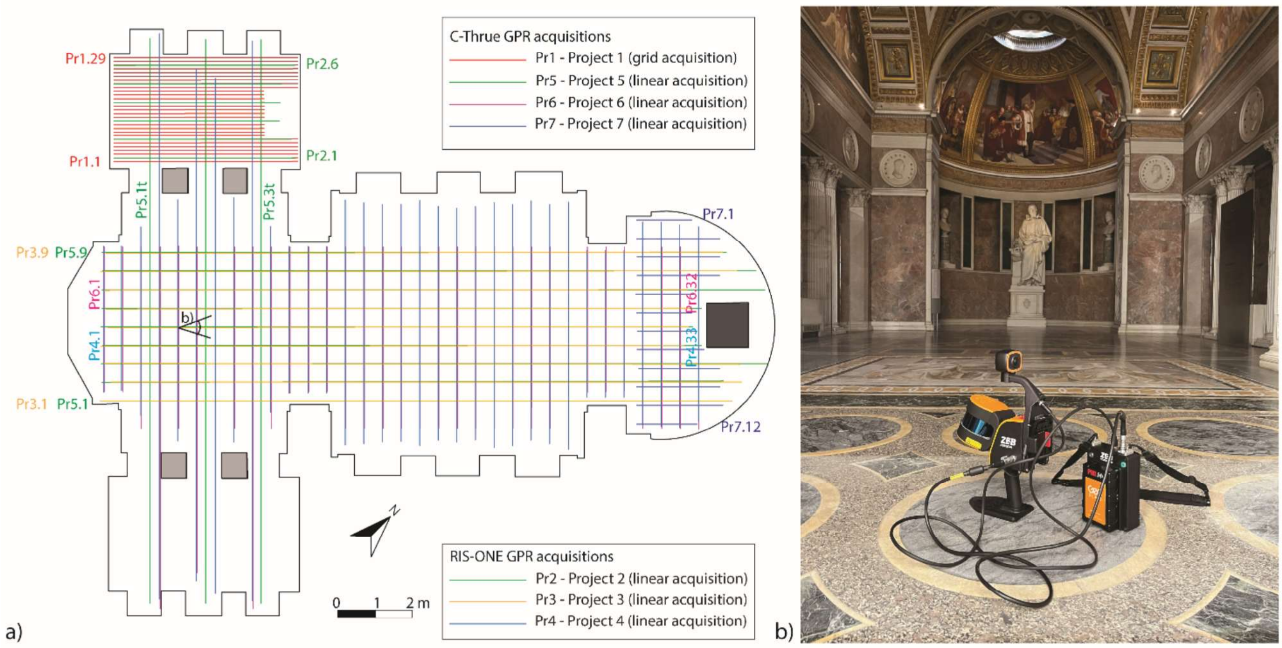

Fig. 1 – a) Plan of the Galileo Tribune showing the location of the GPR traces, acquired with both the C-Thrue (Pr1, Pr5, Pr6, and Pr7) and RIS-ONE antennas (Pr2, Pr3, and Pr4), and of the photo shown in b. b) Photo of the Galileo Tribune. In the centre, the MLS GeoSLAM ZEB-HORIZON RT system used to carry out the LiDAR survey of the Galileo Tribune and its adjacent and underlying areas.

In this study, the GeoSLAM ZEB-HORIZON RT (Fig. 1b) was selected because of its ability to efficiently handle the complexity of the environment (encompassing both interior and exterior spaces), and its capacity for rapid data acquisition. This lightweight instrument, weighing only 2.9 kg, can capture 300,000 points per second within a 360°× 270° field of view. A total of 4 surveys were carried out: 2 which covered both the interior and the atrium of the building, and 2 which were carried out mainly inside the building, trying to always follow the same path. Each survey lasted approximately 18 minutes. This procedure resulted in 4 point clouds, from which the best surveys, in term of noise, of the two pairs were selected. Subsequently, the two best point clouds were merged into a single cloud (Fig. 2a), which was used as the basis for the subsequent analysis. This merged point cloud was cleaned both manually and automatically to remove unnecessary points (noise) and unwanted objects. The merging of the selected point clouds was achieved through a manual pre-alignment for homologous points, followed by a fine alignment using the iterative closest point (ICP) algorithm, which overlapped the two datasets with an accuracy of ±2.0 cm in common areas. Given the objective of the study, it was not necessary to perform a GNSS survey to geo-reference the 3D data in the space. This MLS-generated model was employed to: 1) extract the Galileo Tribune floor plan (Fig. 1a and Fig. 2b), to facilitate the GPR survey planning, ensuring optimal coverage and data quality (Fig. 1a), and 2) obtain the vertical sections along each GPR acquisition (Fig. 2c-d). For the extraction of the 2D vertical and horizontal sections, sub-sets of the point cloud with a thickness of 20.0 cm were considered (thus 10.0 cm with respect to the plan trace). To allow the coupling with the GPR data, each extracted sub-sets of point cloud was vectorialised in a cross-section. The GPR data were correctly oriented in space for both the vertical (Z) and horizontal (X, Y) directions in the same local reference system defined for the MLS-obtained data to ensure the consistency of all spatial data in a coherent reference system. This played a key role in the GPR data interpretation phase, providing a robust 3D framework for an accurate spatial reprojection of the data.

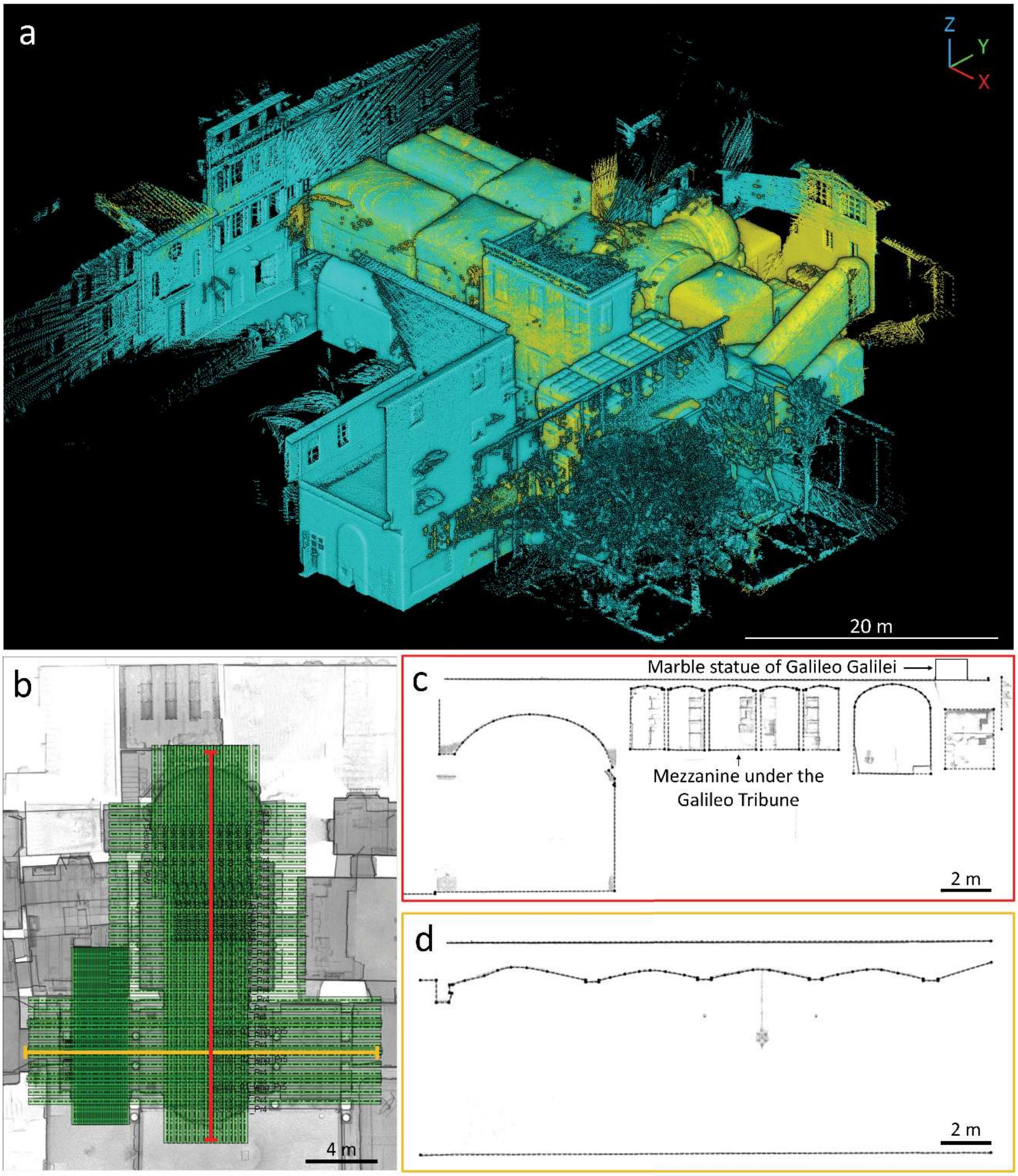

Fig. 2 – a) Complete digital model created by merging the more reliable point clouds obtained by the MLS survey. b) Horizontal sections extracted from the digital model at a hight from the Galileo Tribune floor of 20.0 cm. In green are shown all the vertical sections extracted along the GPR profiles. In c) and d) examples of two vertical sections of the studied spaces.

Results and discussions

The analysis of the MLS data shows that the structure below the Galileo Tribune varies in thickness from a minimum of 0.3 m in correspondence of the mezzanine room below the centre of the Galileo Tribune, to a maximum of 1.5 m - 2.0 m at the vaults of the cloister supporting the vestibule of the Galileo Tribune (see Fig. 2c and d and Fig. 3). Based on these results, the GPR traces acquired with the RIS-ONE antenna were cut at 2.0 m while those acquired with the C-Thrue antenna were cut at

1.0 m. The analysis of the GPR records revealed both the absence of clear reflections attributable to structural elements and the presence of clear diffraction hyperbolas. The first suggests a possible infill above the vault while the last indicates a beam and vaulting structure supporting the floor oriented both outward (normal to the image) or parallel to the GPR traces (numbers from 1 to 6 and white dashed rectangle, respectively in Fig. 3). In correspondence of the mezzanine room, below the centre of the Galileo Tribune, this beam and vaulting structure reaches a thickness of about 15.0 cm, as visible in Fig. 3.

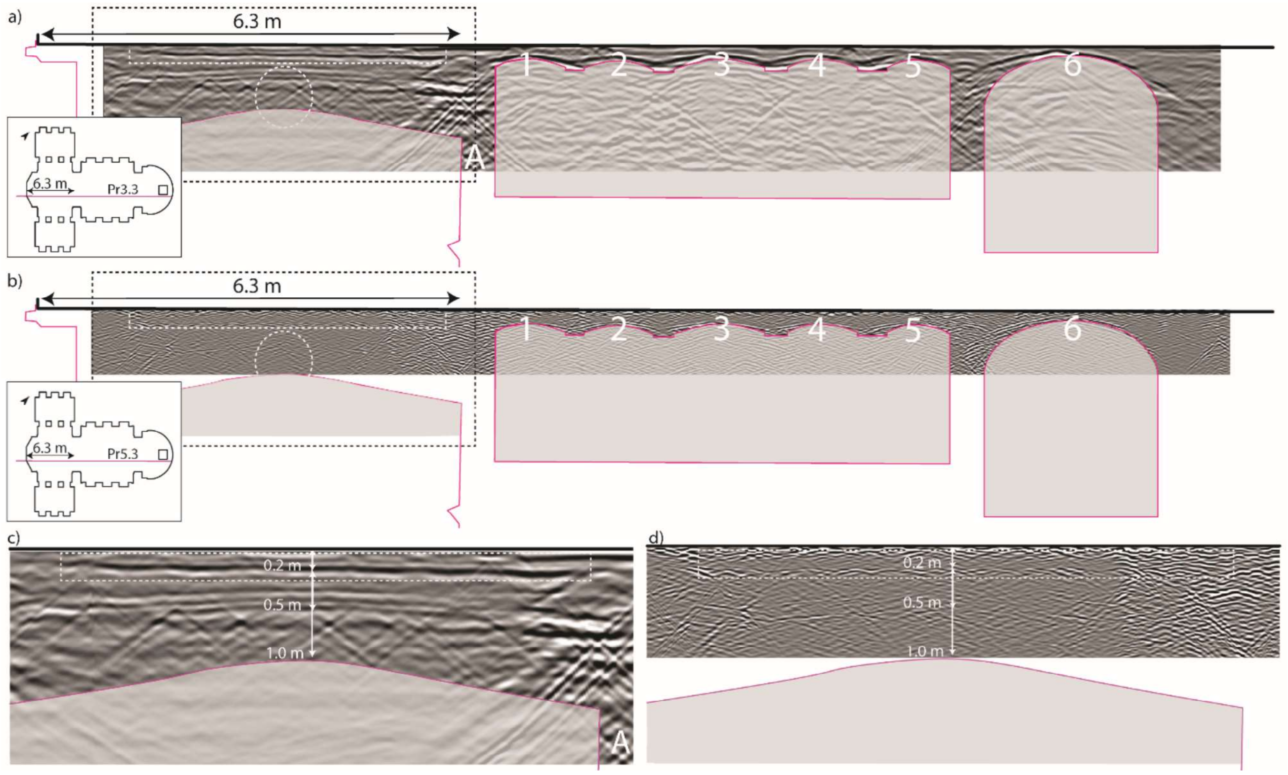

Fig. 3 – a) GPR radargram acquired with RIS-ONE antenna, and b) the one acquired with C-Thrue antenna. The black line on the top of each radargram indicates the floor, while the purple line indicates the vertical section extracted from the SLAM point cloud. The light grey areas indicate the presence of air because of the outside of the structure (area to the left of the letter A) or the room at the mezzanine (areas numbered from 1 to 6). A, in the figure above, identifies the position of the external wall of the structure pre-existing the construction of the Galileo Tribune; the dashed white rectangle indicates the presence of a reflector oriented parallel to the survey; the numbers from 1 to 6 indicate the vaults of the mezzanine roof. The black dashed boxes indicate the area zoomed-in in panels c) and d). In the small plan view of the Galileo Tribune is shown the location of the GPR traces. c) Zoom of the area marked by the black dashed box in panel a), and d) zoom of the area marked by the black dashed box in panel b).

Overall, there is a good agreement between the GPR reflections and the architectural elements (e.g., vaults and walls) reconstructed by the MLS survey. For example, the parabola-shaped anomalies (marked by 1 to 6 in Fig. 3a,b) correspond to the vaulted elements of the mezzanine. Nevertheless, the white dashed circle in Fig. 3 highlights an area where a parabola-shaped anomalies does not overlap to the cloister vault, being shifted in depth. This discrepancy could suggest the presence of voids between the beam/vault structure supporting the attic, and the cloister vaults. In fact, when converting radargrams from delay times to depth, a constant propagation speed of the electromagnetic wave is assumed (12.0 cm/ns in this case), and the presence of a void, in which the electromagnetic wave propagates at a higher speed (30.0 cm/ns), results in an underestimation of the distance travelled by the reflected wave and therefore of the thickness. Thus, the floor-to-ceiling cavity is not filled with the same material everywhere.

Conclusions

This work enhances the integration of subsurface geophysical data (GPR, in this case, but the findings of the work could be extended to other techniques) with surface geospatial features. Through the analysis of one of the most significant radargrams collected to characterize the structure below the Galileo Tribune floor, it is highlighted the importance of a multi-sensor approach that integrate geophysical surveys and high-precision spatial mapping of the building. The GPR traces, as expected, revealed the inner structure of the floor. When combined with the 3D model derived by the MLS survey, a comprehensive spatial and structural characterization of the environment is achieved. Without the digital model of the building, some of the GPR reflections would be probably wrongly interpreted, leading to a mispositioning of structural element with critical consequences on the planning of conservation and restoration works.

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