Terrestrial Laser Scanning for Surveying and 3D Modelling of Underground Built Heritage: A Case Study of Hypogea in the Sassi of Matera

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Abstract

This study explores the potential of Terrestrial Laser Scanner (TLS) technology for surveying and generating accurate three-dimensional (3D) models of Underground Built Heritage (UBH), using a hypogea complex in the Sassi of Matera (Italy) as a case study. This *urban ecosystem*, built through excavation and regeneration, features a vast array of underground structures, with complex geometries and intricate details. The survey conducted using TLS technology and the reconstruction using Reality Capture (RC) software produced a highly detailed 3D model of hypogea that serve as a basis for semantic-enriched Building Information Modeling (BIM). The results demonstrate the potential of advanced techniques through a workflow that combines TLS and RC to achieve adequate UBH representations and fill the gap in knowledge and documentation, which hinder management, exploitation, and valorization.

Keywords

Terrestrial Laser Scanner, Cultural Heritage, Underground Built Heritage, 3D Reconstruction, Sensor Data Modelling

1. Introduction

Underground Built Heritage (UBH) encompasses all underground historical artifacts engrained into the local cultural heritage, both in terms of their material and immaterial value [1]. UBH poses a distinct challenge among cultural heritage sites due to their inherent characteristics, which often result in limited knowledge and documentation, hindering effective management, exploitation, and valorization [2]. Therefore, creating a comprehensive and reliable representation of the architectural spaces and their geometry is crucial for documentation purposes [3].

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Traditional documentation and surveying methods, such as manual measurement, photography, and 2D sketches, are often inadequate in capturing the peculiar UBH spatial relationships, geometries, and details. Furthermore, these methods can be time-consuming, labor-intensive, and error-prone. Conversely, Terrestrial Laser Scanner (TLS) is gaining significance in the architecture, engineering, and construction fields [4, 5] due to the advancements in software and technology and has proven to be a highly effective technique for documenting complex UBH structures [6, 3], as it enables the rapid and accurate capture of high-resolution three-dimensional (3D) data, including detailed geometry and spatial information of both above-ground and underground historical monuments.

In this paper, we propose a workflow to survey the UBH using TLS and reconstruct realistic and optimized 3D models using Reality Capture (RC). The case study of Hypogea in the Sassi of Matera demonstrates that these technologies can produce accurate documentation of the state of fact to be used as a basis for semantic-enriched BIM for the conservation, restoration, and enhancement of the UBH.

2. Materials and Methods

2.1. The case study: Hypogea in the Sassi of Matera

The case study was conducted in Matera, a city in Southern Italy, in the eastern part of the Basilicata region. The distinctive cityscape owes its character to the magnificent interplay between the *Civita*, the *Sasso Caveoso*, and the *Sasso Barisano* neighborhoods, as well as the commanding presence of the *Gravina* canyon. The Sassi and the Park of the Rupestrian Churches complex, UNESCO World Heritage Site since 1993, are an outstanding and well-preserved troglodyte settlement which features the first inhabited zone dating back to the Palaeolithic era, as well as later settlements showcasing significant historical periods [7, 8, 9, 10]. The year 2019 marked Matera's designation as the Capital of Culture [11].

Matera is an intriguing example of a city built through excavation, subtractive architectures, "chthonic constructions": the visible portion of the city, constructed above ground, has a concealed counterpart, excavated deeply into the calcarenite rock. This complex urban system epitomizes the adaptation and regeneration of natural and anthropic phenomena. The millennia-long morphological evolution of the city occurred over successive generations of urban ecosystems [7, 9] that achieved a balance with geomorphology, water systems [12], and solar exposure via adaptations that shifted over time in response to demographic pressures.

The Sassi modeled in a vertical succession of levels totally or partially excavated and built that incorporate natural terraces and vertical cuts of the calcarenite, following the original conformation of the slopes. The resulting network of roads, roofs, and slopes facilitates the water collection and management. The excavations are determined by sunlight exposure and gravity-based water collection, resulting in organic irregular shapes with varying depths and slopes that are not horizontally uniform as one progresses into the excavation. The built volumes stem from the excavated caves below:the *lamione*, the basic building unit, constitutes an external projection of the hypogeal spaces with a cave-like internal spatial configuration [9]. The coexistence of natural caves and lamione types is due to their symbiotic relationship, with lamione walls constructed using calcarenite blocks extracted from caves. Over time, as lamioni

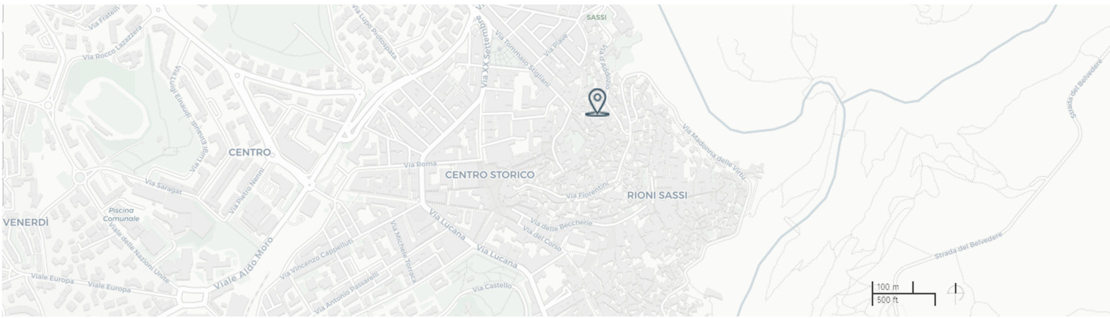


Figure 1: Map showing the location of the Fondazione Sassi in Matera, Italy. The marker indicates the area where the studied hypogea are located, within Sasso Barisano.

evolved into more complex structures, hypogea similarly transformed into true architectural spaces featuring sophisticated geometries, arches, niches, and other decorative elements.

Thus, the chosen location is of particular significance, as it hosts a vast array of UBH [1] that has not been fully surveyed, inventoried, and graphically documented, presenting a unique opportunity for further exploration and research.

The hypogea investigated are owned by the *Fondazione Sassi* (National Foundation for the protection and safeguarding of the architectural heritage of the Sassi of Matera) and are located within the Sasso Barisano, between the streets of San Giovanni Vecchio, San Pietro Barisano, and the district of San Biagio, as shown in Figure 1.

The *palazziate* houses [8], born from the architectural module of the *lamione*, lean against rocky walls and are grafted onto rupestrian habitats. They took on their present form during the Renaissance era [8]. Their structure consists of a network of rooms arranged over overlapping interconnected levels. The subterranean level, the hypogea, served as a warehouse and stable, while the upper levels, *sub divo*, served as residential units. Originally, the upper floors were accessible by means of external staircases and open galleries, partially still visible.

The hypogea, which are composed of a complex of chambers, passages, and staircases, exhibit intricate details such as carvings and ornaments, while encompassing a total area of approximately $410m^2$. Both the major and minor hypogea have east-facing entrances, accessed from the internal courtyard. Descending a few steps, the major hypogeum splits into two large areas, formerly used for sheltering tools, work animals, and preserving agricultural products. On the right side of the entrance lies a *palmento*, a calcarenite vat used for crushing grapes. The barrels to be filled were placed at the *palmento* foot, in the direction of the drainage channel. Once filled, these barrels were rolled down to the cellar. In front of the *palmento* lies one of the three large cisterns, which served as essential water storage resources. The minor hypogeum, excavated in 1584 and expanded in 1642 [13], provides access to the large cistern.

Thus, the investigated hypogea require precise measurements and advanced modeling techniques to accurately represent their unique features. Traditional surveying and 3D modeling methods were not feasible as the irregular geometries, the difficult accessibility, and the lack of precise documentation make it difficult, time-consuming, and error-prone to measure and collect data manually. Photogrammetry, while a promising technique for cultural heritage [10, 14], presented issues as the limited and uneven lighting conditions, the narrow passages, and

Table 1
TLS Trimble X7 scanning performance overview

General	Laser wavelength	1550nm
	Field of view	$360° \times 282°$
	Scanning duration	with images 2 *min* 34 *sec*, without images 1 *min* 34 *sec*
	Scanning speed	up to 500kHz
Range measurement	Principle	high-speed time-of-flight
	Noise	$<$ 2.5mm @ 30m - 80% albedo
	Range	0.6m to 80m
Accuracy	Range	2mm
	Angular	21"
	3D point	2.4mm @ 10m, 3.5mm @ 20m and 6.0mm @ 40m

Figure 2: Spherical photo of the interior of the surveyed hypogea capturing the irregularities of the walls and ceilings, as well as the intricate network of passageways and chambers.

the granular light-colored rock texture resulting in the lack of fixed reference points limit high-quality images capture and automatic processing.

To overcome these challenges, an approach based on TLS was employed. This non-invasive surveying technique eliminates the need for manual data collection, reducing the risk of damage to fragile or valuable artifacts, while providing precise 3D models of the hypogea.

2.2. TLS system

To ensure accuracy and precision, we used the TLS Trimble X7, a high-speed 3D laser scanner with a combined servo-mirror scanning system, integrated imaging, automatic calibration, automatic registration technologies, and self-leveling capabilities for detection (see Table 1).

The scanner is equipped with 3 cameras with 10MP (3840×2746 pixels for a picture), providing a spherical photo for each scan (see Figure 2).

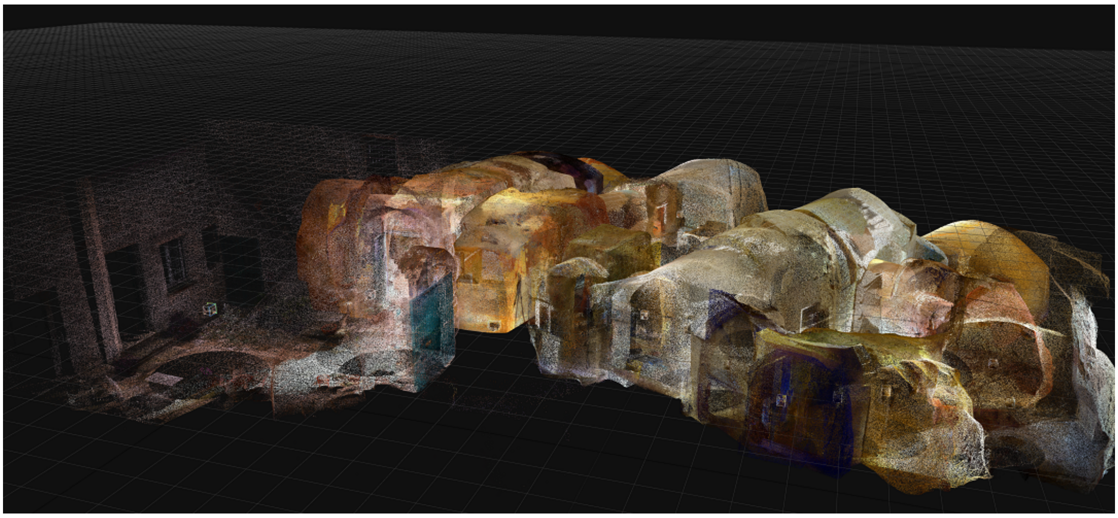


Figure 3: Dense PC imported into RC previously aligned with Trimble RealWorks software. As can be seen, vertices integrate colors.

2.3. Data Acquisition and Processing

To ensure comprehensive capture, we scanned the hypogea from multiple angles and distances with a TLS resolution of $11mln/pnt$ per station. We collected a total of 50 scans, each taking an average of $2.35minutes$ to complete. To guarantee effective data capture, we strategically placed artificial spotlights to simulate a diffused light environment, ensuring even and sufficient illumination. The precise and accurate capture and the Trimble X7 hardware-software integration yielded scans registered and aligned *in situ* and a high-density Point Cloud (PC) with intricate details that faithfully represented the hypogea. While RC can generate 3D reconstructions from unsorted photographs, the same feature is not available for laser scans. Therefore, RC leveraged the alignment provided by Trimble RealWorks software to generate a complete and accurate PC, as shown in Figure 3. The PC was imported with the efficient and flexible $E57$ file format (ASTM E2807-11 standard) [15], supported by several processing software, including RC. The $E57$ file stored metadata such as calibration, color, and other attributes associated with each point that can be used in RC to reconstruct a realistic texture.

RC software was chosen to create the 3D reconstruction model because of its versatility, automation, and high quality output. The PC was used as input data for RC mesh model reconstruction feature in high detail [16, 17] to preserve the maximal possible detail. Based on the geometry complexity, the 3D model can be split into several parts. The reconstruction was implemented using a workstation equipped with Intel® Xeon® W-2275 @ 3.30GHz 256 GB, and an RTX A6000 GPU with 48 GB. Although the GPU allows the visualization of high polygon numbers, RC has a fixed polygon visualization limit to $40M$ for 6+ GB VRAM GPU. Due to these limitations, we simplified the 3D model using the RC simplify tool, which allows setting the desired target triangle count, part number, border simplification, and other visualization and light interaction features like textures. RC features for integrity and topological defect checking detected, respectively, the corrupted triangles, coloring, or texturing and the number

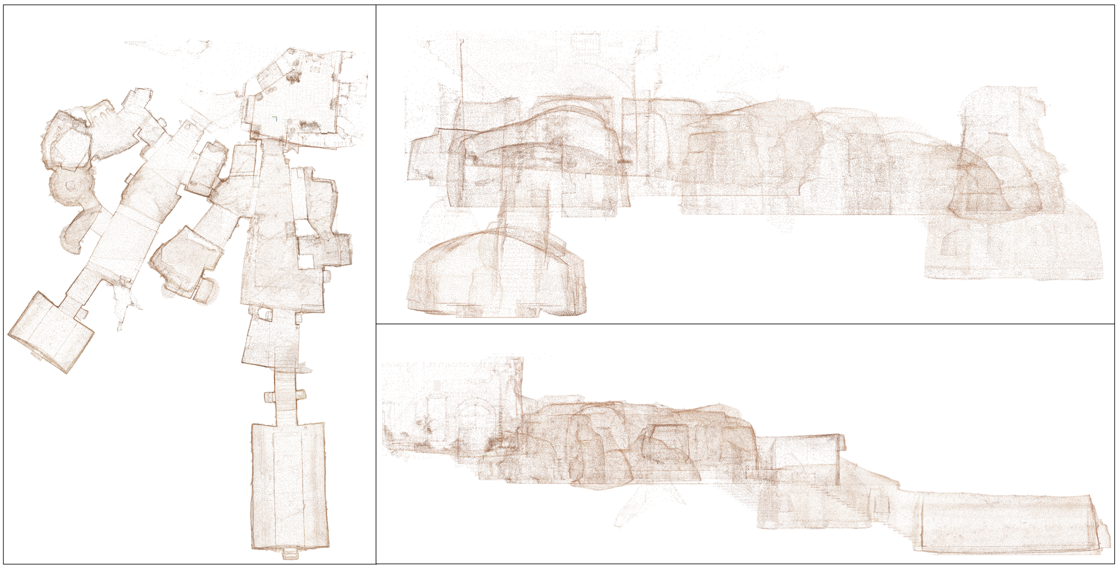


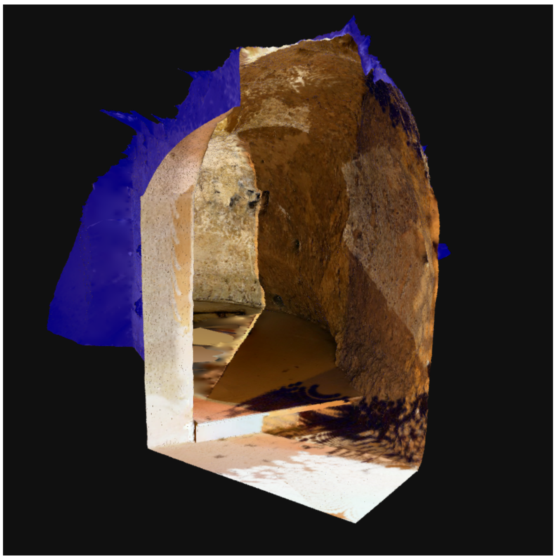
Figure 4: Three views of the imported PC obtained with TLS in RC. The PC effectively reconstruct the intricate geometry of the hypogea.

and dimension of holes, the parts with non-manifold edges and vertices [18], the parts with corrupted internal structure, and the parts with at least one isolated vertex; mesh cleaning and hole closing removed the defects detected from the first two features. To ensure the 3D reconstruction is accessible for external software applications in different contexts, including virtual reality, structural analysis, and 3D visualization, we implemented unwrapping [19] and texture computing techniques to enhance its realism. In particular, the texture was computed using the unscaled images provided from the TLS and unwrapped on the highly detailed 3D model to achieve the highest level of graphical quality. The computed texture can be projected back onto a simplified model while retaining the same level of graphical quality as the original model but with lower geometric complexity. Finally, the obtained model can be exported with several standard formats such as Filmbox FBX, Wavefront OBJ, PLY, Collada DAE, *etc.*.

3. Results

The TLS data alignment was automatically detected by RC without any errors, as mentioned in Section 2.3. We used the “exact” registration setting to preserve the imported poses, define the coordinate system, and retain georeferencing of the imported model (see Figure 4). To facilitate the alignment of laser scanner data and photos, we used “color” as a feature source. When the PCs in $E57$ file format were imported, the RC converts the laser scans in “LSP” internal file format. This binary file can be handled as an image as shown in Figure 5a. Using the “LSP” files, RC can merge laser scans and photos. The laser scans were converted in 300 “LSP” files with 1372×1372 as resolution and 32 as image bit depth, 6 views for each scan. After a manual PC inspection, we removed 13 “LSP” files belonging to points scattered and detached from the main object of the scan.

(a) An example of "LSP" file visualization representing one of the 6 views of a single TLS scan.



(b) A visible fragment of 3D reconstruction of about $5.9M$ of polygons.

The final dense PC features $542M$ of points using filtering of $0 - 20mt$, thus ignoring points further away than $20mt$. The total scanned area was about $410m^2$. As the first attempt, we reconstructed the 3D model with high details, obtaining $368.4M$ polygons and $184.6M$ vertices distributed in 122 model parts. In this reconstruction, the "LSPs" were not downscaled maintaining the initial resolution. Since RC visualization capabilities are limited to $40M$ polygons, we inspect the results by analyzing each model part, with the largest amounting to roughly $5.9M$ polygons (see Figure 5b). The model integrity check detected no corrupted polygons, coloring, or texturing defects. Similarly, we check and clean the model topology detecting 18 holes, and 5 non-manifold vertices. We used this highly detailed reconstruction to extract the most accurate texture possible and provide the final model with a high level of realism. We used 0.002128 meter per texel as texel size, 3 as a fixed number of textures, and 16384×16384 as resolution per texture. With these settings, we obtained a 100% as texture quality in BGRA. The next 3D mesh simplification step reduced the number of polygons and enhanced other software compatibility.

We simplified the 3D model by setting $3M$ as polygon number, $1.5M$ as vertex number, and 8 as part number. We performed the unwrapping of the simplified model and reprojected the high-resolution texture keeping the 100% as quality. In this way, we obtained a less complex geometry with a high-resolution texture and a level of realism as shown in Figures 6a and 6b. By checking the model integrity and topology we detected and filled only 20 and no other artifacts. Using a GPU Nvidia RTX A6000 as CUDA[1] device, the meshing time was $37m11s$, the post-processing time was $2m30s$ and the unwrapping time was $4m19s$. To process and obtain the final and optimized textured 3D model we employed $44m01s$.

To validate the accuracy of our 3D model, we used a set of reference points obtained using the control points system of RC. We placed reference points on the hypogea before scanning

[1]Compute Unified Device Architecture: https://developer.nvidia.com/cuda-zone

(a) Details of a 3D model fragment of a simplified reconstruction at 3M.

(b) A reprojected textured 3D model fragment. The resolution of the whole texture is 16384×16384

and then marked their corresponding points in the 3D model using a control point system. In this way, the 3D model has the same scale size as its scanned environment. The final 3D model accurately represented the intricate details of the hypogea and control points indicated that the model was highly reliable. The use of TLS and RC proved to be an effective method for 3D reconstruction of the hypogea in the Sassi of Matera.

3.1. The semantic-enriched Building Information Modeling (BIM)

Whereas being a widely established methodology for the design, construction, and management of new-construction projects, BIM has gained growing interest in architectural heritage only in recent years due to its ability to capture the complexity and interdisciplinarity of the knowledge involved [20, 21]. The semantic-enriched BIM incorporates additional information, such as its historical context, cultural significance, and materials used, in a standardized format that can be shared across different platforms and applications.

To explore the potential of TLS and RC workflow in a semantic-enriched BIM approach, the accurate 3D model served as geometric base for association with non-geometrical information to obtain a prototype model. Since approaches based on artificial intelligence proved to be the most robust and best-performing method for segmentation [22], a first model segmentation was implemented directly within RC through the *AI Classify* function, then the classification was edited by assigning the classes manually. The three classes represented walls and ceilings excavated or built with calcarenite, flooring and stairs made of different materials, and non-structural objects (Figure 7).

The resulting segmented 3D model was then imported as a mesh into a BIM platform, namely Blender software with BlenderBIM Add-on, where it was further decomposed in the Industry Foundation Classes, which is a standardized format for sharing BIM data, corresponding to the technological components. Each element was characterized by the construction material (using the *IFC Materials* subpanel in the *Scene Properties* tab) and by additional information on the

Figure 7: A view of the PC classification obtained with *AI Classify* function and manual correction in RC: red indicates walls and ceilings excavated or built with calcarenite, green represents flooring and stairs made of different materials, and purple identifies non-structural objects.

state of conservation (using custom *Properties* in the *IFC Property Sets* subpanel).

The final model can be easily published and linked to external sources of information such as documentation, databases, or real-time sensors (*e.g.,* temperature and humidity sensors).

4. Discussion

We successfully scanned all the hypogea environment in a single day, capturing high-quality data and creating a comprehensive 3D model using the Trimble X7's automation. Manual scans alignments were necessary only in areas with complex geometries or limited visibility. The combination of automatic and manual alignment resulted in a high-density and detailed PC. The RC 3D model accurately represented the hypogea at the desired detail level, providing an excellent basis for semantic-enriched BIM models and demonstrating the effectiveness of our data acquisition and processing methodology.

The hypogea's complex and irregular geometries, limited and uneven lighting conditions, narrow passages, difficult accessibility, granular light-colored rock texture, and lack of precise documentation presented significant obstacles for data collection. However, the presented workflow successfully obtained a comprehensive and photorealistic PC dataset using TLS technology for the 3D modeling of the hypogea, proving to be an effective way to digitally document such complex heritage structures. Though additional work must be done to annotate and enrich these models with semantic information, the use of these technologies offers a promising way to improve our understanding of UBH and historical sites and artifacts.

Historical buildings and UBH in particular often consist of highly complex geometries and ornamental features, which typically require more detailed data acquisition and high-resolution surveys to be correctly interpreted and represented as 3D models. The irregular and organic shapes of their components, resulting from historical styles and transformations, are hard to represent with parametric BIM objects or simple solid geometry.

An approach based on accurate TLS surveyed data and advanced RC workflow can benefit the UBH 3D and BIM modelling process, as it is easier and less error-prone than traditional methods. While TLS may have limitations in terms of texture mapping, its many advantages make it a highly effective tool for surveying and 3D reconstructions in underground contexts [23]. As technology continues to improve, it is likely that laser scanning will become an even more essential tool for 3D reconstructions in a wide range of applications.

The obtained models can build essential documentation record needed for different purposes: assess the state of fact of the considered built heritage; guide the conservation process; provide monitoring and managing tools; communicate and disseminate cultural values. Furthermore, the semantically enriched models can be used for digital twins [24], web publishing, visualization [25] and dissemination purposes.

5. Conclusions and Future work

This study presents a TLS-based survey and 3D modelling for semantic-enriched BIM model of the hypogea of the Fondazione Sassi, a unique UBH in the Sasso Barisano of Matera, Italy.

Despite the challenges presented, the proposed workflow successfully obtained a comprehensive and detailed representation of the hypogea and offered useful insights for the understanding of UBH and historical sites and artifacts.

In summary, while the use of TLS and for surveying and RC 3D modeling of UBH sites may not inherently provide semantically enriched models, it forms a reliable workflow for creating high-resolution geospatial datasets and 3D geometry of existing artifacts, covering all visible surfaces, that can be used for further analysis and visualization. Creating high-quality and specific containers for semantic enrichment enables more comprehensive representation and more informative documentation regarding current state, archived digitized semantics, but also assets for future reconstruction or external sources of information (*e.g.,* real-time sensors).

Overall, the combination of these technologies has great potential for advancing the fields of the development of linked data systems specifically for UBH and built cultural heritage.

Future research should further explore the integration of TLS data with other types of data through the use of BIM and semantic web technology [21] to develop linked data systems for UBH. Additionally, further investigations could be conducted on the combination of TLS and photogrammetry techniques to overcome the limitations of both methods and improve the accuracy and realism of 3D models for underground environments.

6. Abbreviations

The following abbreviations are used in this manuscript:

3D	three-dimensional
BIM	Building Information Modeling
PC	Point Cloud
RC	Reality Capture
TLS	Terrestrial Laser Scanner
UBH	Underground Built Heritage

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