

Low-Cost LiDAR Sensors for the Survey of Underground Cultural Heritage: applications on the Siena *Bottini* (Italy)

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Abstract:

The 3D survey of underground systems is an important tool for geometric surveys, thematic mapping, documentation of the state of conservation, monitoring, planning of restoration and maintenance interventions, safety and use. The aim of the research is to test an innovative, economical, rapid and non-invasive system for the survey of underground environments. An example of an underground system is that of the bottini Senesi, a set of tunnels present in the subsoil of the city of Siena for a total development of 25 km. These ancient underground environments, created in the past for the supply and distribution of drinking water in the city of Siena, represent a complex and articulated structure, and constitute an important hidden heritage of the city. Inside them it is difficult to use topographic survey tools, 3D scanners and RTK (Real-Time Kinematics) due to lack of space, brightness and satellite coverage. The LiDAR (Light Detection and Ranging) technology integrated into Apple iPhone PRO devices was therefore used in some sections of the bottini, where the technologies grouped in a single instrument, which are based on photogrammetry, on LiDAR laser pulses and on data processing through triangular meshing, allow for rapid three-dimensional surveys. The detail of the scans was obtained with the use of an electronic stabilizer, for better fluidity in the survey, and of a LED light for intense and homogeneous illumination. All integrated with metric evaluations carried out with the aid of an electronic range finder to verify the measurements taken. The results present clear colours and shapes, despite the presence of a planimetric deviation of a few centimetres given by various factors such as too sudden scanning movements, lack of effective lighting and/or distant positioning of the photogrammetry targets. The adoption of LiDAR technology on mobile devices, therefore, represents a significant step in the documentation and protection of underground systems, such as the Bottini Senesi, characterized by difficult logistical conditions of detection, and offers new tools for the knowledge and conservation of cultural heritage. The integration of a detailed 3D model with GIS software and 3D modeling platforms facilitates historical, archaeological, geological and structural analysis, supporting and documenting maintenance, restoration and conservation interventions. The data collected can also be used for scientific dissemination and the enhancement of heritage, also through digital reconstructions and virtual tours.

CCS Concepts

•Applied computing ~ Arts and humanities ~ Architecture (buildings) ~ Computer-aided design

1. Introduction

Siena's historical water supply and drinking water distribution system consists of a complex underground network of conduits, called *bottini*, a term documented since 1226, with an overall development of about 25 km. These conduits, which had their maximum expansion in the medieval period, were essential to guarantee constant and hygienically safe water, given the absence of permanent watercourses within and in the immediate vicinity of the city. In ancient times Siena, despite the use of cisterns to collect rainwater, also given the difficulty of building wells to intercept the water table, was short of water, so much so that in Canto XIII of Purgatory, Dante jokes about the hopes of finding Diana, the legendary underground river, whose existence was long sought. It was precisely the *bottini* that represented the concrete solution, even if long and difficult to implement, to the city's water problem [Pet06]. Even though the Municipality of Siena has been supplying water to the city with the "Vivo" aqueduct since the second decade of the 1900s, the *bottini* are still functioning, bringing water to the public sources and to some private users.

Due to unfavourable logistical conditions [GMN25] such as poor lighting, limited space and lack of satellite signal, the use of traditional survey instruments, such as total stations, theodolites,

environmental three-dimensional scanners or RTK (Real-Time Kinematics) systems, is particularly difficult. To overcome this problem, in some sections of the *bottini*, LiDAR (Light Detection and Ranging) technology integrated into high-end Apple devices, the iPhone and iPad Pro, has been tested [JV25]. This system, which combines photogrammetry, laser pulses and data processing algorithms via triangular meshing, allows for detailed and precise three-dimensional surveys to be obtained with the help of electronic stabilizers, LED lights and laser distance meters for metric verification. The survey carried out made it possible to integrate the knowledge acquired with a detailed geological reconstruction, identifying geological limits (stratigraphic and/or lithological contacts etc.), and their consequent orientation in space determined by direction (strike), immersion and inclination with respect to the North, and creating a specific section of the three-dimensional substrate analysed (Figure no. 1).

1.1. The geology of the Siena territory

The geology of the Sienese area derives from a prolonged tectonic evolution, beginning with the opening of a marine basin in the Early Pliocene, around five million years ago [Laz93] [LP98], where fine sediments (clays and silts) were first deposited,

followed by sands and gravels as tectonic uplift occurred. These formations, now emerged and shaped by weathering, form the bedrock beneath Siena.

Hydrogeologically, the stratigraphy is favourable: the upper sandy-gravel layers are permeable, enabling rainwater infiltration, while the underlying silty-clayey ones are impermeable, retaining water. This natural configuration, along with the ease of excavating the local sandstone, allowed the development of the *bottini*, a network of underground tunnels designed to efficiently collect, channel, and conserve water.

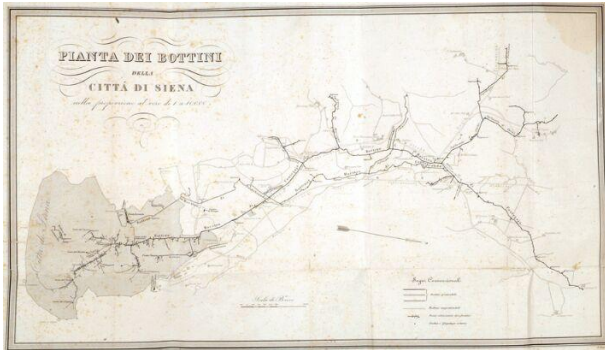


Figure 1: Plan of the *bottinos* of the city of Siena in the true proportion of 1 to 10,000 [Car48].

1.2. The sienese *bottini*'s system

The system of the Sienese *bottini* (Di Trollo et al., 2024) [DGC*24] concerns an extensive network of tunnels built in the subsoil of the city of Siena and in the immediate vicinity (north of the city), two are the main branches of water supply and distribution within the city are called *bottini maestri*. These are the *bottino maestro* of *Fontebranda* and the *bottino maestro* of *Fonte Gaia*, which differ in terms of the flow rate of water and the share of distribution of the water itself within the city. Both were used for the distribution of water that was used for various purposes: human and animal drinking, for wash houses, for manufacturing uses (wool workers, tanners, dyers, etc.), for mills and for extinguishing fires. To date the main public fountains, some of these monumental, inside and outside the city walls, some fed by their own *bottini*, amount to sixteen.

The Municipality of Siena monitors and maintains the main sources and, together with the volunteers of the “La Diana” Association, takes care of the conservation of the network of tunnels, still largely passable today. The network of *bottini* is a fragile system that, like all hypogea, requires knowledge, monitoring and protection for correct conservation. In fact, the protection of the hypogean heritage, as a collective asset, is fundamental to conserve, maintain and pass on to future generations.

2. Instruments

2.1. User-friendly photogrammetry

Modern photogrammetry is evolving towards greater accessibility, thanks to the integration of advanced and low-cost technologies in everyday tools: Apple iPhone and iPad Pro.

These devices are equipped with a LiDAR sensor, designed primarily to enhance augmented reality (AR) experiences, but, if used with specific applications (e.g. Niantic Inc, Scaniverse) and with the support of three-axis stabilizers [RGG25], they can be

adapted for the creation of digital twins intended for cultural heritage management.

2.1.1. Gear setup. The equipment setup includes an Apple Pro smartphone equipped with a miniaturized LiDAR sensor [Sen21], cameras and motion sensors mounted on a three-axis motorized gimbal. Since 2020, this system enables indoor and outdoor spatial acquisition, detecting objects up to 4.90 m [SCTG21] with nanosecond temporal resolution. iPhoneOS integrates LiDAR, camera, and motion data through on-chip computer vision algorithms, enhancing environmental detail and enriching the point cloud. Niantic Inc.'s Scaniverse application [Sca25] exploits this hardware to rapidly capture accurate 3D models of environments, objects, and surfaces, exporting realistic meshes in formats such as OBJ, FBX, USDZ, and STL for further processing. The motorized gimbal actively stabilizes pan, tilt, and roll movements, reducing vibrations and allowing smooth, precise scanning. An attachable LED light improves illumination in low-light conditions, minimizing shadows and enhancing surface detail, crucial for accurate reconstruction and texture analysis.

2.1.2. Laser Distance Meter and Photogrammetry Target. In the context of underground surveys, the integration of laser distance meters and photogrammetric targets proves essential for ensuring measurement accuracy and spatial coherence. Laser distance meters, with an operating range between 0.15 and 25.00 m, are particularly suited for confined or low-accessibility environments. Their operation is based on the emission of a laser beam, which, upon reflection from a surface, enables precise distance calculation through the return time of the signal. However, in subterranean contexts, moisture on walls, caused by water infiltration into the geological substrate, can generate irregular micro-reflections that interfere with the beam path due to the reflective properties of wet surfaces. To counteract these limitations, plastic reflective targets are employed. Simultaneously, photogrammetric targets facilitate the georeferencing and alignment of the three-dimensional point cloud by providing fixed reference points for processing software. Their placement must consider visibility between targets and the scanner, as well as the geometry of the environment, ensuring stable and clearly visible locations distributed along the scan trajectory, including directional changes and elevation variations.

2.1.3. Post-processing with Blender and CloudCompare software. Post-processing was carried out using Blender [Roo25] and CloudCompare [Gir25] with the Compass plugin [TGM18]. In Blender, the 3D model was refined through mesh optimization, texturing, lighting, and rendering to produce accurate digital replicas suitable for archaeometric texture analysis. CloudCompare enabled digital geological mapping by integrating manually traced surfaces, calculating structural orientations and dips, and exporting parameters for statistical processing.

3. Research method

The adopted methodology aims to develop, test and document an innovative, rapid, economical and non-invasive system for the immersive 3D modelling of underground environments. Three sections of accessible hypogean environments were selected for preliminary tests, despite the adverse logistical conditions: narrow spaces, lack of lighting and lack of GPS signal. The survey system combines 3D acquisition using Apple LiDAR and traditional tools for metric validation. Initial inspections assessed accessibility and optimized scanning paths in which distance measurements were

taken using a laser distance meter equipped with targets positioned according to the tunnel geometry for optimal coverage.

Data acquisition was carried out using the Scaniverse app on an iPhone 14 Pro mounted on a three-axis gimbal with an external LED. Scans followed an ideal central path with controlled horizontal and vertical movements, except in broader areas (*Fonte delle Monache* and *Fonte di Pescaia*), where a meandering path was necessary.

Point clouds were exported and processed in Blender for mesh cleaning, texture enhancement, and rendering, producing detailed digital twins. Metric validation was then conducted to compare scanned and measured data. A section of the *bottino* maestro of *Fonte Gaia* was also tested for generating a 3D geological model, aimed at identifying geological boundaries (e.g., stratigraphic or lithological contacts) and their spatial orientation.



Figures 4 a-b-c: LiDAR surveyed sectors in the *bottino* maestro of *Fonte Gaia* (a), in the *Fonte delle Monache* (b) and in the *Fonte di Pescaia* (c)

4. Results

The instrumentation has allowed 3D documentation of part of the spoils of *Fonte Gaia* (Figure. 4a), *Fonte delle Monache* (Figure. 4b) and *Fonte di Pescaia* (Figure. 4c), overcoming the underground environmental constraints.

At *Fonte Gaia* (Figures. 5 a-b-c), geometric and construction elements and lithological variations were detected. The comparison with laser measurements shows a planimetric deviation of ± 15 cm. The geological model (Figures. 5 d-e)

allowed to define the sedimentary contacts and their spatial arrangement.

At *Fonte delle Monache* (Figure. 7 a), the main room, the basins and the tunnels were digitized, highlighting traces of excavation in the Pliocene sand. The surfaces of the vault (at a height from the floor level greater than 5 m) were acquired in several steps with an average deviation within 10 cm.

At *Fonte di Pescaia* (Figure. 7 b), the underground chamber, part of the staircase and the niches were acquired, highlighting calcareous encrustations. The small dimensions limit the deviation to within 5 cm.



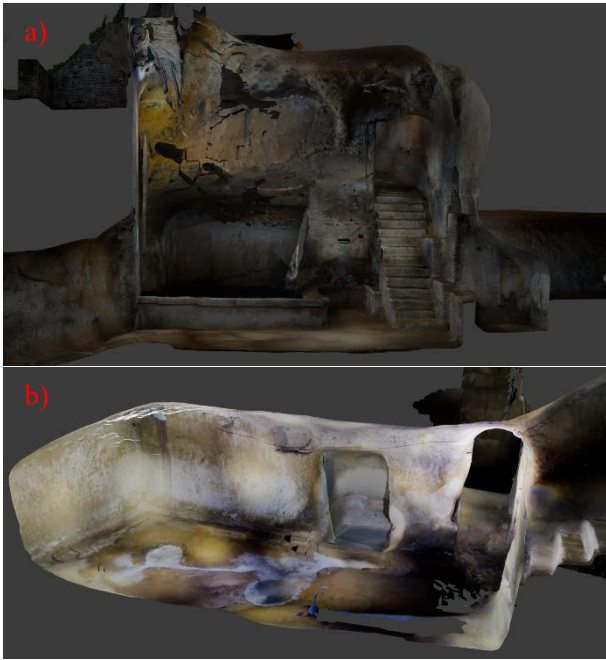
Figures 5 a-b-c-d-e: (a-b-c) rendering of the detected sector of Figure 4a; (d-e) 3D reconstruction of the geological model of a surveyed section with identification of the geological limits between the sands and the gravels, and their consequent orientation in space

5. Discussion of the results

The results confirm the effectiveness of the iPhone Pro with LiDAR as a complementary system for preliminary mapping and documentation of complex underground environments, offering a rapid, low-cost and non-invasive solution, without the use of specialized tools. The methodology adopted has overcome the

operational criticalities related to narrow spaces, poor lighting and lack of GPS signal.

The planimetric deviations between 3D models and metric data vary centimetres-sized for *Fonte Gaia*, minor for *Fonte delle Monache*, minimal for *Fonte di Pescaia*, influenced by geometry, lighting and stability during acquisition. These surveys, although not high resolution, offer a solid basis for subsequent detailed investigations with more advanced instruments.



Figures 7 a-b: rendering of the *Fonte delle Monache*: details of the interior (a) and section of the hypogeum of the *Fonte di Pescaia* (b).

6. Concluding remarks

The experimentation conducted in the two case studies has demonstrated how the integration between an acquisition system equipped in commonly used devices such as Apple iPhone Pro and a dedicated post-processing phase can represent a reliable and accessible solution for the creation of digital twins of underground environments.

Despite the intrinsic limits of the technology used, linked to the resolution and frequency of the point cloud, lighting and operating conditions, the generated models have provided a faithful and sufficiently detailed representation, given the nature of the rapid and non-detailed survey, of the complex geometries of the environments analyzed.

The metric accuracy achieved, with average deviations contained within 15.00 cm for the *Fonte Gaia bottino*, 10.00 cm for the *Fonte delle Monache* and 5.00 cm for the *Fonte di Pescaia*, confirms the validity of the methodology as the error falls within an acceptable range; However, the results obtained cannot replace high spatial resolution surveys conducted with dedicated professional equipment, if high-density and detailed models are required. In this perspective, the use of a compact LiDAR sensor is configured as a complementary resource, capable of facilitating the exploration, mapping and planning phase of much more in-depth interventions.

In conclusion, the experience conducted has highlighted the potential of this technology for the three-dimensional survey of underground environments, opening up application scenarios in

the documentation of underground and poorly accessible cultural heritage.

References

- [Pet06] Bargagli Petrucci, F., 1906. Le fonti di Siena e i loro acquedotti. Note storiche dalle origini fino al MDLV.
- [Car48] Cartografia Storica Regionale [WWW Document], 1848. . CASTORE - Regione Toscana. URL https://www502.regione.toscana.it/searcherlite/cartografia_storica_regionale_scheda_dettaglio.jsp?imgid=244
- [DGC*24] Di Trolio, M.E., Giamello, M., Ceccotti, P., Tizzani, A., Tavarnelli, E., others, 2024. Portare l'acqua dove non c'era: il caso della realizzazione e della fruibilità in sicurezza del patrimonio dei Bottini e delle Fonti storiche senesi. *ETRURIANATURA* 17, 103–113.
- [GMN25] Gentili, F., Madonna, S., Nisio, S., 2025. The Importance of the Census of Anthropogenic Cavities in the Mitigation Geological Hazards: The Case of Grotte di Castro (Italy). *Geographies* 5. <https://doi.org/10.3390/geographies5020019>
- [Gir25] Girardeau-Montaut, D., 2025. CloudCompare.
- [JV25] Jerjomina, A., Varbla, S., 2025. Advantages of low-cost LiDAR sensors in surveying underground utility networks. *Tunnelling and Underground Space Technology* 157, 106325. <https://doi.org/10.1016/j.tust.2024.106325>
- [Laz93] Lazzarotto, A., 1993. Elementi di Geologia, in: *La Storia Naturale Della Toscana Meridionale*. Amilcare Pizzi Editore, Siena, pp. 19–88.
- [LP98] Lazzarotto, A., Pascucci, V., 1998. Aspetti geologici e geomorfologici del territorio senese, in: *Le Terre Di Siena: La Storia, l'Arte e La Cultura Di Una Provincia Unica*. Protagon Editori Toscana, Siena, pp. 151–187.
- [Roo25] Roosendaal, T., 2025. Blender.
- [RGG25] Rossi, G., Gabbriellini, F., Giamello, M., Scala, A., 2025. Non-Invasive Methods for Identification and Detection of Artificial Stone Blocks of Historical Buildings in Siena (Italy). Presented at the 1st International Conference of Young Researchers in Heritage Science HERI SCI, University of Primorska, Koper (Slovenia), pp. 43–45.
- [Sca25] Scaniverse - Free 3D scanner [WWW Document], 2025. . Scaniverse. URL <https://scaniverse.com/>
- [Sen21] sensing-aiot, 2021. Apple LIDAR Demystified: SPAD, VCSEL, and Fusion... - For Data & AI. URL <https://4da.tech/?p=582> (accessed 7.4.25).
- [SCTG21] Spreafico, A., Chiabrandò, F., Teppati Losè, L., Giulio Tonolo, F., 2021. THE IPAD PRO BUILT-IN LIDAR SENSOR: 3D RAPID MAPPING TESTS AND QUALITY ASSESSMENT, in: *Volume XLIII-B1-2021 XXIV ISPRS Congress*. Presented at the The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, pp. 63–69. <https://doi.org/10.5194/isprs-archives-XLIII-B1-2021-63-2021>
- [TGM18] Thiele, S., Grose, L., Micklethwaite, S., 2018. Compass: A CloudCompare workflow for digital mapping and structural analysis, in: *Geophysical Research Abstracts*. Presented at the EGU General Assembly 2018.