3D MAPPING OF UNDERGROUND ENVIRONMENTS WITH A HAND-HELD LASER SCANNER

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RILIEVO TRIDIMENSIONALE DI AMBIENTI IPOGEI CON UN SISTEMA A SCANSIONE LASER PORTATILE

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KEY WORDS: Hand-held mobile mapping system, LiDAR, underground environment, 3D surveying, representation, visualization

PAROLE CHIAVE : Sistema *mobile mapping* portatile, LiDAR, ambiente sotterraneo, rilievo 3D, rappresentazione, visualizzazione

ABSTRACT:
The development of several instruments and techniques for reality-based 3D survey provides for new effective and affordable solutions for mapping underground environments. Terrestrial laser scanning (TLS) techniques demonstrated to be suitable for recording complex surfaces in high resolution even in low ambient lightning conditions. TLS approaches allow to obtain millions of 3D points and very detailed representations of complex environments, but these normally required a very high number of stations. This paper presents the investigation and deployment of a hand-held laser scanning system, the GeoSlam Zeb1, for the fast 3D digitization of underground tunnels. This active hand-held device was employed in two different typologies of underground structures: the Grotta di Seiano (Fig.1 a-b), a 800 m long monumental passage used as entrance of a roman villa in Posillipo (Naples), and some military fortifications (Fig.1 c-d) built during the First World War (WWI) on the hills around Trento. In the first case study, owing to the length of the gallery and the lack of well-defined geometric features on its wall, errors in the alignment were expected. Consequently, the final alignment of the numerous acquired scans was verified. In the second part, the research is focused on suitable procedures for the final three-dimensional representation and visualization of complex underground passages, i.e. the military tunnels. Using an automatic classification procedure on the point-clouds, vegetation was removed and, through a manual segmentation approach, the rooms were classified according to their specific functions. In the paper, the results are critical presented and discussed.

RIASSUNTO:
Lo sviluppo di strumentazioni e tecniche di rilievo 3D *reality-based* offre nuove efficaci ed accessibili soluzioni per la modellazione 3D di ambienti sotterranei. Le tecniche di laser scanning terrestre (TLS) hanno dimostrato di essere ideali per rilevare superfici complesse ad alta risoluzione geometrica anche con scarse condizioni di illuminazione degli ambienti. Le soluzioni TLS statiche permettono di ottenere milioni di punti tridimensionali e rappresentazioni molto dettagliate di ambienti complessi, ma normalmente richiedono un numero elevato di stazioni. Questo articolo presenta lo studio e l'utilizzo di un laser scanner portatile, lo Zeb1 della Geoslam, per la digitalizzazione dinamica di ambienti ipogei. Questa strumentazione attiva è stata impiegata in due diverse strutture sotterranee: la Grotta di Seiano (Fig.1 a-b), un lungo tunnel monumentale utilizzato come ingresso di una villa romana a Posillipo (Napoli), e alcune fortificazioni militari (Fig.1 c-d) costruite durante la Prima Guerra Mondiale sulle colline intorno a Trento. Nel primo caso, a causa della lunghezza della galleria e della mancanza di pareti con caratteristiche geometriche ben definite, erano attesi errori durante l'allineamento delle scansioni, che hanno richiesto ulteriori verifiche. Nella seconda parte, la ricerca si è concentrata sulle migliori procedure per la rappresentazione tridimensionale finale e la visualizzazione di complessi camminamenti ipogei, come i tunnel militari. Dopo l'utilizzo di una procedura di classificazione automatica delle nuvole di punti per il filtraggio della vegetazione, gli ambienti sono stati classificati considerando le loro specifiche funzioni attraverso una tecnica di segmentazione manuale. L'articolo presenta in maniera critica la tecnologia di rilievo, la sua caratterizzazione e i risultati ottenuti.

a) b) c) d)

Figure 1. a-b) Grotta di Seiano – Archaeological Site of Pausilypon (Naples); c-d) WWI underground fortifications around Trento – Monte Celva.

1. INTRODUCTION

Mapping underground passages, such as tunnels and caves, has always required the development of particular procedures. Indeed, such structures are often characterized by particularly complex surfaces, hardly accessible parts and low ambient lightning conditions.

In the past, several specific measuring instruments (special compasses, measuring tapes, plumbing tools, etc.) were developed for acquiring data in natural or artificial underground environments. Their representation has also required the introduction of ad-hoc symbols (Mattes, 2015). More recent tacheometric methods, based on mining compass with inclinometer, theodolites and total station, increased the level of accuracy of documentation, although very time-consuming approaches. Many issues are still open in this research:

- How to record complex surfaces and huge tunnels with high level of details in a reasonable time?
- How to share and access large 3D datasets of such complex environments?
- How to appropriately represent underground structures in these particular environmental conditions?

Nowadays the development of reality-based 3D surveying instruments and methods provides an important support in this field. In recent years, geomatics techniques have been diffusely adopted especially for heritage documentation (Galeazzi et al., 2014; Nocerino et al., 2014a; Remondino and Campana, 2014; Remondino, 2011).

Nevertheless, in underground environments, some approaches are more suitable than others. While image-based techniques (Remondino and El-Hakim, 2006) are strongly limited by low ambient lightning conditions and small passages, whereas range sensors such as terrestrial laser scanners (TLS) allows high resolution geometric surveys also in subterranean spaces. TLS have been frequently used for three-dimensional acquisition of man-made and natural tunnels (Beraldin et al., 2011; Caputo et al., 2011; Roncat et al., 2011; Laurent, 2014; Nocerino et al., 2014b; Wang et al., 2014; Gallay et al., 2015; McFarlane et al., 2015; Rodríguez-Gonzálvez et al., 2015) for various reasons: reasonable instrument weight and transportability, capability of acquiring millions of points even on complex surfaces, possibility of working in different light conditions, etc. However, a great number of TLS stations and many working days may be required for large environments, consequently producing huge amount of data often difficult to be managed and processed.

This paper presents an approach for fast 3D digitization of underground passages. After a laboratory characterization and investigation, two case studies, featuring different shapes, dimensions and constructive elements, are critically discussed, mainly focusing on the issues related to their 3D surveying and final representation. The employed surveying instrument is the hand-held laser scanner system GeoSlam Zeb1 (http://geoslam.com/). The device, suitable for both indoor and outdoor applications (Zlot et al., 2013), was already employed for mapping underground caves and mines (Zlot et al., 2014). The device, which does not acquire neither colour nor intensity information, was selected for its portability, ease of use (the data acquisition is performed simply by natural or artificial walking through the environment) and possibility to operate without GNSS signal.

2. THE ZEB1 HAND-HELD ACTIVE DEVICE

The GeoSlam Zeb1 (Fig. 2) is a hand-held active device equipped with a 2D infrared laser scanner profilometer and an inertial measurement unit (IMU) mounted on a spring. The UTM-30LX laser scanner emits pulses at a high frequency that reflect off surfaces and return to the sensor where signals are converted into range measurements based on the time of flight principle. IMU measurements of angular velocities and linear acceleration, combined with laser data, allow to estimate the device's trajectory. A three-axial magnetometer records magnetic interferences common in underground environments. Laser scanner and IMU are connected to a micro-computer/battery unit which fits in a backpack. This very low-weight instrument acquires up to 43,000 measurement points per second, within a field of view of 270° and with a maximum range of 30 m (15 m outdoor). The device has a range precision up to 3 cm, conditioned by the distance, the incidence angle and the surface reflectivity. The scanning field of view is increased by the swinging mechanism due to a spring that allows to generate three-dimensional profiles of the environment roughly scanned every second. The instrument head can oscillate (or nod) in the front-back/walking direction or side by side (i.e. orthogonally to the advancing direction).

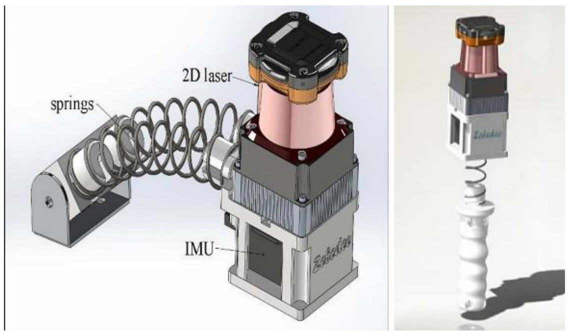


Figure 2. GeoSlam Zeb1 hand-held system.

3D data are acquired simply walking through the environments and keeping the device in one hand. Every dataset has to be acquired in an average range suggested of 20-30 minutes.

Once followed the desired path for data acquisition, the device has to be placed on the ground for some seconds, so as the IMU can indicate the micro-computer to stop the acquisition and to terminate the logging process.

In order to merge all the acquired profiles (by estimating 3D scanner positions and orientations), the device uses a simultaneous localization and mapping (SLAM) algorithm. This solution requires to observe the same features several times. The Zeb1 device acquires the local scene roughly once per second. Local views of the scenes, obtained through the swinging of the instrument, contain position and normal direction of every element recorded. By matching pairs of surface elements acquired in different times, the trajectory is estimated through the relation between surface geometries.

3D point clouds and followed trajectories are provided in standard point cloud file formats, i.e. laz and ply.

3. PRELIMINARY INVESTIGATION

Before running the field campaign, the Zeb1 scanner was investigated in a challenging indoor scenario with a twofold aim: (i) to understand the potentialities and limitations of the sensor and (ii) to identify the best acquisition procedure. The selected environment, a horizontal corridor (X,Y plane) with walls along the vertical direction (Z plane), was characterized by smooth walls with poor geometric features and few elements along its main direction (Fig. 3).

Figure 3. The corridor used for evaluating sensor limitations and best acquisition's procedure.

Four different acquisition strategies were tested:

1) "*round trip*" (i.e. the data collection starts and finishes in the same place) by nodding the scanner front-back w.r.t. the walking direction;
2) "*one way*" (i.e. the data collection starts at the beginning of the corridor and finishes at the end) by nodding the scanner front-back w.r.t. the walking direction;
3) "*round trip*" by nodding the scanner side by side, i.e. orthogonally w.r.t. the walking direction;
4) "*one way*" by nodding the scanner side by side, i.e. orthogonally w.r.t. the walking direction.

The corridor length was measured with a Leica distance-meter, obtaining a reference length of 52.77 m with cm accuracy. Table 1 shows the length and height variation measured on the point clouds obtained through the four acquisition protocols.

Acquisition protocol	*Corridor length*	*ΔZ variation*
1)	52.51 m	< 0.02 m
2)	52.79 m	≈ 0.60 m
3)	52.74 m	< 0.02 m
4)	52.78 m	≈ 0.06 m

Table 1. Corridor length and height variation obtained through four different acquisition strategies.

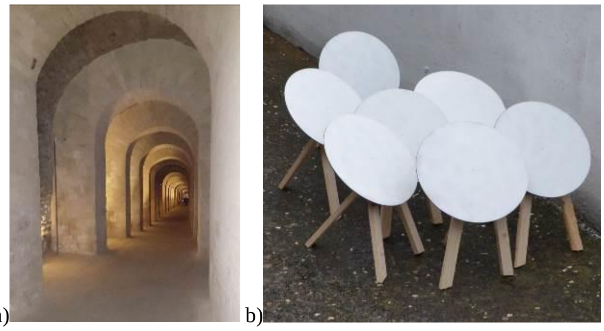
The results achieved by nodding the scanner in front-back w.r.t. the walking direction produced the worst results. Indeed protocol 1) provided a significantly shorter corridor length. The point cloud obtained with protocol 2) showed significant bending in the vertical direction, due to SLAM divergence. The results obtaining with protocol 3) (*round trip* and side by side scanner nodding) resulted within the declared sensor accuracy of 3 cm, in agreement with the scanning procedure suggested by the vendor for featureless corridors.
In the two case studies hereafter presented a hybrid approach, comprising front-back nodding in cooperative structures (i.e. with evident geometric features) and side by side oscillation for smooth surfaces, was adopted.

4. SURVEY OF THE *GROTTA DI SEIANO,* NAPLES

The so-called *Grotta di Seiano* (Soprintendenza Archeologica di Napoli e Caserta, 1999) is a monumental tunnel leading to an ancient maritime Roman villa named "Villa di Pausilypon" which contained also two large theatres. The tunnel is almost 800 m long and it was excavated through the soft volcanic tuff of the hill of Posillipo. It is not clear today if it was realized during the earlier phase of construction of this huge residence or during its transformation into an imperial villa. After centuries of abandon and several collapses, in the 19th century, the passage was reactivated, through the construction of many masonry strengthening arches still today visible (Fig. 4a). The tunnel, used during the Second World War as air-raid shelter, was reopened only in the last years to the public access (as the entire archaeological site). The tunnel is characterized by an elongated shape, with alternation of sections showing geometric elements (strengthening arches) and parts with flat and featureless walls. The tunnel is naturally illuminated, beside at the entrances, by three intermediate ventilation and lightning openings. The other stretches are poorly illuminated with artificial lamps.
The entire archaeological site (tunnel, theatres and villa) was surveyed with multiple techniques and Virtual Reality (VR) applications were developed with the aim of promoting and sharing via web the virtual reconstruction of the site (Farella et al., 2016). The 3D surveying of the tunnel, with its peculiar geometry, would have required a huge number of TLS stations; moreover, low ambient lightning and time constraint excluded a complete photogrammetric survey. Consequently, the hand-handle Zeb1 was considered a good surveying alternative and, in order to assess the reliability and accuracy of the acquisition result in a so critical environment, a topographic survey was also realized.

4.1 Data acquisition

The Zeb1 allowed to acquire data in only one day of acquisitions, covering the entire 800 m underground passage and the area outside the two entrances. Considering a limit of acquisition suggested of 20 minutes per scan and the possible SLAM divergences, eight different dataset were acquired, walking about 150 m for each acquisition.
Every section was scanned according to the "*round trip*" acquisition protocol (Section 3), within the recommended scanning time and maintaining a mean speed of 0.9 Km/h. The sections featuring the strengthening arches were acquired with the front-back nodding procedure, whereas in the parts characterized by smooth and featureless walls the side by side nodding technique was employed.
Moreover some white wooden circular targets of 30 cm diameter (Fig. 4b) were designed and placed in several locations inside the tunnel in the overlapping area between consecutive scans (about 40 m). At least five targets were planned to be visible in each scanned section. The target centres were topographically surveyed with a total station (Section 4.2) to verify the quality and reliability of scanning results.



a) b)

Figure 4. Tunnel's section with the supporting arches (a); wooden circular targets used for the topographic survey (b).

4.2 The topographic network

A TOPCN GPT 7001i total station (Table 2) was employed to survey the tunnel. Constrained by the passage geometry, a combination of triangulation, trilateration and open traverse was used. 3D coordinates of 25 circular targets were also obtained using the adjustment of the open-source software GAMA (Čepek, 2002), whose average coordinate precision in space from least squares adjustment was σ_{xyz} <6 mm.

	Topcon GPT7001i
Range measurement accuracy (non-prism)	±5 mm
Range (non-prism)	1.5 to 250 m
Angle measurement accuracy (non-prism)	1”
Tilt correction	Dual axis
Compensating range	±4”

Table 2. Main technical specifications of the total stations used for the topographic survey of the *Grotta*.

4. 3 Data processing and evaluation of 3D results

The 8 acquisitions (raw scans) were firstly processed by GeoSlam using their SLAM process in the Cloud. Then the derived 3D point clouds were further processed in CloudCompare to align and merge them. After a first manual transformation for a rough alignment between consecutive scans, a finer registration with a traditional ICP method was performed. Considering the previous registered point cloud as reference, this operation was repeated for every adjacent dataset. The maximum RMSE in the registration of consecutive scans was 0.14 m. The final 3D point cloud merged with this method was about 24 mil points (Fig. 5-6-7).
The aligned Zeb1 point cloud was compared with topographic surveying data. Firstly every target visible in the point cloud was isolated and, considering the noise present in the Zeb1 data, the precise coordinates of their centres (measured also with the total station) were estimated in PolyWorks through best fitting procedures (Fig. 8).

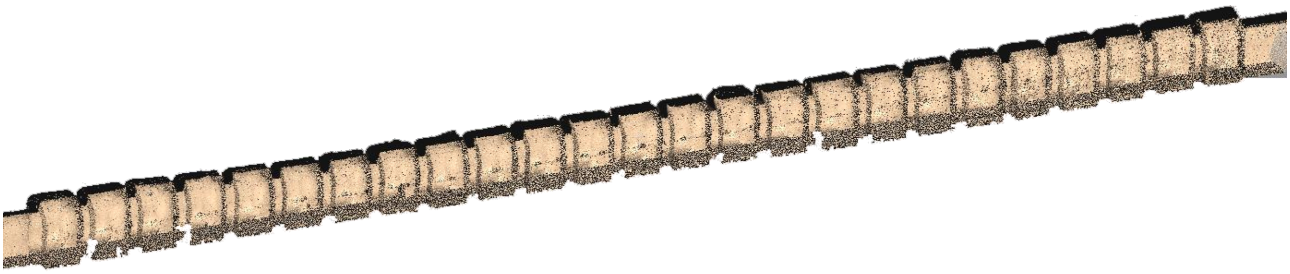


Figure 5. Particular of the *Grotta di Seano*: section with masonry arches.

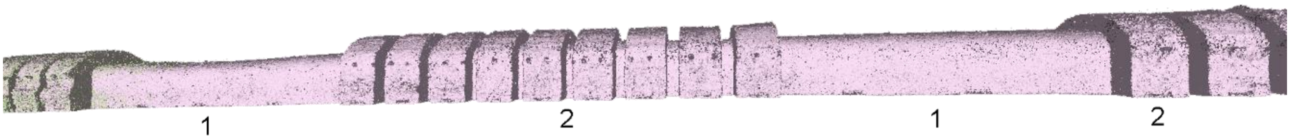


Figure 6. Central part of the *grotta* showing the alternation of smooth and featureless walls (1) and geometric elements (2).

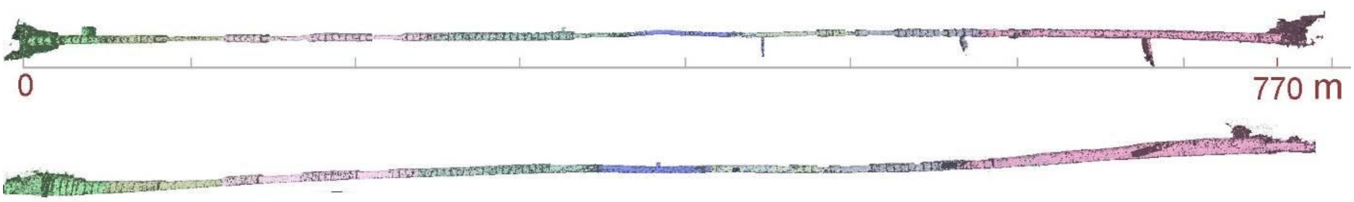


Figure 7. Top and side views of the whole *Grotta di Seiano* showing the aligned point clouds in different colours.

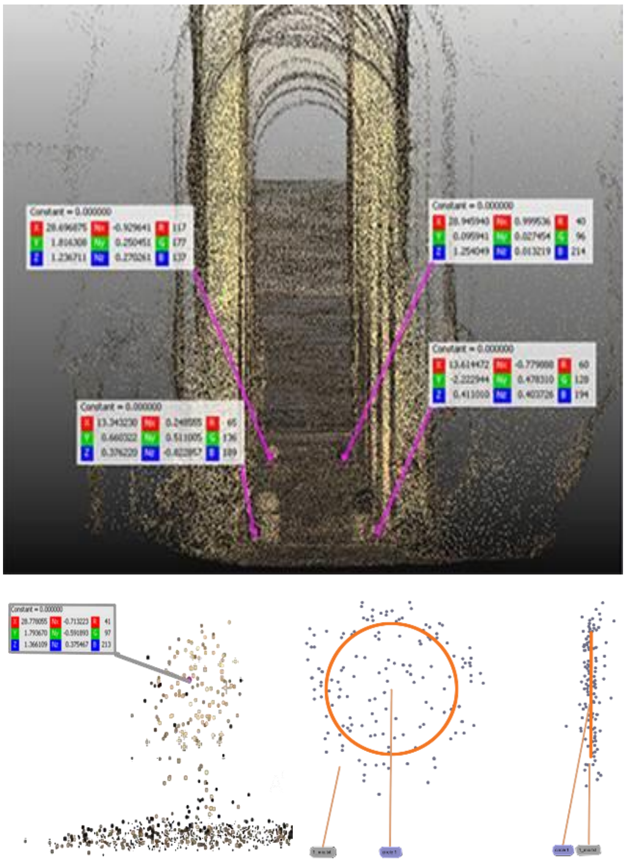


Figure 8. Selection of targets in the Zeb1 point cloud (above). Best fitting of circular planes and extraction of centres (below).

Using as reference the topographic data, a rigid similarity transformation was performed using topographic and laser scanner coordinates of the targets. The final RMSE of the alignment resulted of 9.44 m. The probable reasons of this value are: (i) an error in identifying the centres of the targets (due to the low-res and noisy Zeb1 point clouds) and (ii) a *block deformation* of the acquired scans. For these reasons, the same procedure was repeated employing only the coordinates of targets visible in each scan and verifying the achieved RMSE. This procedure allowed to highlight the point clouds with higher alignment error (Table 3 – central column).

DATASET	RMSE (m) of single ***complete*** scan	RMSE (m) of segmented scans
1	3.266	0.072
2	0.607	0.637
3	0.042	0.050
4	5.824	0.082
5	2.027	0.109
6	0.041	0.089
7	0.023	0.034
8	0.862	0.051

Table 3. RMSE of the similarity transformation between the topographic points and the single Zeb1 acquisitions (central column) and for each segmented point cloud (last column).

The registration results were further investigated as big errors were still present for those point clouds containing long walls, with no geometrical elements (no strengthening masonry arches – datasets 1, 4, 5). The registration was then repeated following a new procedure: each single scan was segmented in correspondence of the circular targets and only the segments showing a low transformation error with respect to the topographic coordinates were retained. With this procedure much better RMSE were obtained (Table 3 – last column). The final mean RMSE of the complete 3D point cloud registered with this procedure was then 0.13 m.

This final point cloud will be used for traditional two–dimensional drawings (plans, sections, details, etc.) used in the archaeological investigation for highlighting different roman constructive techniques adopted for this construction.

5. SURVEY OF WWI FORTIFICATIONS IN *MONTE CELVA*, TRENTO

Before the First World Word (WWI) outbreak, numerous Austro-Hungarian fortifications (tunnels, trenches, forts, etc.) were built on plateaus, hills and mountain tops around the city of Trento for protecting and monitoring the territory (Nocerino et al., 2014). Indeed the Trentino – Alto Adige region was part of the Austro-Hungarian Empire until 1918: it represented the hot southern border with the Italian kingdom and, consequently, it was disseminated of many military fortifications. The shape and dimension of the built military fortifications were generally planned a-priori but many structures (e.g. tunnels and trenches) were normally decided directly on the field. The fortifications were built in concrete, often hand-carved in the stone and organized with main bodies, casemates and several connecting galleries.

Some of these military structures are today still partly visible in the Trento's region, like on *Monte Celva*. The 996 m height mountain represented a strategic place for the defence of Trento and belonged to the so-called Fortress of Trento (Marzi and Borsato, 2000; http://trentocittafortezza.fbk.eu). Some of the underground military constructions present in *Monte Celva*, (galleries, batteries in caves, shelves for ammunitions, rifle emplacements, etc.), along with an outdoor (not underground) defensive system (trench) connected to the artillery batteries in the cave (Fig. 9), were surveyed with the Zeb1 hand-held system. *Monte Celva* presents a huge and complex underground network, with some parts difficult to be reached and others only partially cleared from rubbles due to structural collapses.

a)

b)

c)

Figure 9. The excavated trench connected to the tunnels and artillery batteries in caves (a, b) and a rifle emplacement (c).

Therefore an active hand-held surveying device was the most appropriate instrument. In addition to the surveying issues, the (3D) representation of such complex underground systems poses not trivial problems. Therefore, the last part of this case study focuses on the identification of suitable procedures and methods for the final representation and visualization of the digitized tunnels.

5.1 Data acquisition

Five different areas were surveyed with the Zeb1, corresponding to several fortifications that occupy the low and middle part of *Monte Celva*. Each military structure was surveyed in about 30 minutes, covering an average path of 200 m. Every fortification was acquired following the "*round trip*" surveying approach (Section 3) with a mean speed of 0.8 Km/h and alternating the front-back and side by side nodding procedure. The entrances of the military structures were also digitized, thus collecting many elements of the external natural environment like trees, vegetation, rocks, etc.
After the raw data processing, the Zeb1 point clouds of each area were further processed for data cleaning and classification (Section 5.2), global alignment and final representation (Section 5.3).

5.2 Point cloud classification

The exterior and surrounding parts of tunnels and trenches, although fundamental to co-register the Zeb1 data with the LiDAR landscape model, need to be removed for better understanding and representation. Instead of manually cleaning the large and complex point clouds, an automated procedure was run. The Canupo classification algorithm (Brodu and Lague, 2012) implemented in CloudCompare was thus used to separate natural and man-made structures (Fig. 10). The Canupo plug-in allows to create own classes as well as to use existing classifiers for segmenting point clouds into subsets (e.g. vegetation, ground). This supervised method is based on 3D geometrical properties of the point cloud across multiple scales and, employing a probabilistic approach, the points with high uncertainty can be removed from the wrong class. For creating a new class, a sample of points representing each class have to be manually identified. For the WWI structures and underground passages, both new and available classifiers were tested:

- LongRange Classifier: for brush and trees scanned at intermediate resolution (down to 5-10 cm point spacing);
- RangiCliff Classifier: for brush and trees scanned at high resolution (down to 1-2 cm point spacing).

The RangiCliff Classifier provided the best classification results and was then adopted for all the acquired point clouds. The separation between man-made structures and natural elements was useful to better represent and map the surveyed military structures.

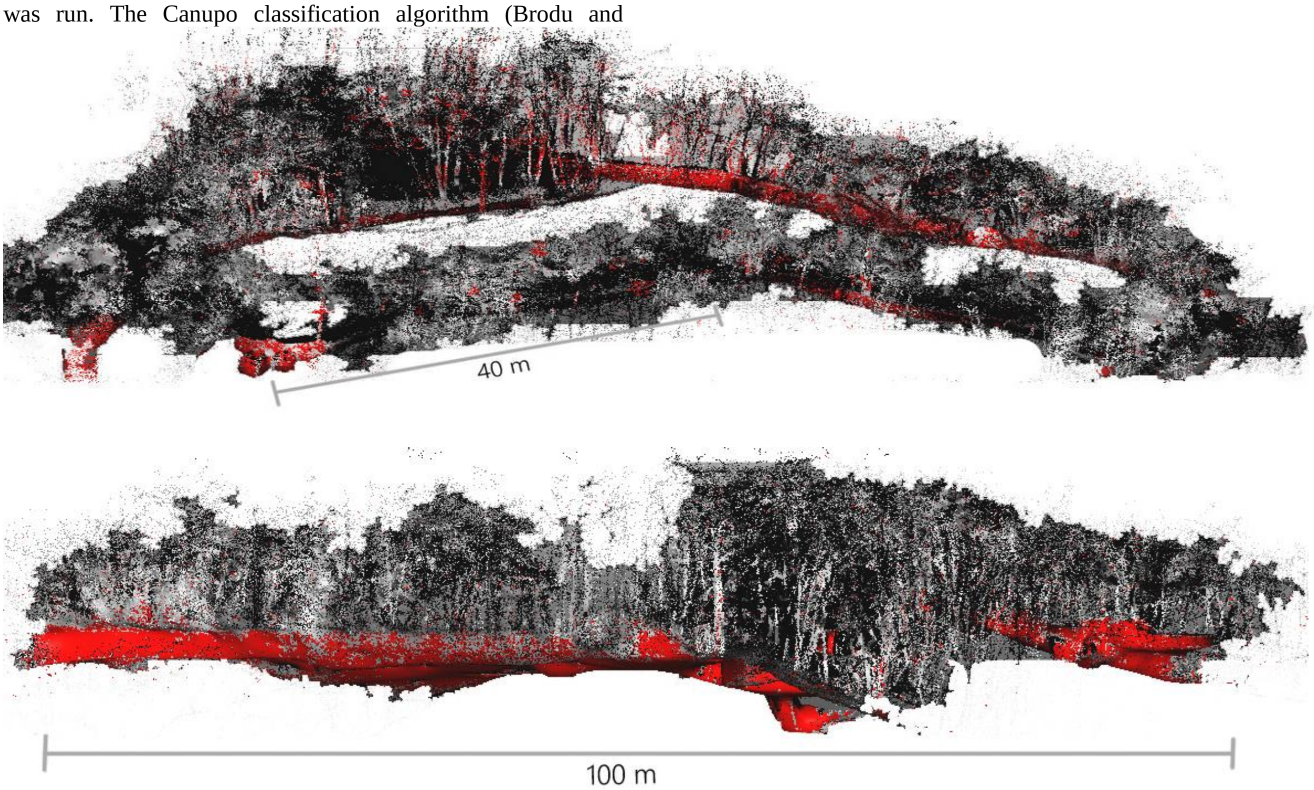


Figure 10. Point cloud classification with Canupo plug-in. RangiCliff classifier (red: man-made military structures; grey: vegetation samples).

5.2 The 3D representation of WWI fortifications

The segmented point clouds were aligned among them and also with the LiDAR-based terrain model of the area. Then they were manually segmented in CloudCompare, highlighting the functions of the different spaces and their extensions and curved shape inside the mountain (Fig. 11-18).

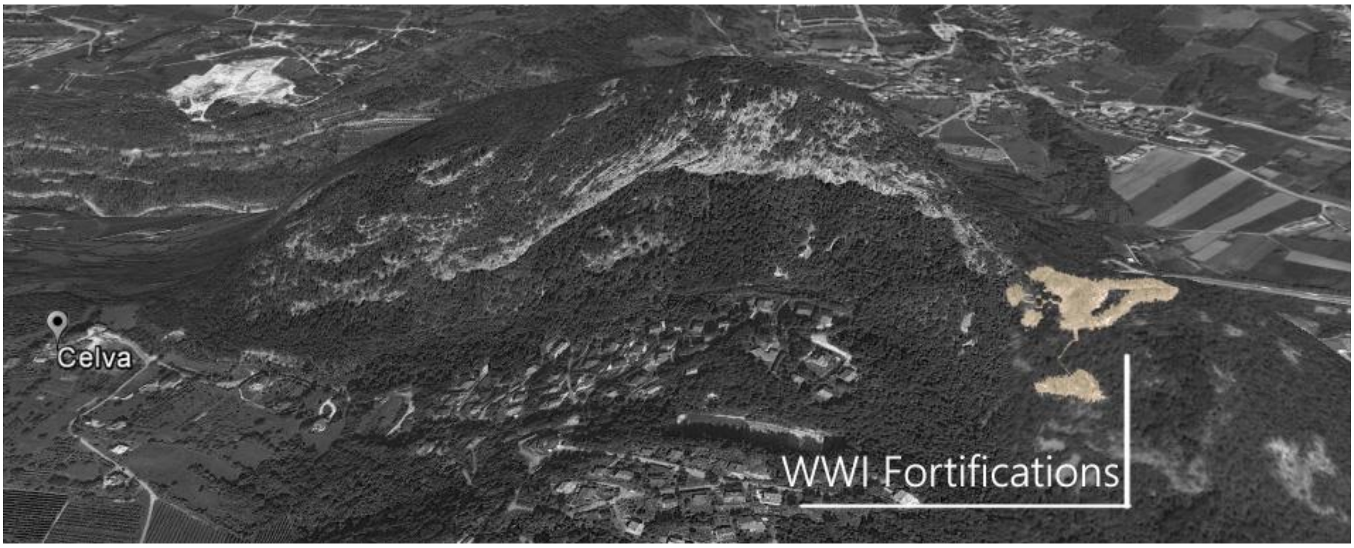


Figure 11. WWI fortifications in *Monte Celva.*

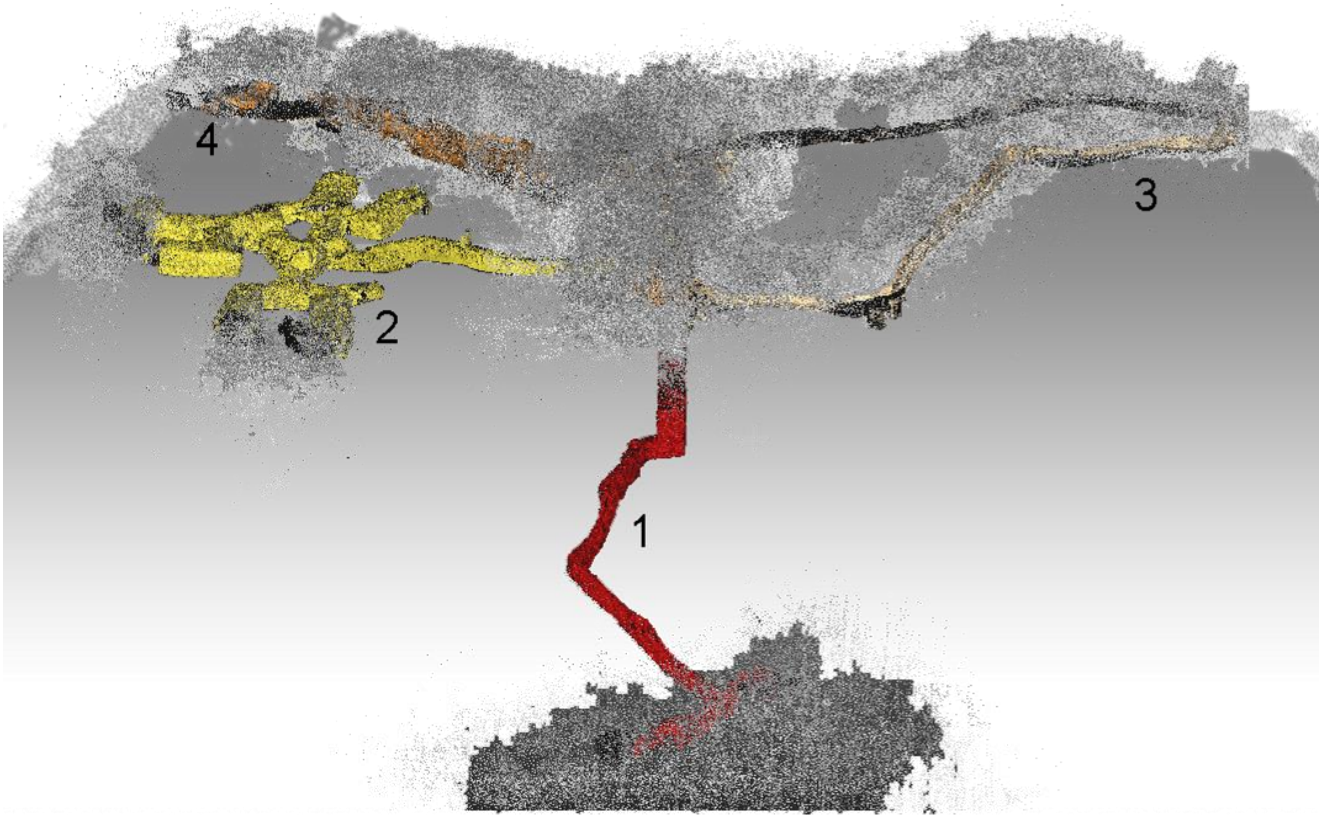


Figure 12. Four registered point clouds: second battery or “100 steps stairway” (1), third battery (2), trench (3) and fourth battery (4).

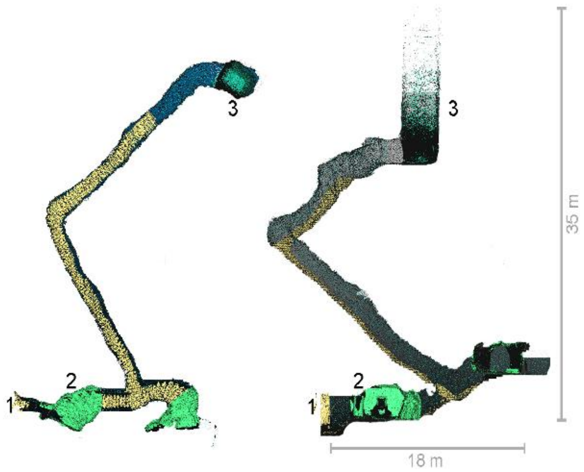


Figure 13. Second battery in cave, the so-called “100 step stairways”: entrance (1), riflemen emplacements (2) connecting well with the upper trench (3).

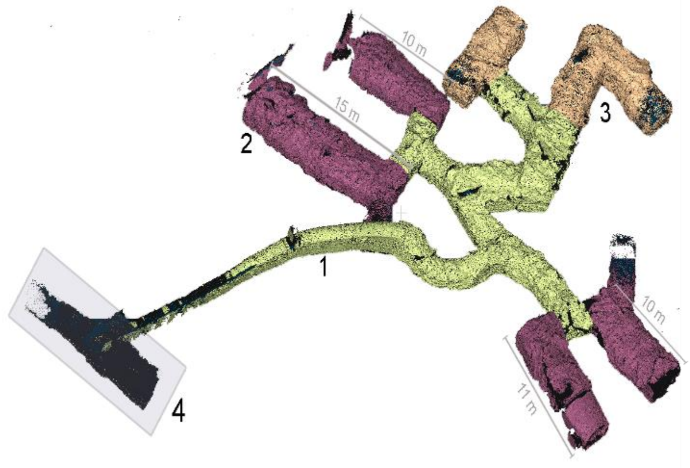


Figure 14. Third battery in cave: connecting underground gallery (1), artillery battery in cave (2), barracks (3), connection with trench (4).

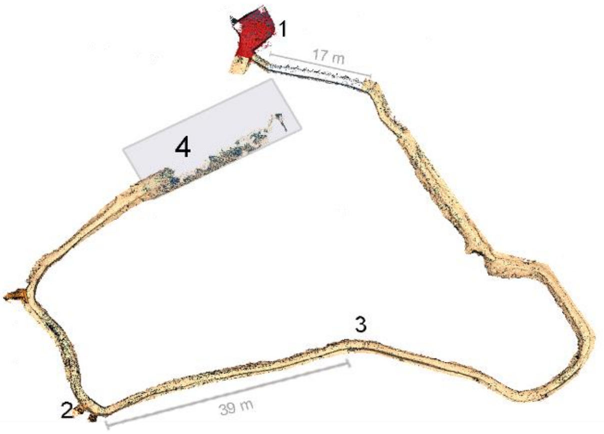


Figure 15. The trench structure: gun emplacement (1), casemate (2), foxhole defensive position (3), connection with third battery (4).

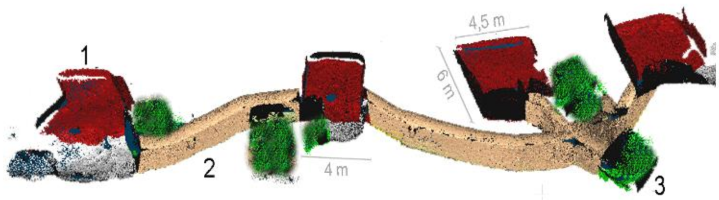


Figure 16. Fourth battery in cave: gun emplacements (1), connecting underground gallery (2), underground casemate (3).

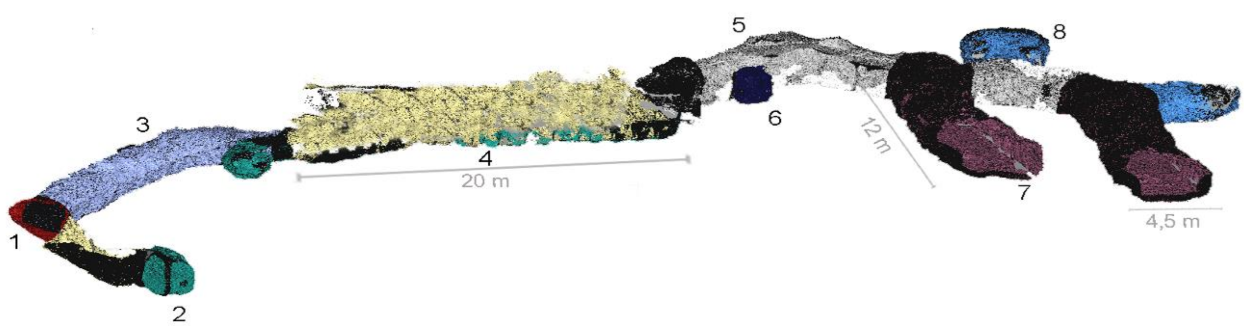


Figure 17. First battery in the cave in the lower part of *Monte Celva* (1: entrance of the structure; 2: lower casemates; 3, 5: connecting galleries; 4: riflemen emplacements; 6: guard post, 7: artillery battery in cave, 8: ammunition depot).

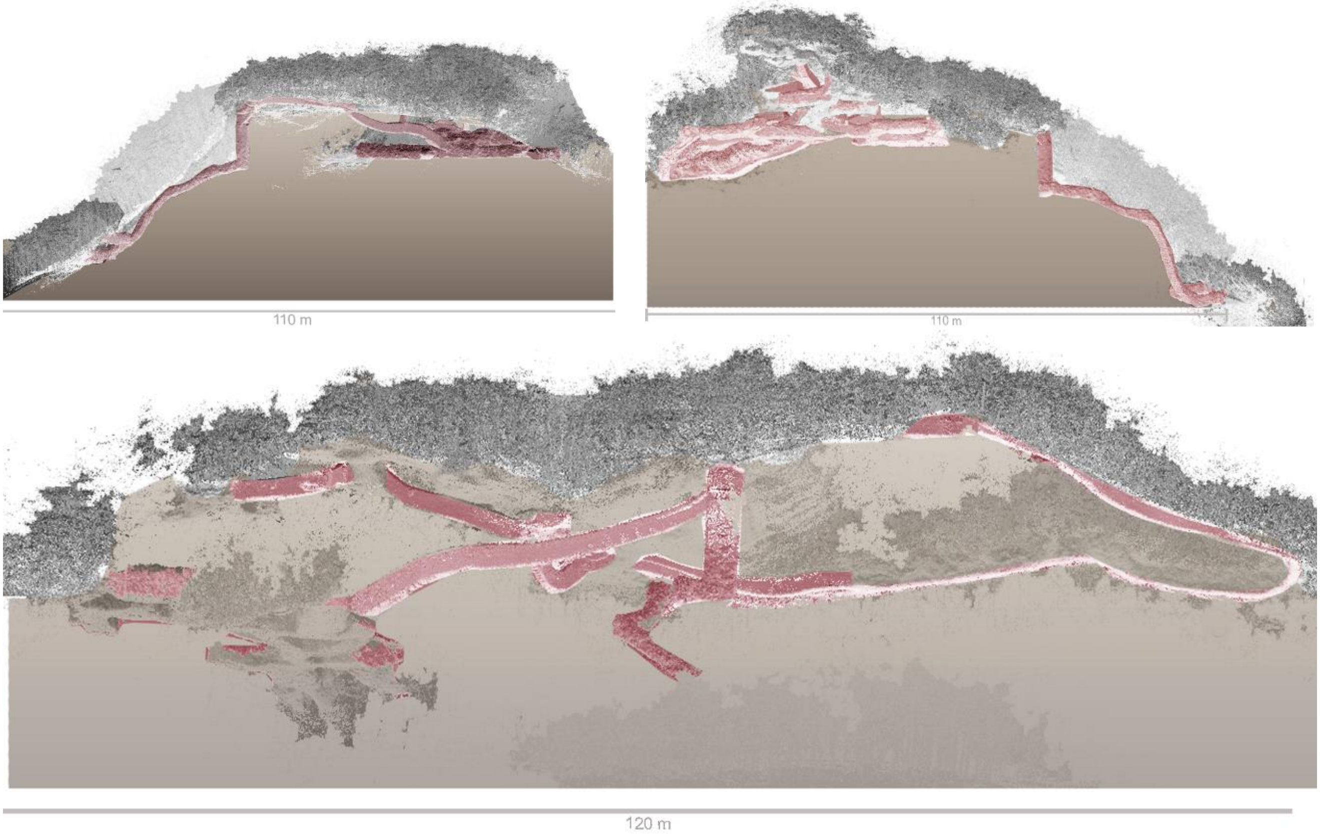


Figure 18. Views of some WWI underground passages in *Monte Celva* integrated into the 3D terrain model of the area.

6. LESSON LEARNT AND CONCLUSIONS

The paper described the investigation and use of a hand-held laser scanner system to survey and map several underground and complex heritage structures. The device (GeoSlam Zeb1) is able to map in short time large and complex structures, although on-site and post-processing procedures must be implemented to verify its accuracy and reliability, especially for long and featureless structures. Moreover, when textural information is important, an additional acquisition (for example, through a photogrammetric survey) is necessary. In the Grotta di Seiano survey, the comparison between the Zeb1 3D data and classic surveying showed a maximum RMS error of 10 m. This was mainly due to a block deformation of the scans acquired, especially in the segments with poor morphological features. From the lab investigations and field experiences, the nodding speed and direction, along with the walking speed were the most critical factors while using the Zeb1 system. In this work it was verified the importance of keeping a constant speed of walking and a stable oscillation of the sensor to guarantee better results. Moreover, an overlapping area between consecutive data acquisition at least of 20%-30% is advisable. In case of structures with alternation of featureless parts and rich geometric elements, a hybrid acquisition approach (side by side and front-back nodding) can provide most reliable results. Moreover, a “round trip” approach (turning back in every scans to the starting point) is essential to reduce errors and deformations. The new version of the sensor offers an automatically oscillating head in order to reduce user-dependent results and facilitate the acquisition, avoiding undesirable and erroneous motion or divergences in the acquired point clouds. Investigations with this new head are planned.

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