THE USE OF SLAM AND UAV TECHNOLOGY IN GEOLOGICAL FIELD FOR MONITORING: THE CASE STUDY OF THE BOSSEA CAVE

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The use of SLAM and UAV technology in geological field for monitoring: the case study of the Bossea Cave

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ABSTRACT:
The geomatics survey in the speleological field is one of the main activities that allows adding a scientific and informative value to the exploration of caves and is of fundamental importance to have a detailed knowledge of the hypogean cavity: only thanks to the reconstruction of the three-dimensional environment through range-based techniques, are possible orientation, inland navigation, lithological understanding, as well as a better organization of the exploration of the cave itself. This work describes the surveys made in the Bossea Cave, in the province of Cuneo (NW, Italy), considered among the most suggestive and geologically interesting in Europe because they also have an underground karst laboratory managed by the Scientific Station of Bossea (CAI of Cuneo) and the Department of Environment, Land, and Infrastructure Engineering (DIATI) of the Politecnico di Torino, with the collaboration of the department of Cuneo of ARPA Piemonte and the Radiation Section of ARPA Valle d'Aosta. The survey activities described below have been concentrated both on the internal environment and the mountainside above the cave. The work presents the analytical measuring principle of the portable rapid mapping system, and it is dedicated to analysing the performances of this instrument in terms of the accuracy and completeness of 3D point clouds generated. The proposed validation method follows the assessment of point cloud deviation between data based on SLAM technology and 3D point clouds obtained from a terrestrial LiDAR system. The trajectory covered about 1km, with a height difference of about 120m, reaching differences between SLAM and LiDAR sensors of about 15 cm in the plan and 22 cm on the vertical component.

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1. INTRODUCTION

Geomatics surveys are one of the most useful activities for mapping underground caves. These surveys typically involve the use of specialized equipment and techniques to collect data on the shape, size, and location of the cave passages and chambers.
One common technique used in these environments is laser scanning: this methodology is based on using a laser scanner to create a detailed 3D map of the cave environment (Gallay et al., 2015; Idrees and Pradhan, 2016). The scanner emits laser pulses that bounce off the cave walls and floor, and the time it takes for the pulses to return to the scanner is used to calculate the distance to each point on the cave surface. This data is then combined to create a detailed 3D model of the cave.
Another quite common technique used for reconstructing underground caves is photogrammetry (Zhang et al., 2010; Dabove et al., 2019; Pukanská et al., 2020). This involves taking multiple overlapping photos of the cave environment from different angles, and then using specialized software to stitch the images together and create a 3D cave model.
Both of these techniques can be very effective for mapping underground caves, but they require specialized equipment and expertise. In both cases, the georeferencing activities in global reference systems require a huge amount of work, which is time-consuming. Thus, starting a few years ago, another methodology began to be considered.
Even if the survey in underground caves with digital technologies is still a relatively underdeveloped methodology, it has started to gain more and more ground, especially following the development of Simultaneous Localization and Mapping (SLAM) techniques (Giordan et al., 2021). SLAM techniques were initially developed in the field of robotics, but for some years, they have been increasingly used in detection and autonomous driving. They allow a device to determine its position while detecting an unknown environment simultaneously. This has great importance, especially in areas where the Global Navigation Satellite System (GNSS) is unavailable due to the impossibility of receiving satellite signals, such as in indoor environments like underground caves. Suppose we add the necessity to perform the reconstruction of the 3D environment. In that case, this methodology becomes fundamental since it also guarantees the possibility of determining the orientation and performing indoor navigation and lithological understanding, as well as a better organization of the exploration of the cave itself. This activity is fundamental to having excellent geological, geomorphological and tectonic knowledge of the subsoil, both for speleological or geological purposes and for the analysis of cavity stability (Columbu et al., 2022). Starting from these considerations, in this contribution, we present the analytical measuring principle of one portable rapid mapping system, the analyses of the performances of this instrument in terms of the accuracy and completeness of 3D point clouds generated, comparing these results with those obtainable with a LiDAR system, considered as reference.

1.1 The case study

The study focuses on the Bossea cave, a natural underground cave situated in the southern region of Piedmont (NW Italy) within the Marguareis Alps, bordering the Maritime Alps. The cave is located in the small village of Bossea in the municipality of Frabosa Soprana, on the western side of Val Corsaglia (Cuneo). It is believed to have been discovered in 1816, with its first exploration carried out in 1850 by a mineral researcher named Domenico Mora. Currently, this hypogeal structure shows large environments containing a considerable amount of limestone concretions and several paleontological findings, including the skeleton of an Ursus Spelaeus lived presumably between 27 000 and 120 000 years ago, attracting tourists in this way. Although it is a tourist cave, its geomorphological and hydrogeological characteristics it also attracts notable scientific interest, with three laboratory: the Karst Laboratory of Bossea and the Karst Hydrogeology Laboratory, managed by the Italian Alpine Club (CAI) and the Department of Environment, Land and Infrastructure Engineering (DIATI) of the Politecnico di Torino situated within its premises, and the PALEOLab, which was set up by DIATI under the cc@polito project, in order to study the effects of climate change on the hypogeal environment. The Bossea cave is ideal for experimental scientific research due to its optimal environmental conditions and the presence of the karst phenomenon in different stages of evolution. The cave of Bossea is characterized by a constant temperature of about 11°C and high humidity (about 96%), which, however, can adversely affect the topographical surveys. The cave (Figure 1) has a WNW-ESE orientation, a development of approximately 2800 m, and a total height difference of 184 m. The entrance is located at the height of 836 m, formed by the resurgence of the river Mora when the bed of the stream Corsaglia was raised by around 30 m. As the underground stream continues its karst erosion, the spring's share is decreasing with the lowering of the water stream.

Figure 1. An example of the environment in the Bossea cave.

2. MATERIALS AND METHODS

This study consists of four fundamental steps: the use of a DJI Phantom 4 RTK drone to collect data for creating a 3D terrain model, the collection of data using terrestrial laser scanners (TLS) and portable SLAM-based mapping systems, and the creation and analysis of DEMs and 3D models.
In the discussion section, we analyze and compare the accuracy and results obtained from various techniques.

2.1 UAV data acquisition and processing

Aerial data acquisition was performed manually above the area encompassing the Bossea cave extension (about 40 ha) using a DJI Phantom 4 RTK aircraft. The UAV platform incorporated a GNSS receiver that facilitated the acquisition of differential corrections deriving from the Service of the Permanent Refence Network of the Piedmont Region (SPIN GNSS), and resolution of the ambiguity phase, enabling the estimation of projection center positions with a centimetric accuracy. The UAV was outfitted with a 20-megapixel camera sensor featuring an 8.8 mm focal length. To achieve a comprehensive reconstruction of the irregular mountain slope, multiple flights were executed, generating 999 images with both nadir and oblique orientation. Flights characteristics are shown in the Table 1.

Camera model	Ground Sample Distance	Focal length	Pixel size	Average height from the ground
FC6310R 20MP x 1" sensor	2.54 cm/pix	8.8 mm	2.41 x 2.41 µm	93 m

Table 1. Camera and average flights parameters.

Photo alignment was carried out using proprietary software Agisoft Metashape by identifying GCPs within the area of interest, resulting in a 3D georeferenced model of known accuracy, as presented in Table 2. Both nadiral and oblique images were processed simultaneously. The following steps involved optimizing the estimated camera parameters and generating a dense point cloud. To eliminate noise caused by dense vegetation, a "high" level of detail and an "aggressive" depth filtering technique were utilized to produce the 3D dense point cloud consisting of approximately 208 million points.

GCPs	RMSE X [cm]	RMSE Y [cm]	RMSE Z [cm]	Total RMSE [cm]
5	0.646	0.366	0.887	1.157

Table 2. GCPs Root Mean Square Error (RMSE).

Subsequently, a high-quality mesh was realized in order to be able to extract the Digital Surface Model (DSM) of the area in the WGS84-UTM 32N coordinates system.
Since one of the main aims of this study is to investigate the thickness of the rock lying between the surface and the roof of the cave, we needed a DTM. For this purpose, an automatic classification was realized using Agisoft Metashape. A specific tool allowed the identification of the points related to the vegetation, the man-made object and terrain classes. After extracting only the terrain points, the classification was manually optimized in order to remove some wrongly classified points. From this last dataset, we were able to obtain a DTM with a resolution of 5 cm.

2.2 SLAM-based data acquisition

The primary objective of the experiment is to assess the effectiveness and potential issues of using a Mobile Laser Scanner mapping system based on SLAM technology, such as the BLK2GO by Leica Geosystem and the Kaarta Stencil-2.
The BLK2GO is a handheld device that combines LiDAR SLAM, Visual SLAM, and IMU technologies to compute the device's position and movement based on LIDAR analysis of surfaces, camera identification of homologous features between sequential images, and IMU movement sensing. It has a scan rate of 420,000 pts/sec, can reach ranges of up to 25m, and has a 360° Field of View (FoV). Its strength lies in its small size, the weight of less than 1kg, and ease of use. The device can work in complete darkness as it can recognize the geometry of acquired objects. The KAARTA Stencil 2 is a 3D rapid mapping standalone system that can generate point clouds of the environment in real-time with an acquisition range of 100m. The device utilized comprises a 3D LiDAR Velodyne VLP-16 (30° FoV), a MEMS inertial platform, and a feature tracking camera interconnected to an i7 processor. The system's measurement principle merges laser range data with feature tracker and image information to deduce 6-DOF motion and save the points collected by LiDAR. Data processing follows a two-step workflow (Zhang and Singh, 2018). Firstly, visual-inertial odometry algorithms are employed, integrating vision and IMU to optimize motion estimation and associating depth

information related to features using laser points. Simultaneously, laser points are registered in a local system utilizing speed information derived from the odometry. A mapping algorithm detects geometric features in the point cloud and matches them to optimize registration. This solution permits the instrument to be deployed solely with LiDAR-odometry, circumventing the requirement for images for feature tracking. This instrument weighs 1730 g and is slightly heavier than the BLK2GO. The Stencil 2 was affixed to a small pole and interfaced with a screen for the purpose of verifying real-time data acquisition.

It is important to remark that several factors could affect the results of the survey, such as the operator's walking speed, the way the instrument is handled and turned, and the characteristics of the surveyed environment. Also, to prevent drift errors, it can be helpful to follow loop paths or revisit areas that have already been surveyed, according to the environment configuration.

For the purposes of our acquisition tests, we traversed the touristic path within the cave. The route commences in a narrow corridor that leads to a wider environment, culminating in a terrace. Ascending a staircase from the terrace leads to a junction with two staircases that descend into the so-called "Bear's Room". From this point, the tourist path becomes relatively flat before splitting into two steep staircases, connected by narrow passages, which ultimately lead to the Ernestina waterfall. To conduct the two SLAM-based acquisition tests, we commenced outside the cave entrance and traversed the touristic route in a back-and-forth fashion, alternating paths where possible to create rings. Both tests shared identical starting and ending points, situated just prior to the main cavity entrance. As both the stairs and some paths were very narrow, it was only possible to travel in circles and scan the same area multiple times in the "Bear's Room".

Data acquisitions were executed using the default configuration parameters for the Stencil 2, which were optimized for structured outdoor environments or large indoor spaces (Kaarta, 2018). These default settings incorporate values for voxel size (0.2 m), namely the point cloud resolution in the map file, point cloud resolution for scan matching and display (cornerVoxelSize, surfVoxelSize, surroundingVoxelSize) (0.2 m - 0.4 m - 0.6 m), the minimum point-to-point distance for mapping (blindRadius) (1.5 m), and no restrictions on the planarity of motion. Conversely, the Blk2Go system cannot be customized with any capture parameters.

2.3 The reference data

To predict the accuracy of the 3D data obtained from SLAM-based instruments in a cave, a laser scanner survey was conducted using the Faro Focus Cam2 3D scanner. A total of 87 scans were acquired with 1/4 resolution, requiring approximately 7 minutes for cloud acquisition and 1 minute for image collection per scan. The geometric quality of the point clouds was evaluated by measuring markers placed at various locations within the cave using topographic instruments. A reference network was established outside the Bossea cave using GNSS techniques to establish high-precision coordinates of the markers. The entire survey campaign took about 14 hours to complete.

The GNSS data were post-processed using a Virtual RINEX generated from the data measured by the SPIN GNSS network, achieving residuals of less than 2mm in plan and less than 4mm in altitude. A geodetic traverse was then carried out using a total station, starting from external points of known coordinates, to measure the position of the markers inside the cave. A total of 37 vertices were used to build the traverse inside the cavity along the tourist path of the cave. From each station point, 178 checkerboard markers were measured and placed on stable walls of the cavity for registration and georeferencing of the laser scanner point cloud. These measurements were adjusted with a least square approach on the MicroSurvey StarNet v.7.0 software, which enabled the determination of the coordinate of the markers with millimeter accuracy and a centimetric error on the last portion of the cave.

The laser data were registered using FARO's proprietary software called Scene. Firstly, an Iterative Closest Point (ICP) (Besl and McKay, 1992) approach was used to register the point clouds in the initial step. Afterwards, the measured markers were utilized for the overall georeferencing of the point cloud, resulting in a registration error of approximately 1 cm, which is consistent with the accuracy of the topographic network and the instrument itself.

Upon processing the laser-scanned data, a 3D-coloured point cloud consisting of roughly 3.5 billion points was generated (Figure 2). Due to the high point density of the final model, it was determined that the dataset should be reduced to a point cloud with a 2 cm resolution.

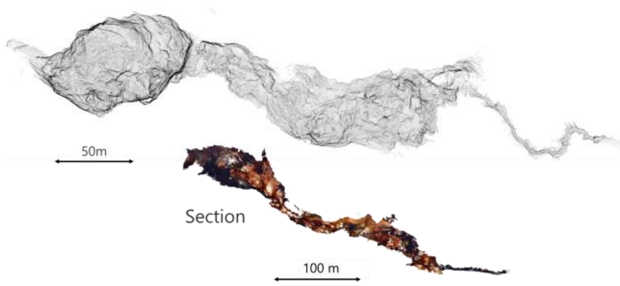

Figure 2. The top view and a coloured section of the reference LiDAR point cloud.

3. RESULTS ANALYSIS AND POST-PROCESSING

3.1 Rock-thickness estimation

One of the objectives of this study was to determine the thickness of the rock layer above the cave's shell. By utilizing the thickness of the rock and the 3D model of the speleothems, specific analyses of the shell's stability can be conducted.

To achieve this, a model of the raster surface of the cave's roof was created with the software CloudCompare, using the LiDAR point cloud. For each pixel, the maximum height of the points inside was associated with obtaining a DSM of the cave's roof with a 10 cm resolution.

By computing the mathematical difference between the DTM of the ground generated from the UAV data and the DSM of the cave, it was possible to estimate the thickness of the overlying rock and its variations (Figure 3). Furthermore, with the aid of several installed thermometers positioned in the dome and walls of the cave, the researchers of PaleoLab were able to study how temperatures propagate from the outside to the inside of the cave.

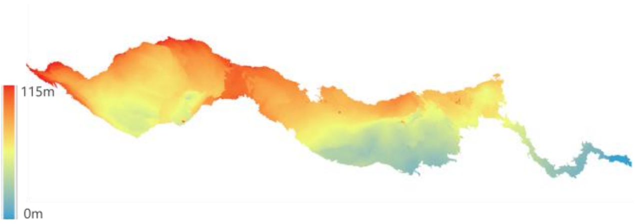

Figure 3. Rock thickness, estimated as difference between the DTM of the mountain slope and the DSM of the underground cave.

3.2 The real-time solution with SLAM technology

One of the primary advantages of utilizing SLAM-based technology is the immediate accessibility of data without the requirement of additional input data, including GNSS position and reference maps of the environment. Upon completion of the acquisition phase, the estimated trajectories, point clouds, acquired images, and raw data are saved.
This section aimed to evaluate the accuracy and completeness of the real-time solution's obtained data. **Table 3** presents an overview of the primary features of the products obtained by the two SLAM systems in real-time.

Data	**Acquisition time [h:m:s]**	**Trajectory**		**N. points 3D point cloud**
		N. points	Length [m]	
Stencil-2	00:50:59	15254	1420.7	~258 millions
BLK2GO	00:38:06	-	1380.9	~349 millions

Table 3. Characteristics of the real-time solutions of the SLAM-based acquisition tests.

Figure 4 and Figure 5 show the trajectories and point clouds acquired with the Kaarta Stencil-2 and BLK2GO systems, respectively.

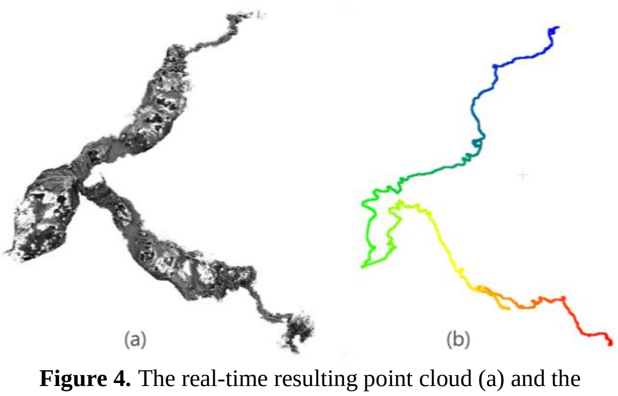

Figure 4. The real-time resulting point cloud (a) and the trajectory (b) from the Kaarta Stencil-2 acquisition test.

Figure 5. The top view of the point cloud generated by the BLK2GO system. In red are identified the waypoint.

From a first observation of the results, it is evident that there is a severe error in estimating the trajectory in the dataset of Kaarta Stencil 2, despite the cloud of points seeming relatively dense. In contrast, the point cloud generated by the BLK2Go system is more consistent with the cave’s morphology, even if the trajectory file is unavailable, while only some waypoints are visible.
Furthermore, it was observed that the BLK2GO solution generates a point cloud with color information, whereas the Kaarta Stencil-2 produces a product that includes only the point's reflectivity and timestamp data.

3.3 KAARTA Stencil-2 data post-processing

As previously anticipated, the Kaarta Stencil 2 has a dedicated tool for post-processing the acquired data. On the contrary, the data management software of the BLK2GO, Leica Register 360, does not allow for modification of the acquired trajectory and point cloud. Instead, it is only possible to rigidly rotate and translate the entire block and register it with other data or georeference it.
Regarding the Stencil-2 system, conducting data reprocessing at a lower speed than the original acquisition speed is possible. This can improve the registration of point clouds where the instrument may have failed in real-time. Furthermore, the software provides the ability to modify the configuration parameters to adapt them to the specific environment in which the surveys were conducted.
The configuration parameters of the acquisition test were modified to reprocess the data obtained in the Bossea cave. The default parameters were set for acquisitions in large indoor environments. Still, due to the tight indoor environment of the Bossea cave, it was deemed appropriate to adjust the parameters accordingly. Additionally, the blindRadius parameter was limited to 15 cm to account for the limited acquisition distance in some narrow passages (Kaarta, 2018). After several trials, a set of parameters was identified that allowed us to obtain the best solution for trajectory estimation and point cloud generation (**Table 4**).

Configuration parameters	
voxelSize [m]	0,4
cornerVoxelSize [m]	0,1
surfVoxelSize [m]	0,2
sorroundVoxelSize [m]	0,6
blindRadius [m]	0.15

Table 4. Set of parameters used for the Kaarta Stencil-2 data post-processing.

Another post-processing tool offered by Stencil 2 is the Loop Closure tool, which utilizes a series of functions to enhance the overall coherence of the scan registration and trajectory estimation. The global drift errors are corrected by using trajectory paths that come close to each other and performing a scan match. Additionally, the tool enables the user to enforce overlap between the initial and ending points. The data post-processing took about 3 hours to complete the first phase and about half an hour to optimize the result with the Loop Closure tool, generating a point cloud of about 591 million points. In Figure 6, it is possible to see the point cloud, and the trajectory obtained.

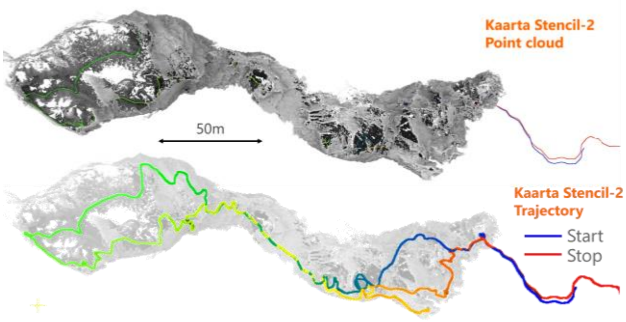

Figure 6. Results of the Kaarta Stencil-2 data post-processing.

The point cloud thus obtained is particularly dense near the travelling path, while it has some holes in the larger spaces, especially near the highest areas of the ceiling. This is due to the instrument's limited range.

3.4 Comparison of the 3D models and discussion

Two procedures were implemented to evaluate the accuracy and correspondence to the reality of the laser-visual-inertial odometry approach (the BLK2GO real-time solution and the Kaarta Stencil-2 post-processed data). The first one involved computing the distance between the generated and reference point clouds. The second procedure involved evaluating the profile distance. The analyses were performed using the open-source CloudCompare software.

3.4.1 C2C comparison: The Cloud-to-Cloud (C2C) tool can be used to estimate the difference between the reference cloud and the SLAM maps. The tool employs the Nearest Neighbor algorithm to calculate the Euclidean distance between each point of the compared cloud and the nearest point of the reference cloud. In order to perform the calculation, the involved point cloud should be georeferenced in the same coordinate system. To align and register the models generated by the mobile mapping tools with the reference data, a rough registration can be conducted using pairs of equivalent points identified in the point cloud to be registered and in the reference model, following an automatic method based on the ICP algorithm (Besl and McKay, 1992) for a more precise registration can be exploited. This procedure was executed for both SLAM solutions, resulting in a final RMSE of approximately 0.45m for the Kaarta Stencil-2 post-processed solution and 0.50 m for the BLK2GO dataset.
The C2C tool was utilized to identify outliers by classifying points that were more than 2 meters distant from the reference model, as the errors of interest were lower than this threshold. The significant results obtained from this procedure are depicted in Figure 7.
Regarding the Stencil-2 solution, the computation of differences confirmed the model's metrical accuracy and revealed that the more significant discrepancies are located in an inaccessible area during the acquisition campaign - the Karst Laboratory. This area was not surveyed with the terrestrial laser scanner, resulting in a lack of data.

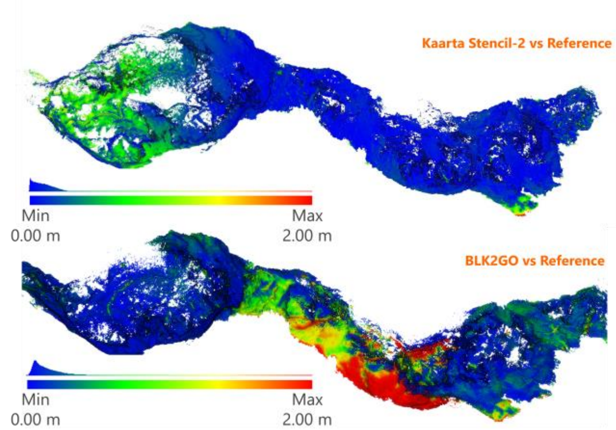

Figure 7. C2C analysis between the reference point cloud and the SLAM solutions.

In the final part of the cave, there are significant deviations between the two clouds of points, which can reach up to 70 cm. It is the part that is most affected by the drift of the instrument, where there is no overlap between the return route and not even overlap of features, as the environment is vast.
Observing the BLK2GO solution, there are evident differences in the central part of the cave. A close analysis of the data shows a split of the tourist route into outbound and return due to an incorrect recording of the cloud of points. On the contrary, it is noted that in larger rooms, with greater mobility by the operator and, consequently, a greater presence of features, the quality of the data BLK2GO is more similar to reality.
Table 5 reports the statistical parameters derived from the analysis with the C2C tools, such as maximal distance, average distance and standard deviation.

C2C	Avg. Distance [m]	Max distance [m]	Std.dev. [m]	Error distribution [m]	
				50%	80%
Stencil-2	0.253	2	0.302	<0.152	<0.333
BLK2GO	0.267	2	0.382	<0.133	<0.403

Table 5. Statistical results from the distance comparison between the SLAM point clouds and the reference point cloud.

Starting from these results, it is possible to state that both solutions are reasonable. It should be emphasized that the BLK2GO solution has been obtained in real-time, while the Kaarta one has been obtained in post-processing, which significantly improved the performances. It should also be highlighted that many areas of the cave have wet surfaces, which reflect the signal, affect the result of the recording, and create noise. Obviously, all these aspects have a non-trivial role in the results obtained.

3.4.2 Profile comparison: A second analysis was made by comparing some significant profiles extracted by the point clouds (Figure 8). Using the specific tool in CloudCompare, three vertical slices 5 cm thick were extracted from each model, in the middle of the two main rooms and along the path that connects them.
The evaluation was carried out to verify the degree of deviation from the reference point cloud in correspondence with specific geomorphological features (Figure 8 to Figure 11), as well as its variation in relation to both height and distance from the path.

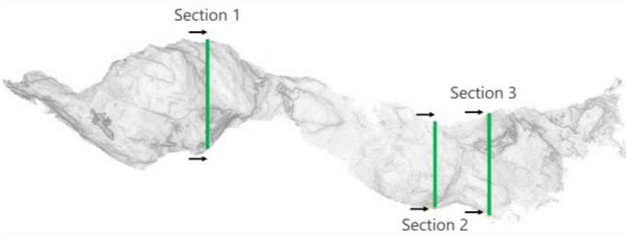

Figure 8. Sections extracted from the analysed point clouds.

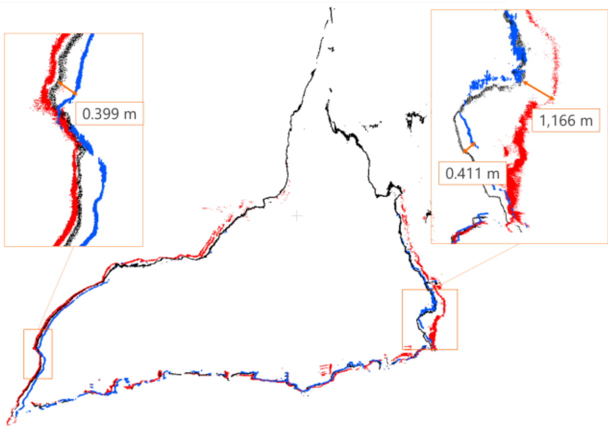

Figure 9. Section 1: representing the reference point cloud (black), the Stencil-2 data (red) and the BLK2GO solution (blue).

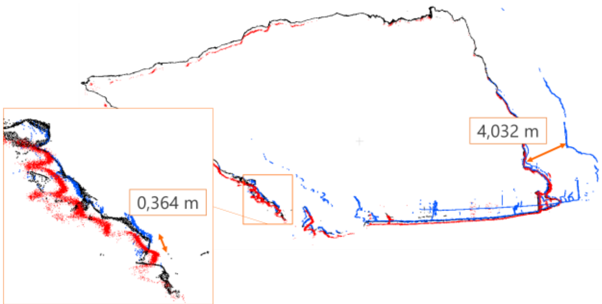

Figure 10. Section 2: representing the reference point cloud (black), the Stencil-2 data (red) and the BLK2GO solution (blue).

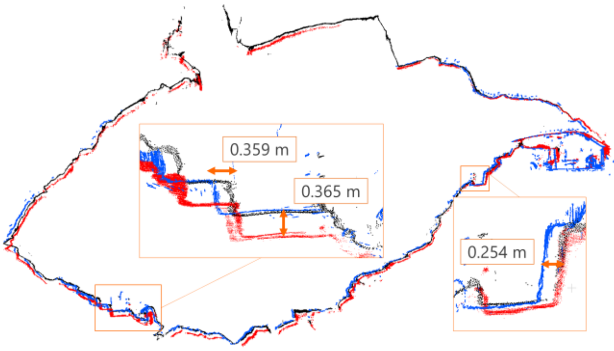

Figure 11. Section 3: representing the reference point cloud (black), the Stencil-2 data (red) and the BLK2GO solution (blue).

The verification of the deviations has not only shown the noise that characterizes the clouds acquired with the laser-visual-inertial odometry approach and some misalignments (probably due to an incorrect ICP alignment), but has also highlighted that SLAM data is not always sufficient to describe the roof of the cave.

4. CONCLUSIONS

New technologies, instruments, and algorithms have expanded the possibilities of conducting three-dimensional surveys in underground environments like caves. One such enhancement includes using portable laser range finders, which allow for faster measurements and data storage either in built-in memory or an application. The proposed methodology, which has been tested in research, aims to achieve a complete three-dimensional reconstruction of caves while ensuring accuracy in positioning. To this purpose, two different SLAM-based acquisition systems have been compared.
The survey activities performed in the presented work have been concentrated both on the internal environment and the mountainside above the Bossea cave. Indeed, an external photogrammetric aerial model was later integrated with the 3D underground model, which allowed us to approximate the thickness of the rock lying between the surface and the cave roof, comparing two different DEMs.
Starting from the obtained results, it is possible to affirm that the instruments used have guaranteed good performances in terms of acquisition times, data accuracy, ease of use, and manoeuvrability.
Considering the results' performances, the accuracy of trajectories is strongly influenced by acquisition conditions (type of environments, variations in light, variations in altitude, humidity) and by the operator.

Despite the deviation found in the results obtained in real-time, the implemented processing algorithms allow for obtaining accurate clouds, which can be used for 1:1000/2000 scale returns. The tested SLAM technology has demonstrated the possibility of integrating the tool with different other technologies to allow data georeferencing. For example, one of the possible next steps could be integrating these measurements with those obtainable with UWB technology in order to perform indoor positioning and 3D reconstruction, everything georeferenced in a global reference system.
Besides, the use of captured images could enhance indoor navigation solutions and improve the knowledge of the environment.

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