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3D mapping of karst caves of varied morphological complexity, using mobile LiDAR scanning

Fran DOMAZETOVIĆ [1*], Nina LONČAR [2], and Ivan MARIĆ [3]

[1] University of Zadar, Department of Geography, Center for Geospatial Technologies, Trg kneza Višeslava 9, 23000 Zadar, Croatia.
[* Corresponding Author] E-mail: fdomazeto@unizd.hr

[2] University of Zadar, Department of Geography, Center for Geospatial Technologies, Trg kneza Višeslava 9, 23000 Zadar, Croatia.
E-mail: nloncar@unizd.hr

[3] University of Zadar, Department of Geography, Center for Geospatial Technologies, Trg kneza Višeslava 9, 23000 Zadar, Croatia.
E-mail: imaric1@unizd.hr

Abstract: Caves are among the most common endokarstic features within the Dinaric Karst of Croatia, although currently only a few have been adapted for touristic purposes. Because of their complex morphology, 3D mapping and inventorying of caves commonly present significant challenges. However, detailed 3D mapping is crucial to the sustainable management of show caves, because it allows better understanding and supervision of the cave geomorphological characteristics and their potential vulnerability. Traditional cave mapping is a lengthy and demanding process, which often results in insufficiently accurate, incomplete, or even false, representations of cave morphology. Furthermore, use of the existing traditional methods requires prolonged and extensive speleological surveys. To increase the efficiency and value of 3D mapping, traditional methods are gradually being replaced by various geospatial technologies. This study examines the potentials and challenges for the application of mobile LiDAR scanning (MLS) for detailed 3D mapping of selected karst show caves of varied morphological complexity (length, area, volume, etc.).

Detailed 3D mapping, using the Zeb Revo MLS, was carried out for three selected show caves with different levels of morphological complexity: Modrič Cave near Rovanjska (Croatia), Vrlovka Cave near Kamanje (Croatia) and Biserujka Cave on Krk Island (Croatia). Special attention was paid to the different challenges encountered during the application of this technology to the 3D mapping of the three caves, as well as to the difficulties that occurred during the processing of the large amount of data collected. Based on the 3D mapping results, detailed high-resolution 3D models of the caves were created, from which the parameters of selected morphometric features were calculated. The application of MLS enhanced the level-of-detail (LoD) of the cave models significantly, thereby improving the results of the cave morphology analyses and geomorphometric assessments. Because of its high mobility, rapid acquisition of dense point clouds, and superior accuracy, MLS demonstrates great potential for detailed 3D mapping of complex karst cave systems.

Keywords: mobile LiDAR scanning; 3D cave mapping; Dinaric Karst; geomorphometric analysis; Croatia.

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Introduction and background

Unique shapes and complex geological formations, coupled with challenging natural conditions such as restricted access, minimal light, high humidity, and the potential presence of water, make caves very difficult to map (Konsolaki *et al*., 2020; Vassilakis, Konsolaki, 2022). Reflecting the establishment of speleology as a scientific discipline and advances in survey instrumentation, various methods of cave mapping have been adopted and used at different times (Idrees and Pradhan, 2016). The development of tourism and increased human influence on the equilibrium of these sensitive environments gave a special stimulus to refining the methodologies of cave measurement (Pisoni *et al*., 2022; Vassilakis and Konsolaki, 2022).

Early speleologists produced freehand drawings to document their visual interpretation of the cave (Fryer *et al*., 2005). Subsequently, simple traditional surveying devices, such as tapes, compasses and clinometers, were used (Tsakiri *et al*., 2007). Typically this approach involves manually measuring and determining the direction between a series of stations spaced up to several tens of metres or more apart, depending upon the nature of the passages involved (Ballesteros *et al*., 2014). At each station, measurements of range (fibreglass tape) and bearing (compass and clinometer) are carried out (Kershaw, 2012; Konsolaki *et al*., 2020). Details are obtained and recorded by means of hand-drawn sketches augmented by left-right-up-down distance measurements (Zlot and Bosse, 2014).

Authors of the cited publications (see References)	Scanned cave name and [broad location]	Detailed cave location and [nature of host bedrock]	Mobile laser scanning (MLS) system	Derived volume of scanned cave (m³)	Scanning traverses total length (m)	Number of points (mil. = million; mlrd. = billion)	Duration of scan acquisition (h:min:s)
Konsolaki *et al*., 2020	Koutouki Cave [Greece]	Northeastern side of Hymettus Mountain [limestone]	GeoSLAM ZEB Revo	6,900	—	80 mil.	—
Zlot and Bosse, 2014	Koonalda Cave [Australia]	Nullarbor Plain in South Australia [limestone]	CSIRO Zebedee	—	9,100	300 mil.	—
Pisoni *et al*., 2022	Valdemino Cave [Italy]	Borgio Verezzi territory, in Liguria [dolomitic limestone]	KAARTA Stencil 2	—	—	—	—
Acosta-Colón *et al*., 2019	Water, Pupuk Mentar, Mbelin, Sibayak and Jodoh Cave [Indonesia]	Batu Katak village, [Batumilmil Formation: dark grey to reddish-grey limestones affected by palaeokarstification]	ZEB1 LiDAR	—	1,200	126.6 mil	—
Ullman *et al*., 2023	Har Sifsof Cave [Israel]	Upper Galilee [Late Cretaceous limestone of the Sakhnin Formation]	ZEB Horizon LiDAR	—	—	780 mil. (1,850 points/m²)	—
Grasso *et al*., 2023	Bossea Cave [Italy]	Cuneo (NW Italy) [limestone]	BLK2GO	—	1,380.9	~349 mil	00:38:06
Grasso *et al*., 2023	Bossea Cave [Italy]	Cuneo (NW Italy) [limestone]	Kaarta Stencil-2	—	1,420.7	~258 mil	00:50:59
Rissolo *et al*., 2024	Ocho Balas and Las Manitas [Mexico]	Quintana Roo, Mexico [limestone]	Hovermap 100	—	—	—	—
Vassilakis and Konsolaki, 2022	Koutouki Cave [Greece]	Northeastern side of Hymettus Mountain [limestone]	GeoSLAM ZEB Revo	6,900	—	80 mil.	—
Lozano Bravo *et al*., 2023	Las Cuevas Cave [Belize]	Chiquibul Forest Reserve in Belize [limestone]	Hovermap (UAV and hand-held)	—	335	4.1 mlrd.	4 days
Liu *et al*., 2024	Six Caves in Yunshui Cave [China]	Southern slope of Shangfang Mountain Fangshan District Beijing [limestone]	ZEB Horizon	131,240 (6 caves)	>600	few hundreds of millions	—

***Table 1**: Overview of previous 3D cave-mapping using the SLAM-based MLS. [**Note**: the symbol "—" indicates that data were not published.]*

Such measurements are prone to human errors associated with transcription, recognition of stations and instrument-sighting (Hunter, 2010). It is time-consuming, subjective, labour-intensive work that is commonly carried out under high-risk conditions (Gallay *et al*., 2015; Lozano Bravo *et al*., 2023). This approach was replaced or augmented by adopting total stations (Haddad, 2011), theodolite systems (Rüther *et al*., 2009) and handheld laser distance measurement devices (Dryjanskii, 2010). These instruments improved point accuracy but were not designed to map complete irregular geometric shapes (3D models) (Haddad, 2011). Also, the use of total stations or theodolite systems for data acquisition is time-consuming (Lozano Bravo *et al*., 2023) and impractical in many underground situations because of their size, weight and fragility (Slavova, 2012; Zlot and Bosse, 2014). Attempts were made to address the 3D-mapping deficiencies by use of photogrammetry (Pukanská *et al*., 2020), but, because this method is light-dependent, the specific texture (reflection, humidity) of the cave's walls and mineral deposits limits the possibility of its application (Fryer *et al*., 2005; Gautier *et al*., 2020; Liu *et al*., 2024).

During recent decades, 3D mapping has been revolutionized by the development of laser (LiDAR) technology, i.e. by the use of terrestrial laser scanners (TLS) (Caprioli *et al*., 2003; El-Hakim *et al*., 2004; Zlot and Bosse, 2014; Gallay *et al*., 2015; Konsolaki *et al*., 2020, Pisoni *et al*., 2022). However, the application of TLS also has its limitations (Pisoni *et al*., 2022). Firstly, TLS is typically mounted on a stationary tripod, and because of the complex cave geometry, many scanning stations are needed to achieve sufficient coverage and prevent "shadows" caused by occlusions in the point cloud (Zlot and Bosse, 2014). For example, Lindgren and Galeazzi (2013) needed 350 separate scans to produce effective overlaps between nine chambers in the cave network of Las Cuevas, in Belize. Secondly, dealing with the substantial size, weight and fragility of the equipment, and with the need to mount the scanner securely necessitate significant investments in operator care and time (Zlot and Bosse, 2014; Konsolaki *et al*., 2020). Thirdly, the processing of such large datasets can be extremely challenging (Gallay *et al*., 2015).

Thus, the latest 3D cave-mapping methodologies based upon ongoing development of geospatial technology involve Mobile Mapping Systems (MMS) (Di Stefano *et al*., 2021). Specifically, different versions of mobile LiDAR scanning (MLS) technology are becoming more popular (Acosta-Colón *et al*., 2019; Ullman *et al*., 2023; Ellmann *et al*., 2022; Vassilakis and Konsolaki, 2022; Rissolo *et al*., 2024; Liu *et al*., 2024). MLS involves the use of a handheld MMS instrument, based upon Simultaneous Localization and Mapping (SLAM) technology, which uses various strategies for mapping the scene while also tracking the device itself (Di Stefano *et al*., 2021; Grasso *et al*., 2023). This approach speeds up the data acquisition times and returns colorimetric information about the scanned environment. It takes advantage of IMU[1] measurements and it is commonly based on laser scanners (Hess *et al*., 2016) and RGB/-D images (Newcombe *et al*., 2011). Essentially, SLAM algorithms are used for tracking the trajectory of the platform in caves, and in other GNSS-denied environments, where use of satellite positioning is not feasible (Grasso *et al*., 2023). Point clouds generated employing this technology are constructed from paths computed using algorithms that combine image navigation with IMU integration (Pisoni *et al*., 2022). Although SLAM technology is becoming more widely available, there are still only a few localities where it has been applied to the 3D mapping of caves. In the resulting papers published so far, only some of the user-defined parameters (point density, number of polygons, length and shape of scanning path) and items of obtained morphological data (e.g. volume, length, width, height) essential for the interpretation of 3D mapping are provided (Table 1).

[1] *Inertial Measurement Units.*

In the Dinaric Karst region as a whole, spanning from high mountains to areas below present sea-level, more than 20,000 caves and pits have been identified (Hajna, 2019), offering substantial potential for tourism development (Bočić *et al*., 2006). However, the complex morphology and commonly inaccessible nature of these speleological features pose significant challenges for 3D mapping, such that only a few caves have yet been mapped. This paper focuses on the application of MLS in the 3D mapping of three different show caves within the Croatian segment of the Dinaric Karst. It aims to address challenges in cave 3D mapping, such as inaccessible terrain, complex geological formations and large amounts of data. Through the three case studies, this research illustrates how MLS technology can facilitate the derivation of comprehensive 3D cave models, offering insights into cave morphology and associated environmental conditions. The main objectives of research are to:

1. Evaluate the applicability of an MLS for 3D mapping of karst show caves with varied passage sizes and complexities;
2. Create detailed 3D models for chosen show caves;
3. Derive reliable values for the morphometric properties (length, area (A), volume (V), average passage width) of surveyed caves.

Study area

The study area is within the Croatian part of the Dinaric Karst region (Fig.1), characterized by thick, highly deformed, and well-karstified carbonate rocks (Vlahović *et al*., 2005; Korbar, 2009). This region features a well-developed deep vadose zone, containing large, vertical, and complex cave systems (Buzjak *et al*., 2018). Approximately 43.7% of Croatia is covered by karst, with a common and widespread occurrence of various speleological features (Bognar *et al*., 2012). Although 5,500 speleological objects are registered officially in the Cadastre of Speleological Objects of the Republic of Croatia (*see Reference* URL 1), the actual number of explored caves is estimated to exceed 10,000 (Surić *et al*., 2010). Among these, only 74[2] speleological sites have been developed as show caves (Fig.1).

Three show caves with varied morphological complexity and abundance of speleothems were selected to host the research (Fig.2).

Biserujka Cave is a small show cave, located in the northeastern part of Krk Island (Fig.1). Discovered in the early 19th century, the cave had a stone house built above its entrance during 1913 (Božić *et al*., 2009). Originally 6–8m deep, the entrance, is now accessed via a 10m concrete staircase, leading to a cave floor at about 30m above sea level. The cave is developed within deformed Late Cretaceous deposits, which are now inclined at 85° towards the north-northeast (Božić *et al*., 2009). Initial cave development is attributed to the corrosive action of water moving along fault fractures. Extending south-southwestwards for 110m from the entrance, the main channel consists of several segments: Entrance (pit), Great Hall, North Channel, Hall of Bridges, and Cimpres Hall (Fig.2A). Currently, the first 65m of the cave have been adapted to facilitate tourist access, under the jurisdiction of the Public Institution "*Natura Viva*".

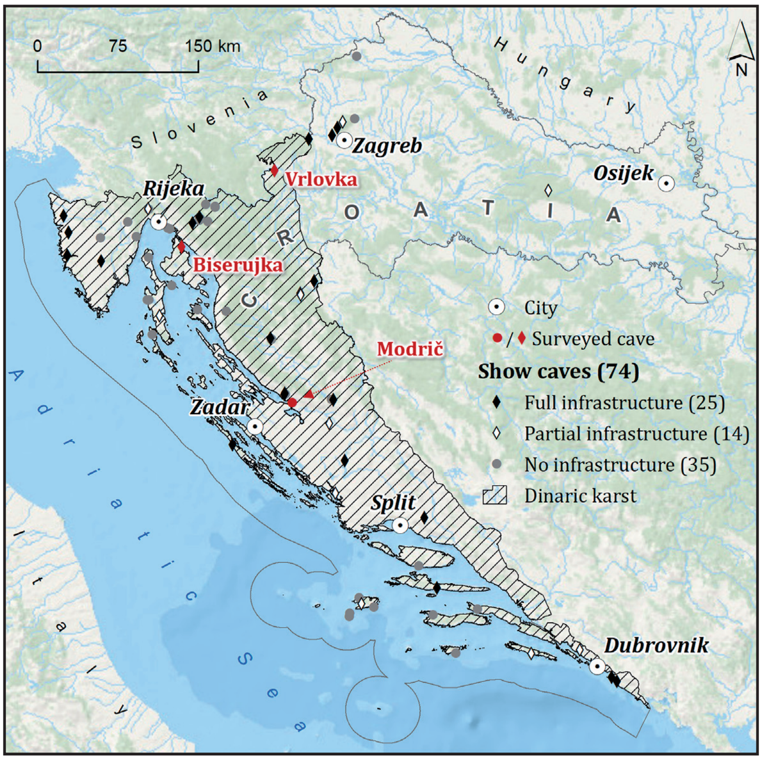


Figure 1: Locations of the three surveyed show caves in relation to all existing show caves in Croatia.

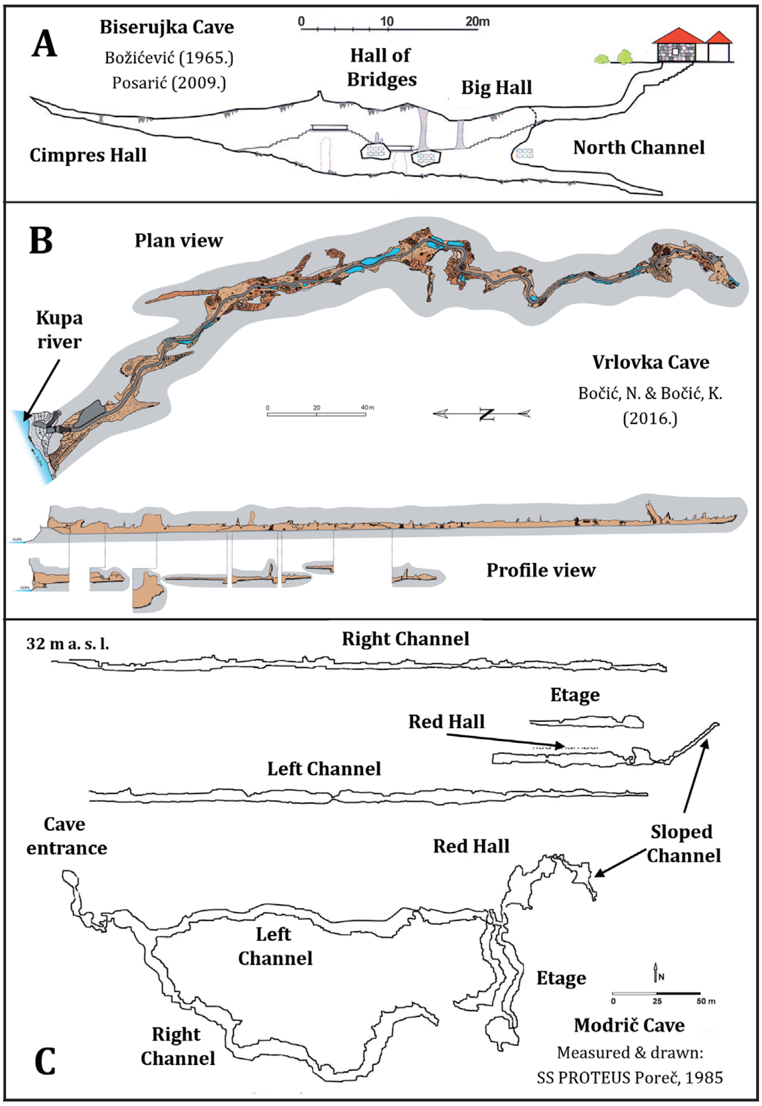


Figure 2: Existing 2D maps, based upon manually measured survey data: (A) Biserujka Cave, (B) Vrlovka Cave, and (C) Modrič Cave.

[2] *Number and location of show caves in the Republic of Croatia, according to the Bioportal of the Ministry of Environmental Protection and Energy of the Republic of Croatia. (see Reference: URL 1).*

With obvious entrances by the Kupa River near Ozalj, Vrlovka Cave was among the first caves to be explored in Croatia. It has been explored to a length of 380m, with 330m accessible to visitors, under the jurisdiction of the Public Institution "*Priroda*". Rich in speleothems, Vrlovka features calcite formations such as curtains, cascades, stalagmites, and stalactites. Geomorphological and sedimentological features within the cave have attracted public attention since 1928, leading to it becoming a popular tourist destination. In 1962, it was designated as a geomorphological natural monument. Formed within thickly bedded Jurassic limestones, the cave consists of a main channel with a spacious entrance hall and four additional chambers connected by narrower passage sections (Fig.2B). It is classified as a simple speleological structure, with two entrances facing the Kupa River. Show cave visitors use the main entrance, which opens into a channel extending west-northwest to east-southeast (Ozimec and Basara, 2022). Length of the main and secondary channels totals 479.5m (or 473.3m in plan projection), with a height differences of 22.2m between the highest and lowest points and 6.2m between the highest entrance and the lowest point; the plan distance between the cave's farthest points is 289m (Bočić and Barudžija, 2022). According to the most recent measurements and mapping (Fig.2B and N. Bočić Archive), the total area of Vrlovka Cave is 2,396.7m², with a total cave volume of 8,533.2m³.

Modrič Cave is a horizontal system in the southwestern foothills of Velebit Mountain, about 120m from the Adriatic Sea coastline, at an elevation of 32m above sea level. Formed in fractured limestones of Cenomanian–Turonian age, it extends eastwards and branches into two main passages (left/north) and right/south), with a total length of 829m (Kuhta *et al*. 1999; Fig.2C). All parts of the cave are rich in speleothems, particularly many active stalactites and stalagmites and several massive columns. A height difference of 29m separates the lowest point in the central part of the Left Channel from the highest point reached in the Sloped Channel (Fig.2C). The southern (right) passage contains evidence of human activity, such as bones and pottery, with bone fragments from an Upper Pleistocene fauna, including a skull of the cave bear *Ursus spelaeus* (Malez, 1987). Categorized as a geomorphological monument, the cave is part of the Velebit Nature Park.

Methods

The methodology applied can be divided into field 3D mapping of show caves using MLS (Fig.3A), and data processing plus creation of 3D cave models (Fig.3B–E).

3D mapping of show caves with MLS

3D mapping of three selected show caves was conducted using the GeoSLAM Zeb Revo MLS. This compact and lightweight LiDAR scanner facilitates the collection of up to 43,000 points per second, with a scanning range of 30m (*see Reference* URL 5). Due to the integration of collected LiDAR data with a professional-grade IMU and the SLAM algorithm, the Zeb Revo can reconstruct its trajectory and surrounding objects accurately, even without an external positioning system (Giordan *et al*., 2021). Featuring a wide field of view (360° vertical × 270° horizontal), this scanner is ideally suited for capturing data in small and confined natural cavities (Lozano Bravo *et al*., 2023; Grasso *et al*., 2023) or in man-made underground voids (Sammartano and Spanò, 2018; Fahle *et al*., 2022).

The first of the chosen sites to be surveyed was Biserujka Cave, on 05 May 2022. Because of its small size and wide underground passages, the 3D-mapping process took only 12 minutes and 39 seconds. Given the cave's simple morphology, loop closure during the 3D mapping was straightforward, and there were no narrowings or other complex segments that could complicate the surveying process. Whereas the upper section of the cave was surveyed from the tourist path, the lower part and a few smaller, narrow, side passages had to be accessed and surveyed from beyond the path. The detailed survey plan is shown on Figure 4A.

3D mapping of Vrlovka Cave was carried out on 10 July 2022. Although significantly longer than Biserujka Cave, this cave is also characterized by a relatively simple morphology that allowed perfect loop closure. The 3D scanning loop started on a plateau just outside the cave entrance, from where the 3D scanning trajectory followed the main cave passage to its terminus before returning to the starting location, completing the loop. The duration of the 3D mapping operation was 33 minutes and 22 seconds, and the detailed survey plan produced is shown on Figure 4B.

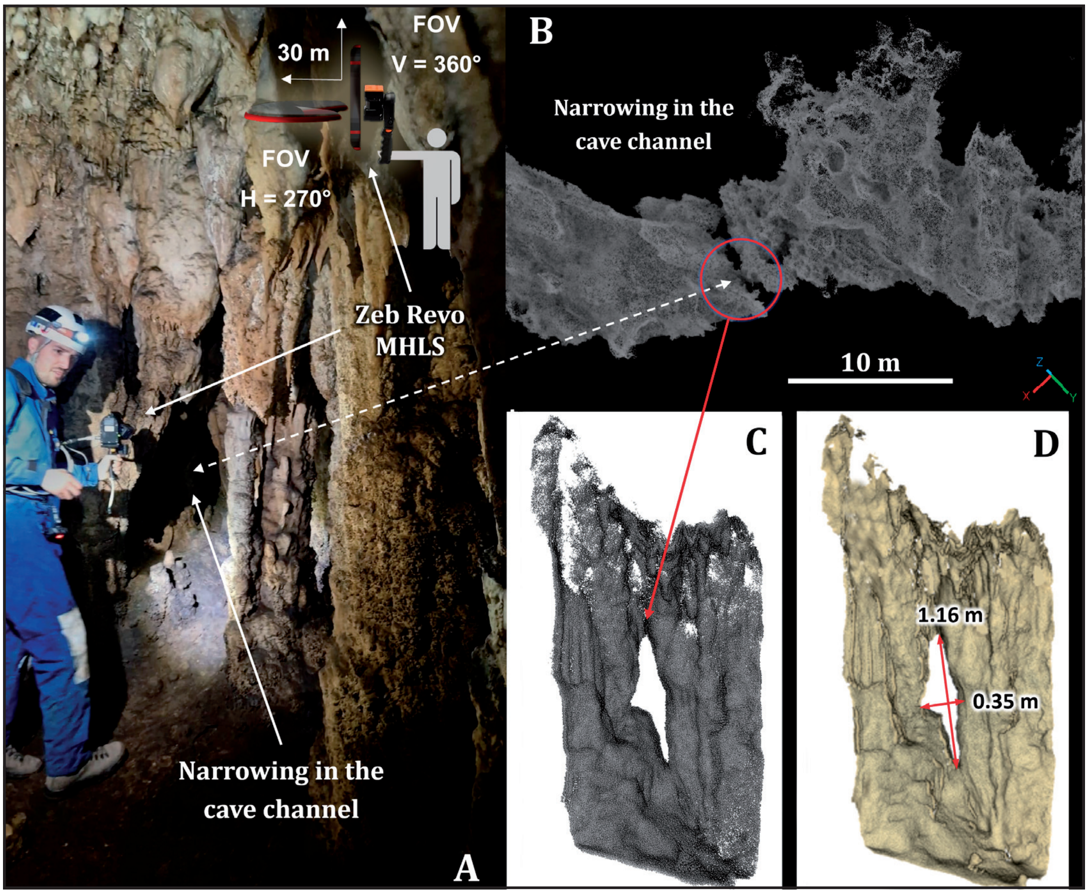


Figure 3:
Steps within the methodology applied to the 3D mapping of show caves:
(A) field 3D mapping using MLS;
(B) registration and filtering of collected point cloud data;
(C) calculation of point cloud normals;
(D) creation of the 3D model (meshing) and
(E) calculation of selected cave morphometric characteristics.

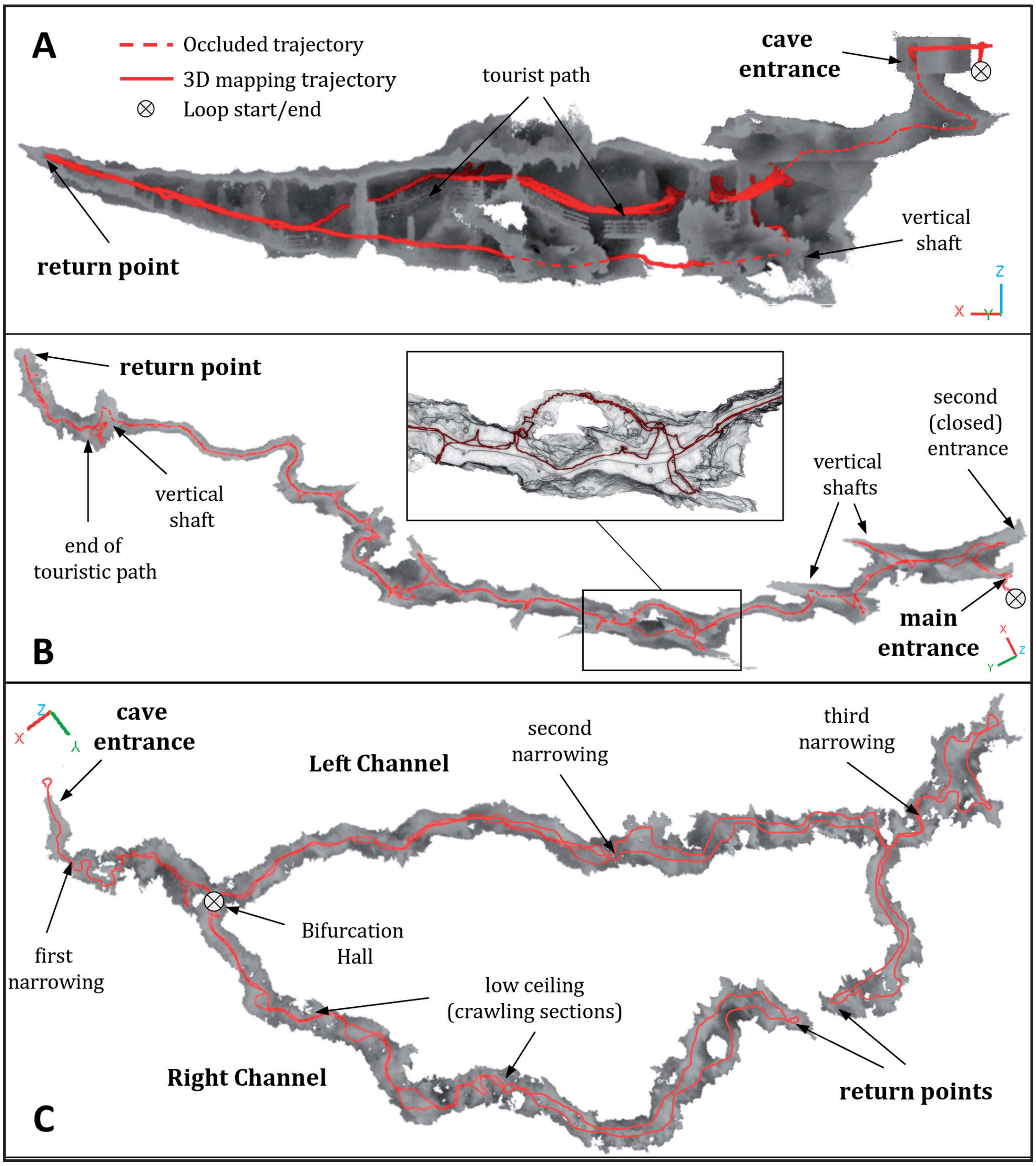


***Figure 4**: Survey plans derived from the 3D mapping of:*
(A) Biserujka Cave – profile view;
(B) Vrlovka Cave – ground plan view;
and
(C) Modrič Cave – ground plan view.

Surveying Modrič Cave was more challenging and time-consuming, primarily because of its branching morphology, several very low and narrow segments, and the absence of any tourist paths or other anthropogenic modifications that would facilitate movement through the cave. To accommodate the complexity of the cave morphology, the 3D mapping was divided into three sections, which had an identical initialization point but covered distinct parts of the cave. Because of the presence of several narrow passages and contrasting with the procedure used in the previously surveyed caves, , the loop start/end location was placed within the cave at the Bifurcation Hall, located at the branching of the left (tourist) and right cave channels. The initial 3D mapping, conducted on 07 July 2022, took 1 hour, 41 minutes, and 18 seconds. However, to rectify issues with loop closure, an additional 3D mapping traverse of the branching part of the cave was performed on 07 March 2023, with a duration of 18 minutes and 16 seconds. Poor loop closure during the initial 3D mapping resulted in an apparent and significant displacement of the surveyed cave channels. Hence, the additional scanning in Modrič Cave was carried out in such way that whole branching segment was surveyed within a single traverse. Additionally, it should be noted that, because of their steepness and complexity, two smaller channels (Sloped Channel and Etage), which are continuations of Red Hall (Fig.2C), have not been mapped. A detailed survey plan based on the initial and second 3D mapping of Modrič Cave is shown on Figure 4C.

Data processing and creation of 3D cave models

Registration of all scans collected during the field 3D cave mapping was carried out using Faro Connect software, which supports automated registration of scans collected using the MLS. Whereas Biserujka and Vrlovka caves were mapped with just one scan, the larger and more complex Modrič Cave had to be mapped via several partially overlapping scans.

The raw scans and their trajectories were registered using GeoSLAM Stop and Go georeferencing registration, with the Capture environment set to *Tunnel*. Registered point clouds were exported in E57 file format, containing stored information about point cloud normals, as collected by the MLS.

To create the detailed 3D models of the three surveyed caves, the registered point clouds were post-processed using the CloudCompare (CC) and MeshLab (ML) open-source software. This systematic post-processing included the following steps:

(Step 1) *calculation of point cloud normals;*

(Step 2) *surface reconstruction;*

(Step 3) *final 3D model filtering;*

(Step 4) *calculation of morphometric cave properties*.

Detailed schematic representations of the post-processing methodology and of important user-defined parameters are presented in Figure 5.

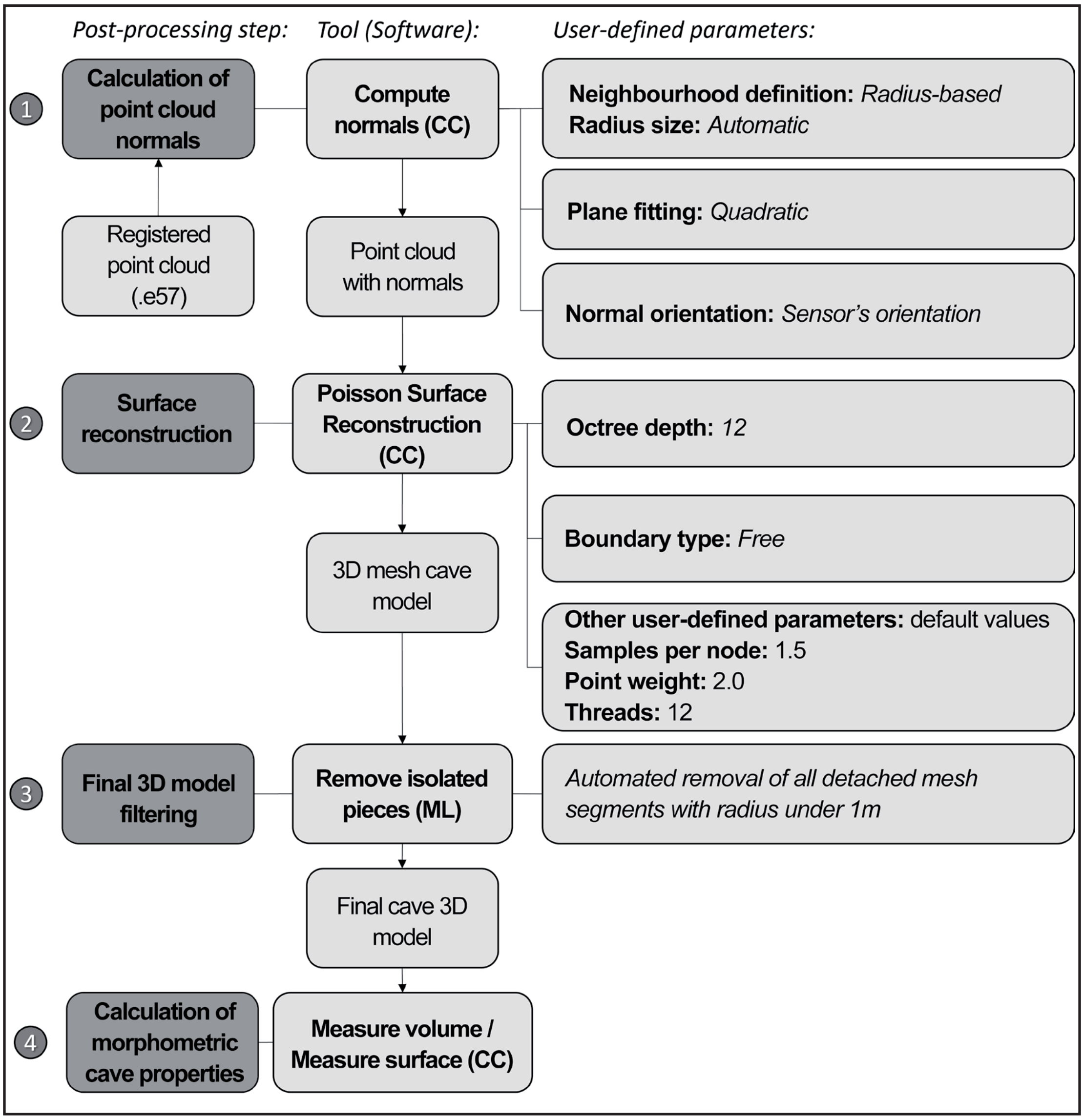


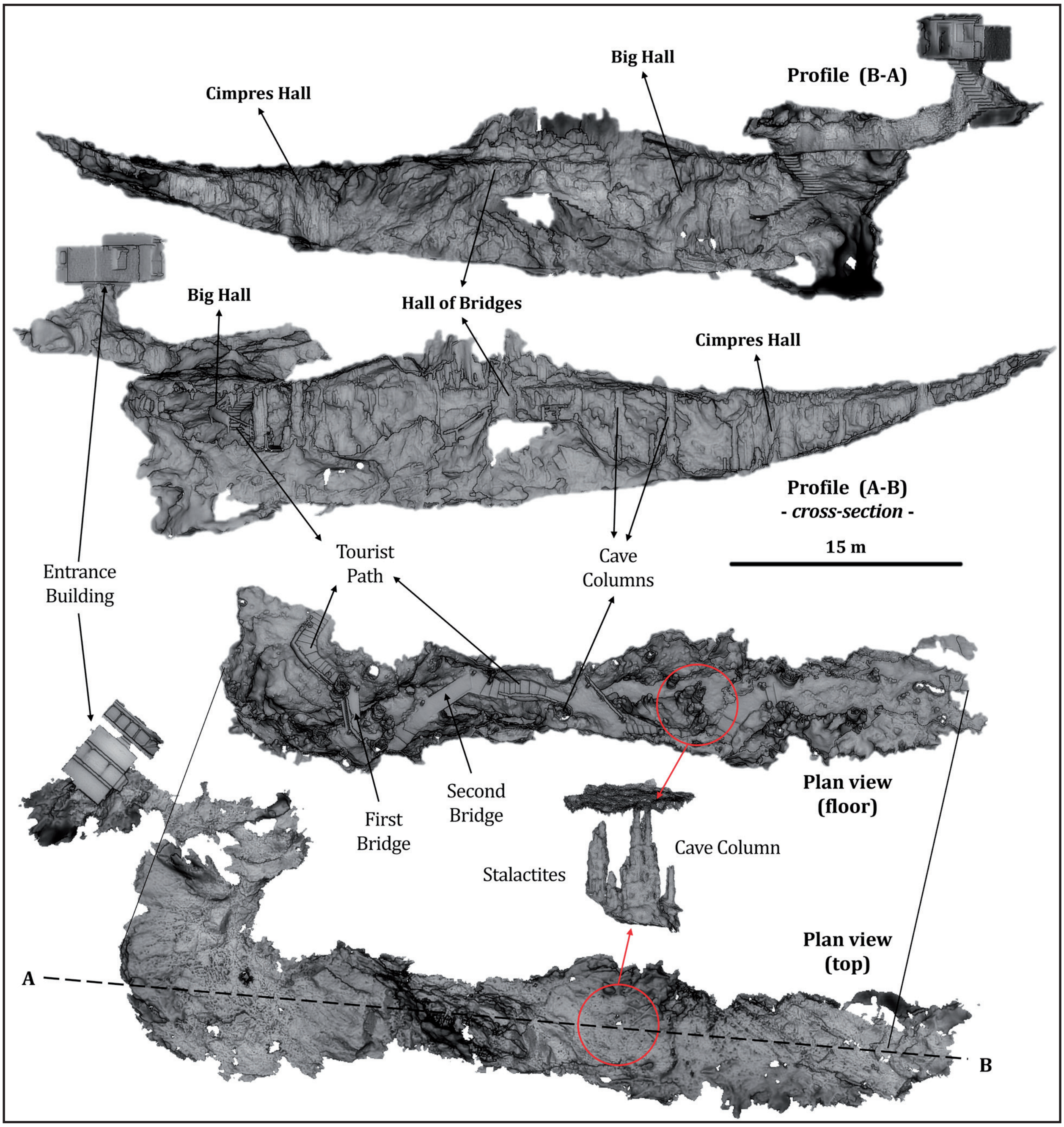
***Figure 5**: Post-processing methodology applied for the creation of the final 3D cave models using CloudCompare and MeshLab open-source software.*

Calculation of point cloud normals (Step 1 above and in Figure 5) represents a crucial step in creation of detailed 3D cave models, because point cloud normals provide information about the orientation of each point in the point cloud. Performance of surface reconstruction (meshing) is affected substantially by point cloud normals, because incorrect normals can lead to creation of significant errors and holes in 3D models. Reflecting their complex morphology, caves are among the most challenging objects for meshing, because inadequate calculation of point cloud normals can result in significant errors within the surface reconstruction (Idrees and Pradhan, 2016). To achieve optimal point cloud normal estimation, iterative calculations were carried out using different combinations of user-defined parameters. Calculation of point cloud normal was performed in CC software using the *Compute normals* tool, where user-defined parameters are related to (1.1.) *neighbourhood definition*, (1.2.) *plane fitting* and (1.3.) *normal orientation*. *Neighbourhood definition* (1.1.) refers to the method used to select nearby points for calculating the normal vector of each point in the cloud. After several iterations, the radius-based neighbourhood was selected, with the optimal radius calculated automatically, based on the point cloud's characteristics. The second user-defined parameter is *plane fitting* (1.2.), which approximates the local surface by fitting a plane to the neighbouring points. The *Quadratic* method was applied for this parameter, because it is most effective for curved surfaces such as complex cave walls. Iterative normal calculation revealed that *normal orientation* (1.3.) is a critical parameter for cave surface reconstruction, with a direct influence upon the percentage of incorrectly oriented normals, which appeared as black areas in the point cloud. Among the available options, only the sensor's orientation produced satisfactory results for complex cave morphology. In contrast, other methods such as *preferred direction* resulted in a high prevalence of incorrectly calculated normals. Notably, for the sensor's orientation, the point cloud must contain sensor position information, which is not stored within the LAS file format but is available in the E57 file format. After determining the optimal user-defined parameters, point cloud normals were calculated for all three surveyed caves using consistent settings: a quadratic local surface model, sensor orientation, and a high minimum spanning tree (kNN = 12), where kNN represents the "k-nearest neighbours", the number of neighbouring points considered when calculating the normals of a point in a point cloud.

Surface reconstruction (step 2 above and in Figure 5) or meshing in CC software was performed using the Poisson Surface Reconstruction (PSR) algorithm, a triangular mesh generation algorithm that allows accurate reconstruction of complex shapes and surfaces (Kazhdan and Hoppe, 2013). The most important user-defined parameter for cave surface reconstruction in PRC is *Octree depth* (2.1.), which controls the level of detail (LoD) in the surface reconstruction. Although a higher octree depth results with the greater LoD of 3D cave models, it increases processing time significantly, or can even cause the CC software to crash[3].

[3] *CloudCompare crashed repeatedly during PRC application when an octree depth greater than 15 was applied to any collected cave point cloud.*

***Figure 6**: Selected views of the created 3D model of Biserujka Cave.*



The second user-defined parameter in PRC is *Boundary type* (2.2.), which defines how the borders of the point cloud will be handled during surface reconstruction. To ensure the consistency of created 3D models, identical user-defined parameters within the PRC algorithm were used for reconstruction of natural surfaces for all three of the surveyed show caves. Those include the high Octree Depth (12) and Free Boundary Constraints.

Final filtering (step 3 above and in Figure 5) involved removing meshing artifacts, created by outlier points, from the final 3D cave models. Automated mesh cleaning and filtering were performed in ML software, using a *remove isolated pieces* tool. This tool was employed to remove all small, detached, segments with a radius less than 1m.

The final created 3D models were used in the CC software for the calculation of the main morphometric properties of the surveyed show caves (step 4 above and in Figure 5). This included calculations of area (A) and total cave volume (V), as well as measurements of cave length and width. Whereas volume was calculated for the entirety of the cave models, area was calculated only for the cave floor surfaces. Additionally, morphometric properties were calculated for separate chosen parts of the surveyed caves, such as cave columns, cave narrowings, vertical shafts, specific channel segments, and so on.

Results

3D model and morphometric characteristics of Biserujka Cave

The 3D survey of Biserujka Cave resulted in a point cloud consisting of 26,825,815 collected points, based upon which a detailed 3D model was created (Fig.6)[4]. Because Biserujka is a relatively small cave, the created 3D model depicts fine details successfully, including tourist-related infrastructure (entrance building, stairs, paths, bridges, fences, and lights) and natural features (stalagmites, stalactites, cave columns, etc.). According to the created 3D model, the total area of Biserujka Cave is 462.42m², and its volume is 1,475.05m³. Biserujka is 83m long, whereas its width varies significantly, from just 1m in the entrance channel, to a maximum width of 12.21m in the "*Big Hall*", with an average of 8.87m.

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[4] *The created 3D model of Biserujka Cave can be accessed and downloaded from Sketchfab. (See Reference URL 2.)*

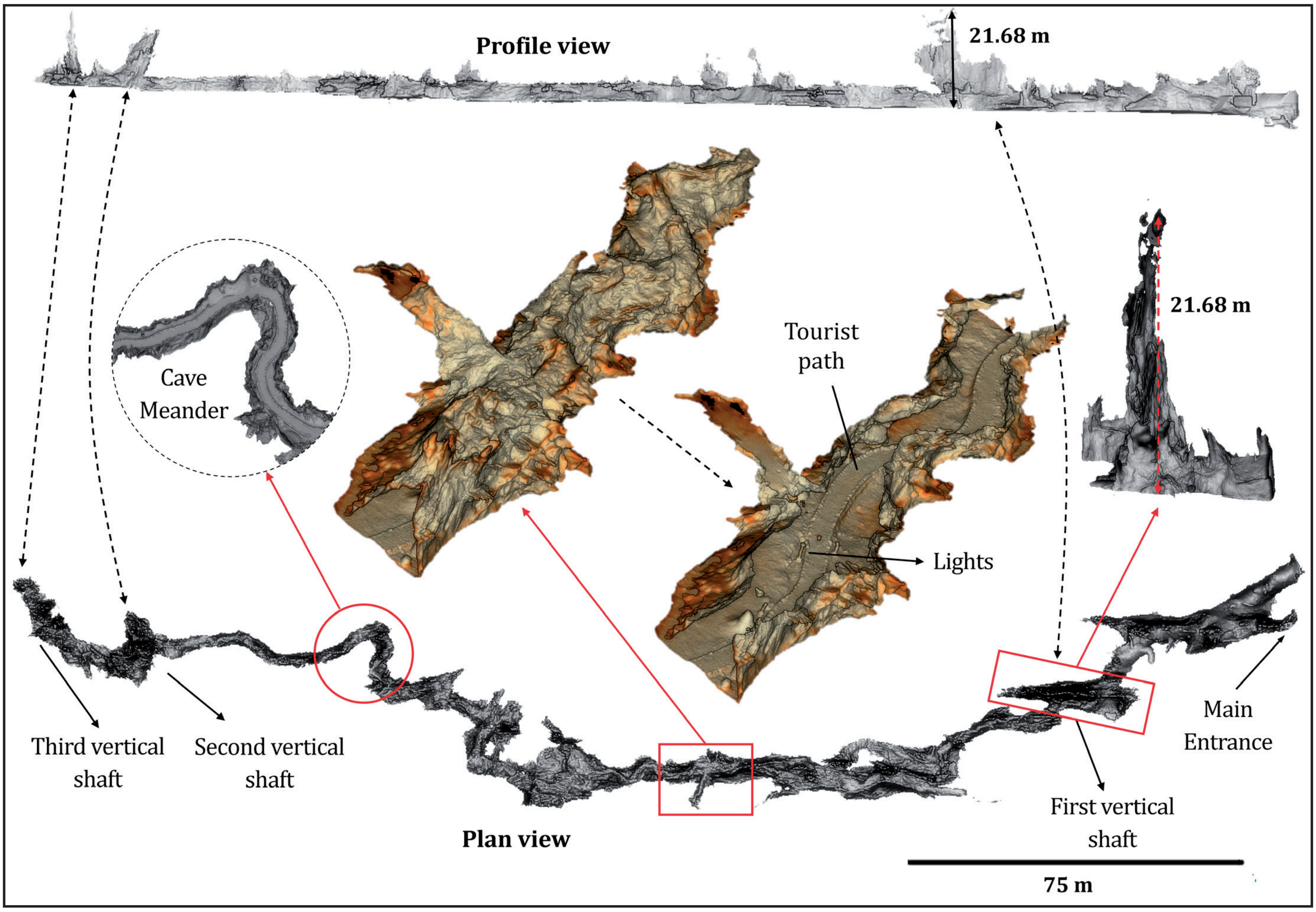

***Figure** 7: Selected views of the created 3D model of Vrlovka Cave.*

3D model and morphometric characteristics of Vrlovka Cave

Detailed 3D mapping of Vrlovka Cave produced a point cloud containing 70,507,226 collected points, which were used to create a comprehensive 3D model[5]. The profile and planar views of this model are illustrated in Figure 7. Vrlovka Cave covers an area of 2,404.89m² and has a volume of 4,651.6m³, making it 80% larger than Biserujka Cave in terms of area and 68% larger in terms of volume. Vrlovka Cave consists of a single meandering primary channel approximately 380m long. This channel was part of a relict drainage system that directed rainwater from the surrounding slopes above Kamanje to the current Kupa riverbed (Ozimec and Basara, 2022), resulting in the elongated and meandering cave morphology. The width of the main channel ranges from 2–3m in narrow meandering segments up to 15m in wider parts of the cave. Although the main cave channel is predominantly horizontal and flat, with a nearly constant height of about 3–4m, several vertical shafts are observable in the profile view (Fig.7). These vertical shafts, some of which exceed 20m in height, represent potential connections to surface dolines. It should be noted that upper portions of those vertical shafts were mapped unevenly, resulting in their potentially inaccurate representation and underestimation of their vertical extent. Despite the size of Vrlovka Cave, the created 3D model successfully represents the tourist infrastructure (path and lights), as well as natural features, such as cave columns, cascades or dried and active pools.

[5] *The created 3D model of Vrlovka Cave can be accessed and downloaded from Sketchfab. (See Reference URL 3.)*

3D model and morphometric characteristics of Modrič Cave

The 3D survey of Modrič Cave produced a point cloud consisting of 197,248,584 collected points. Due to processing constraints, the data had to be downsampled by some 60%, resulting in a point cloud with 75,478,340 points. This downsampled point cloud was used to create a detailed 3D model, with the planar and profile views shown in Figure 8[6].

Modrič Cave, the largest and most complex of the three surveyed show caves, posed the greatest challenge for both 3D mapping and subsequent data processing and model creation. The cave's total length is approximately 758.83m[7], with an average width of 8.86m (maximum width = 14.37m, minimum width = 1.38m). With an area of 4,993.1m² and a volume of 13,309m³, Modrič Cave surpasses the other two caves significantly in both size and complexity. Approximately 50m from the entrance, the cave branches into two separate channels. The left channel, being longer, wider, and higher than the right channel, is used for show cave purposes. A few metres beyond the second narrowing, there is a vertical shaft next to one of the largest cave columns, which stands 8.5m high and is 1.5m wide (Fig.8E). About 50m before its end, the left channel branches again into two directions: leftwards through a narrowing into the Red Hall, and rightwards towards the end of the right channel (Fig.8F). The ends of the left and right channels almost merge, with only 4.24m of rock separating them. Despite its shorter length, the right channel is characterized by several narrower and lower segments, due to which it is not open for tourist visits.

[6] *The created 3D model of Modrič Cave can be accessed and downloaded from Sketchfab. (See Reference URL 4.)*

[7] *Total length of Modrič Cave, not including Sloped Channel and Etage.*

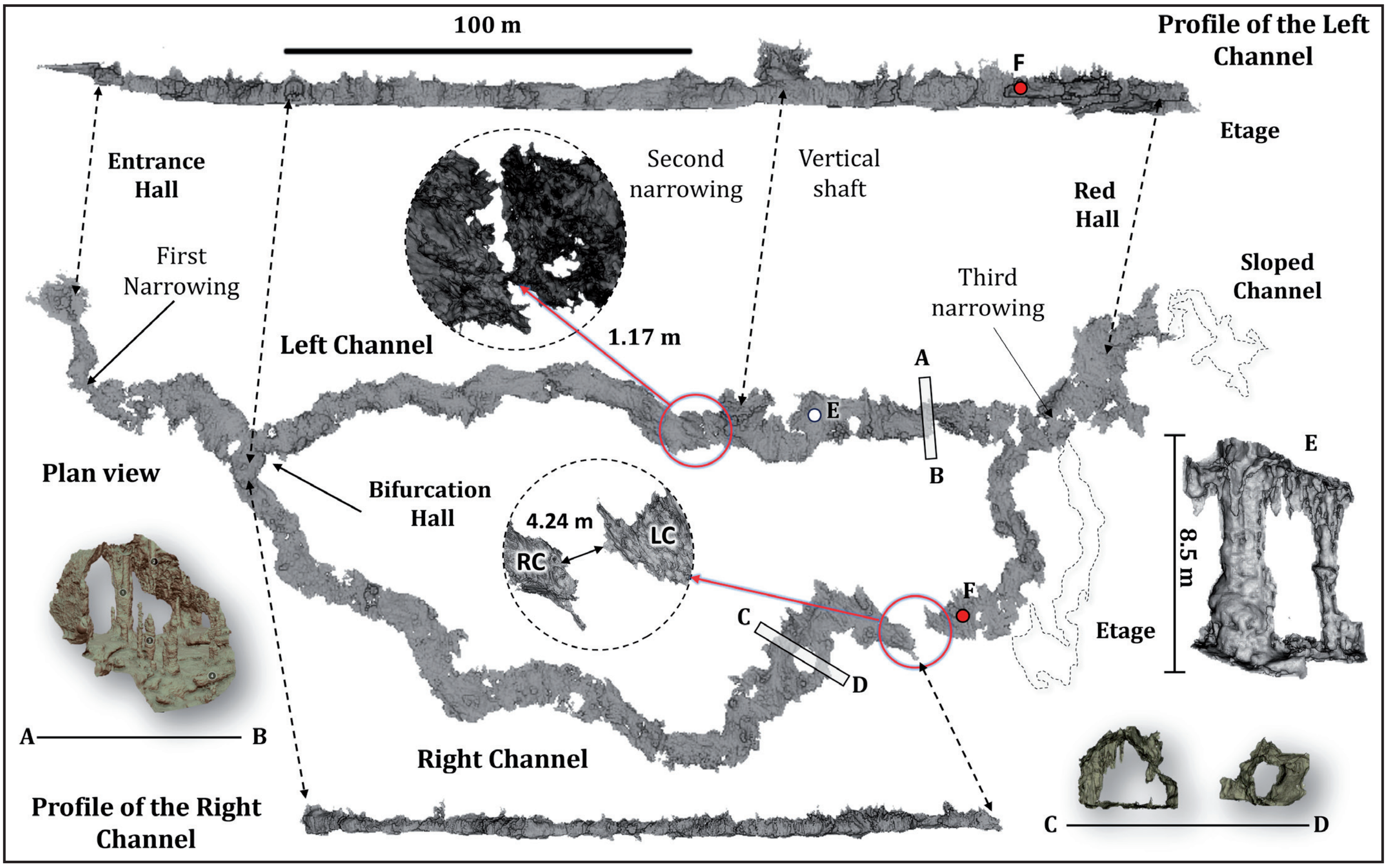

Figure 8*: Selected views of the created 3D model of Modrič Cave.*

Discussion

Comparison of MLS-based 3D cave modelling with traditional survey methods

The results of this study are consistent with prior research in the domain of 3D cave mapping, particularly regarding the application of MLS technology (Table 1). Several studies have substantiated the efficacy of MLS in cave surveying, underscoring its capacity to capture high-resolution spatial data within complex environments where conventional methods might be inadequate (Idrees and Pradhan, 2016; Fahle *et al*., 2022). The study conducted has demonstrated that MLS-based 3D cave models are significantly more detailed than models created by traditional cave mapping methods. This is best demonstrated by comparison of the area and volume of Vrlovka Cave, calculated by traditional cave mapping techniques (Bočić and Bočić, 2016.) with values derived from the MLS-based 3D model. Whereas the difference between the area calculated from the 2D model of Vrlovka Cave, created using traditional mapping techniques in the COMPASS cave survey software (*see Reference* URL 6), and the 3D model derived from the MLS-based 3D cave survey is only around 1%, the difference in terms of volume is significantly higher. According to the comparison between the volume of the existing 2D model (V = 8,533.2m^3) and the 3D model created in this study (V = 4,651.6m^3), the 2D model overestimates the total cave volume by almost 50%. This significant overestimate probably reflects the fewer measured points necessitating a generalized and oversimplified cave representation that exaggerates its volume. These findings raise critical concerns regarding the accuracy of volume calculations for all caves measured using traditional surveying methods. The potential for substantial discrepancies underscores a need to re-evaluate previous cave survey data and adopt more-accurate technologies, such as MLS, for future cave volumetric assessments.

It is important to emphasize that the relationship between volumes calculated using data obtained using traditional mapping techniques and those derived from MLS-based cave 3D survey remains insufficiently explored. Consequently, further research is required to compare volume measurements across a larger dataset of speleological objects, encompassing ranges of size and morphological complexity.

Advantages and limitation of 3D cave mapping with MLS

Based on the surveys conducted, four advantages of 3D cave mapping using an MLS can be identified: (1) rapid surveying; (2) high LoD and model completeness; (3) capability to survey vertical shafts; and (4) high accuracy of measurements.

Cave mapping using MLS is significantly more efficient compared to the use of traditional cave survey techniques. While small caves can be mapped with MLS within a few minutes (Biserujka Cave – 12.39 minutes), larger caves can be surveyed within just one to two hours (Vrlovka Cave – 33.22 minutes; Modrič Cave ~ 2 hours). Furthermore, the density of the collected point cloud enables the creation of 3D models with a very high LoD, which is challenging to achieve using traditional methods that capture only a limited number of data points at each measurement location within the cave (Ballesteros *et al*., 2013; Mattes, 2015; Giordan *et al*., 2021). High LoD is crucial not only for 3D modelling of entire cave systems, but also for creating high-quality 3D models of speleothems, vertical shafts, narrow passages, and other individually significant cave features. Moreover, use of MLS facilitates the mapping of vertical shafts and other difficult-to-access or potentially hazardous cave segments. This capability is demonstrated by the successful survey of three vertical shafts in Vrlovka Cave and one in Modrič Cave, where in some areas heights exceed 20m. Additionally, MLS application leads to highly accurate representations of cave morphology, and enables near-exact calculation of various morphological parameters, such as surface area and volume.

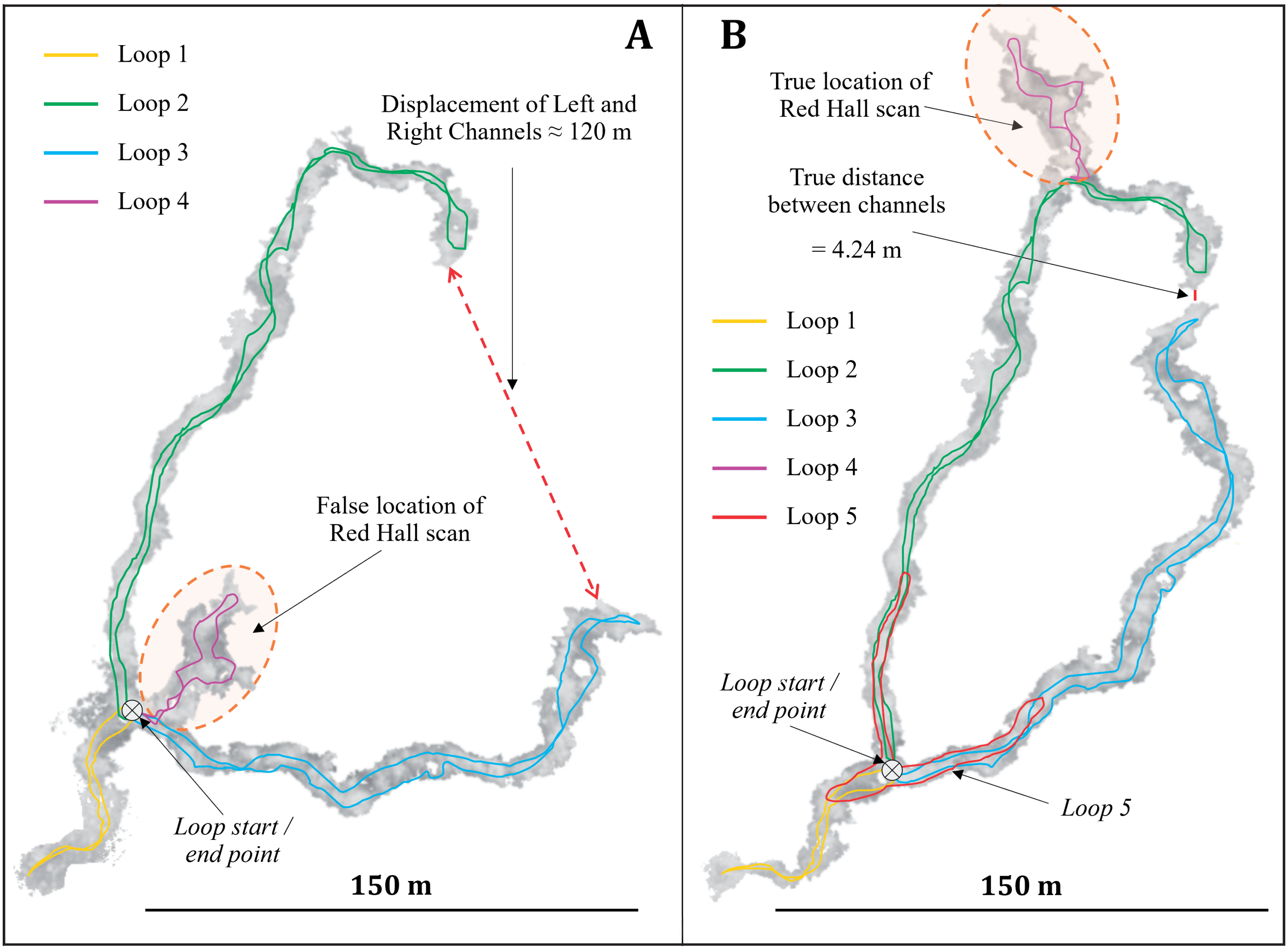

***Figure 9**:*
(A) Erroneous displacement of the cave channels displayed in the first created model of Modrič Cave, caused by incorrect loop closure;
(B) the corrected point cloud registration displaying a more realistic survey overlap.

However, this study has also shown that 3D cave mapping with a MLS has certain limitations, including: (1) challenges with loop closure; (2) limited surveying range; (3) difficulties in the surveying of complex cave segments; and (4) challenges related to data processing. As demonstrated by the initial survey of Modrič Cave, inadequacy of loop closures linked to insufficient overlap between neighbouring MLS survey traverses can result in the creation of significant errors in cave geometry and morphology reconstruction. In this case, poor loop closure introduced an apparent 120m displacement between the left and right cave channels, and led to erroneous positioning of the Red Hall (Fig.9A). Following an additional survey of the cave's branching section, with improved overlap, the point cloud registration was corrected, resolving the issue of exaggerated displacement between the left and right channels (Fig.9B). It is recommended here that, when surveying branching cave segments with MLS, the entire branching area should be scanned in a single continuous pass to minimize the risk of introducing unrealistic displacements of channels. Although MLS succeeded in surveying the high vertical shafts in Vrlovka and Biserujka caves, its 30m range is inadequate for successful 3D mapping of high underground channels such as those typical of some larger cave systems in the Dinaric Karst (e.g. the Crnopac Cave System (*see Reference* URL 7)). Therefore, in caves that include such features, MLS should be conducted using scanners with a range of 100m or more. Additionally, complex segments, including those that are tight/narrow (Figs 3C and 3D), or the low passages in Modrič Cave, remain obstacles that make 3D mapping challenging and potentially hazardous both for equipment and for surveyors.

Conclusions

This study has demonstrated the significant advantages of using MLS for the 3D mapping of show caves within the Dinaric Karst region. The GeoSLAM Zeb Revo system was applied successfully to generate high-resolution, accurate 3D models of cave interiors, offering detailed morphometric data that could not be achieve using traditional surveying methods. The MLS system provided high-quality models of the selected caves, with a LoD sufficient to support scientific analysis. The accuracy of the created 3D models enables measurements of cave features, contributing to a deeper understanding of the caves' morphologies. The study's results revealed several key findings:

- Mapping of Modrič Cave highlighted some of the limitations of applying MLS technology in environments that include highly irregular geometries and confined spaces. The requirement for a second scan to rectify loop closure issues underscores the importance both of careful planning and of recognition of the potential need to apply supplementary techniques (e.g. TLS or photogrammetry) in such environments.
- The study underscored the challenges associated with the large data volumes generated during creation of MLS scans, particularly in larger cave systems. The need for robust data processing tools and significant computational resources was evident, emphasizing the importance of post-processing capabilities in ensuring the high quality and usability of created 3D models.

- MLS-based 3D cave modelling has demonstrated that traditional cave mapping methods can lead to significant overestimation of cave volume, as exemplified by the results from Vrlovka Cave. Such substantial discrepancies underscore the need to re-evaluate previous data and adopt more-accurate technologies, such as MLS, to enable future cave volumetric assessments.

Given that all the caves are located within protected areas, the high-resolution 3D models generated in this study hold significant potential for use as part of ongoing conservation efforts. These models can be employed as accurate tools to support monitoring and help assess changes in cave morphology, including the condition of speleothems over time. By providing a detailed baseline, the models enable detection of subtle alterations that might result from environmental factors, human activity, or natural processes. Exploitation of this capability is crucial for ensuring the preservation of these delicate structures and maintaining the integrity of the caves' natural heritage.

In conclusion, whereas MLS technology presents some challenges, particularly in data processing and in mapping within complex cave environments, its advantages far outweigh the limitations. The ability to create detailed, accurate, 3D models offers significant benefits for the scientific study, conservation, and sustainable management of caves. Future research should focus on optimizing data processing techniques and exploring the integration of MLS with other surveying technologies, further to enhance the accuracy and applicability of 3D cave mapping.

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