Mapping and geomorphometric analysis of 3-D cave surfaces: a case study of the Domica Cave, Slovakia

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Abstract—**Recent development in the laser scanning technology has provided new tools and methods for a very accurate and cost-effective way of mapping complex volumetric landscape features such as caves. In the presented case study, we use the laser scanning point cloud data representing over 1,500 meters of the Domica Cave in Slovakia to demonstrate the methodology of reconstructing the 3D digital cave surface at a high-level of detail. The digital 3D model was generated for a particular section of the cave. The model was used to analyze mean curvature of the cave surface at multiple levels of scale. The approach was performed in open-source software.**

I. INTRODUCTION

Caves represent specific underground landscape features which have a longer geomorphological memory than the superficial landforms. Studying their morphometry and genesis often provides clues for explaining also the evolution of the above-surface landscape [10]. Traditionally, the caves were mapped with mine surveying tools based on tacheometric principles and levelling [15]. With these approaches, the main principle is relatively straightforward to measure the general azimuth, slope angle, length and size of the underground corridors every few meters. The methods are applicable even in very narrow and difficultly accessible parts. However, the survey requires long time and physical effort of the surveying team. Also capturing the detail of the corridors and domes was based on expert manual drawings and sketches which potentially leads to inaccuracies.

Recent development in the laser scanning technology enabled rapid and accurate mapping of caves with an unprecedented level of detail. Terrestrial laser scanners (TLS) acquire millions of points in a single scan resulting in a three-dimensional (3-D) point cloud within a few minutes. TLS has been used in previous studies to obtain accurate three dimensional models of caves. These studies were motivated by the need for improved cartographic visualization and geomorphological analysis [5, 6]. Others have used TLS for archaeological and zoological research [1] and for heritage management and tourism [4, 23]. Some recent studies go further and combine the TLS data with other spatial data, for example, cave photography [18], orthotermography [3] or data from the surface above the cave [16].

The main challenge is in processing such a large amount of point measurements and generating 3D surfaces from them [16, 19, 20]. A good choice of software tools exists for rapid visualization of point cloud data and their basic processing (e.g., LAStools[1], lidarview[2], Bentley Pointools[3]). The tools enable efficient visualization and basic measurements of the cave 3D geometry such as the length, width, and height of a corridor, relative height of corridors, cross-sectional profiles which was explored in several studies. However, more complex analysis of the cave system requires digital reconstruction of the 3D cave surface and its integration with superficial data [16, 20, 21]. The concept of geographic information systems (GIS) is well suited for this purpose as it enables handling various geospatial data and naturally comprises tools for their analysis including geomorphometry.

Contemporary methods of digital geomorphometry are based on analyzing 2.5 surface models generated preferentially in a raster format (i.e. rectangular grid) [14]. While this approach is sufficient to handle most of the superficial landforms it poses constraints in handling landforms of a complex 3D shape such as caves. Such objects need to be modelled in 3D in different software and afterwards they can be imported into GIS. Examples of tools enabling the 3D visualization comprise NVIZ in GRASS GIS [12] or ArcScene in ArcGIS [9]. However, limited options are available in terms of analyzing the shape of a 3D surface in GIS packages and other software has to be

1 http://rapidlasso.com/lastools/
2 http://lidarview.com/
3 http://www.bentley.com/en-US/Promo/Pointools/pointools.htm?skid=CT_PRT_POINTOOLS_B

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explored to perform the analysis, for example, Meshlab[4], Blender[5], Geomagic Studio[6].

In this paper, we show preliminary results of reconstructing a 3D digital cave surface model and analysis of the 3D surface morphometry based on data acquired within terrestrial laser scanning of the Domica Cave in Slovakia. The research is conducted within the national research project titled: New methods of spatial modelling with laser scanning data and 3-D GIS (Nr. APVV-0176-12[7]).

II. Study site

The study area comprises the Domica Cave situated at the south-western edge part of the Slovak Karst near the state border of Slovakia and Hungary (Fig. 1). The total length of the cave is almost 5400 metres, however, its further continuation into the Hungarian Aggtelek Karst (the Baradla Cave) generates a multi-level single genetic cave system as long as 25,000 metres. The Domica cave evolved within several levels ranging between 318 - 341 meters a. s. l. It is the beginning part of the cave system formed by corrosive-erosive action of fluvial waters and temporary streams which sink underground at the contact of the Middle Triasic white limestones and the Pontian fluvio-lacustrine gravel-sand-clay sediments [2, 8]. The cave was inhabited by the Neolithic people but after a natural blockage of the entrance the cave was rediscovered by Ján Majko in 1926. The showcave part is accessible since 1932 and presently it is over 930 metres long. The cave was thoroughly mapped in 1960s by [8] and the last surveying was done by the Geological Survey, national enterprise, Spišská Nová Ves in 1976. The cave system named Domica-Baradla is a listed UNESCO Natural Heritage Site since 1997. Laser scanning of the cave provided non-disturbing means for highly detailed parameterisation of the cave corridors enabling to study specific landforms such as fluvial channels carved into the ceiling, faults, and abundant shapes of speleothems.

III. Laser scanning the cave

The data used in the presented study were acquired with a terrestrial laser scanner in combination with RTK-GPS surveying within a 5 days mission in March 2014 in the Domica Cave, Slovakia. FARO Focus 3D scanner was used to scan around 1,500 metres of the cave from 328 scanner positions within 40 hours in total. The scanning density point spacing was set to 20 millimetres at 10 metres. The scans were oriented relative to each and with respect to the Slovak national coordinate system (S-JTSK) in SCENE[8], proprietary software by FARO. The final point cloud contained almost 12 billion of points representing the entire show cave and some parts inaccessible by public (Fig. 2). The total accuracy of registration of the scans was 4-5 millimetres. Georeferencing of the registered point cloud in the national grid achieved accuracy of 12 millimetres measured as the total RTK-GPS positioning error. The survey is thoroughly described in [11]. The point cloud provides a very high detail which enables viewing even small geomorphological features such as speleothems (Fig. 2). Visualisation of the point cloud allows for basic measurements of the cave morphometry but it is not applicable for defining morphometric parameters such as curvature or orientation for which a 3D volumetric surface is needed [20].

IV. Generating the 3D surface model

In the current stage of the research presented by this paper, we are testing different approaches to handle such a massive dataset in order to derive a 3D surface model at different levels of detail. For now, we selected a part of the cave (Fig. 2, 3) to reconstruct its volumetric body to demonstrate the methodological approach. The acquired TLS point cloud provided a discontinuous (point) representation of the cave

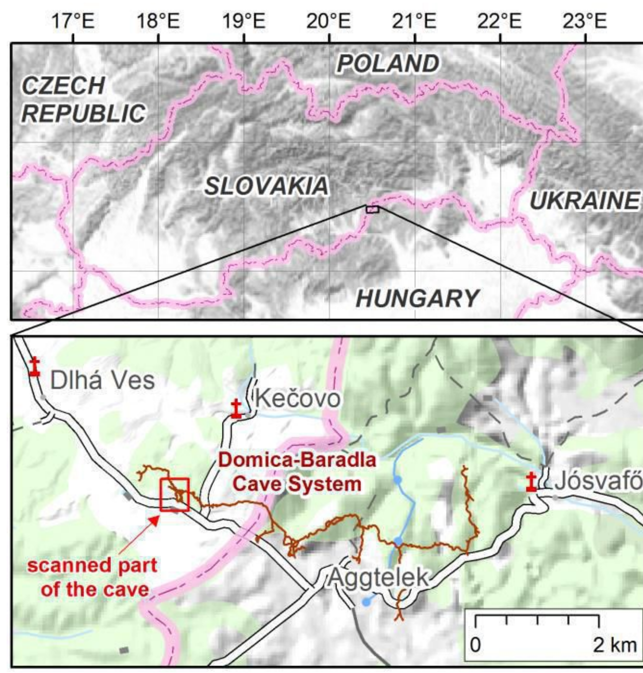

Figure 1. Location of the scanned part of the Domica Cave.

4 http://meshlab.sourceforge.net/
5 http://www.blender.org/
6 http://www.geomagic.com
7 http://spatial3d.science.upjs.sk/
8 http://www.faro.com/faro-3d-app-center/stand-alone-apps/scene

surface and for this reason it is necessary to generate a surface model. Computational representation of 3D surfaces is a widely studied problem in computer graphics and disciplines where 3D surface is the concern of research (e.g., biology, medicine, physics, geology). Surfaces are usually represented as a polygonal mesh which comprises a collection of vertices, edges and faces defining the shape of a polyhedral object [22]. In this work, we adopted a triangular 3D-mesh consisting of triangular faces. Each facet is defined by a set of three vertices and its orientation (the angle of azimuth and slope) is defined by a vector normal to the facet. Usually, it is meaningful to reduce the input point cloud before these steps are performed to test the methodological approach. Therefore, we decimated the point cloud of the sample cave section in the SCENE software to extract only 1 percent (268,720 points) of the original set. The Meshlab software [7] was used to generate the 3D triangular mesh. Meshlab is free and open-source software for mesh processing and editing capable of working with numerous 3D file formats. Generation of a 3D surface model in Meshlab involves several steps: In the first step, normals for the points (future mesh vertices) are estimated based on a defined neighbourhood of points for which a plane is fitted and its normal is calculated. Also viewing position has to be set for a correct orientation of the normals.

After computing the normals, the surface model (mesh) can be reconstructed using several algorithms. We tested the Poisson surface reconstruction approach by [17]. A similar study was conducted by [21] who modelled the surface of a cave chamber and identified stalactites based on local minima of the 3D surface. The authors also designed a web interface for viewing the model in 3D. The reconstruction of the 3D surface is based on the observation that the normal field of the boundary of a solid can be interpreted as the gradient of the solid's indicator function. Therefore, given a set of oriented points sampling the boundary of a solid, a 3D-mesh can be obtained by transforming the oriented point samples into a continuous vector field in 3D. This is performed finding a scalar function whose gradients best match the vector field, and extracting the appropriate isosurface. A thorough definition of the Poisson surface reconstruction can be found in [17]. It is important to mention that the vertices of the reconstructed triangular 3D meshes do not coincide with the points of the survey. With this algorithm, the octree depth is a key input parameter controlling the level of surface detail. It is the maximum depth of the tree that will be used to define the neighbourhood of points for fitting the indicator function reconstructing the 3D surface. The number of faces and vertices comprised in the resulting 3D mesh increases with the higher value of the octree depth as it is shown in TABLE 1.

After reconstructing the 3D mesh (Fig. 3), further processing and surface analysis can be performed, for example, filling the

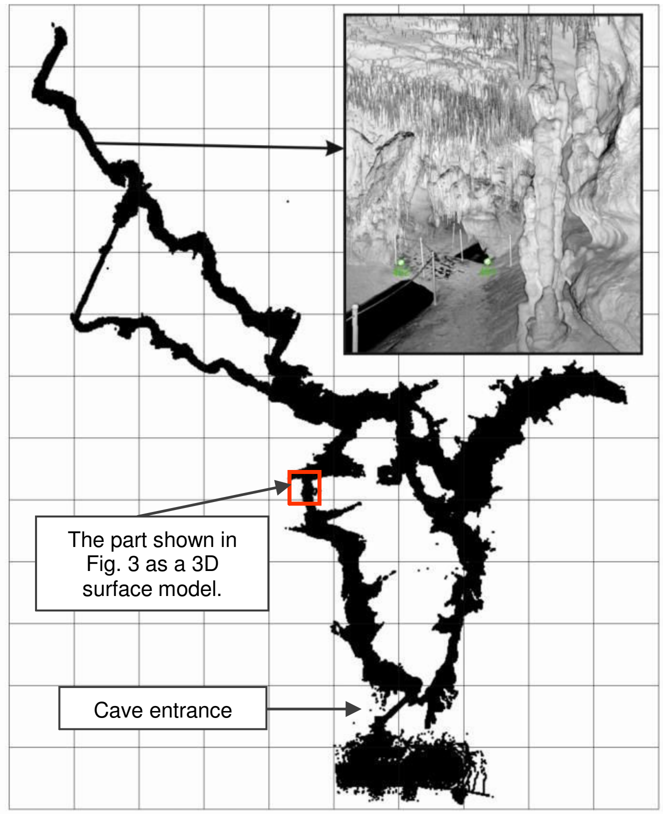

Figure 2. Top view of the entire point cloud representation of the Domica Cave containing 12 billion of points oriented towards north. The scale is given by the reference grid of 50 metres cell size. The picture in the upper right visualizes a perspective view of the cloud demonstrating the acquired level of detail in a paved corridor with the channel of the Styx River (black areas of no laser reflectivity).

holes, decimation of the mesh, or mesh parameterization. We explored the multi-scale parameterization of the mean surface curvature. Computation of the mean curvature requires points or mesh faces equipped with oriented normal [13]. The mean curvature is a measure of the surface convexity/concavity analogous the mean curvature of a 2.5 digital elevation model which is commonly analysed in GIS. As a result, peaks (stalactites, stalagmites) have positive mean curvature values and sinks have negative values (Fig 3).

V. Resulting 3D surface and morphometric analysis.

The reconstructed 3D surface model of the part of the Domica cave is shown in Fig. 3. Table 1 reports the settings of the Poisson surface reconstruction approach and the time

TABLE I. PARAMETERS OF THE POISSON SURFACE RECONSTRUCTION

Dataset	Octree depth	Processing time [sec]	Number of vertices in the mesh
Cave corridor	6	0.5	4,310
	8	5.4	6,712
	9	13.8	140,631
Cave ceiling	10	3.5	28,091
	12	9.1	58,577
	13	25.5	66,025

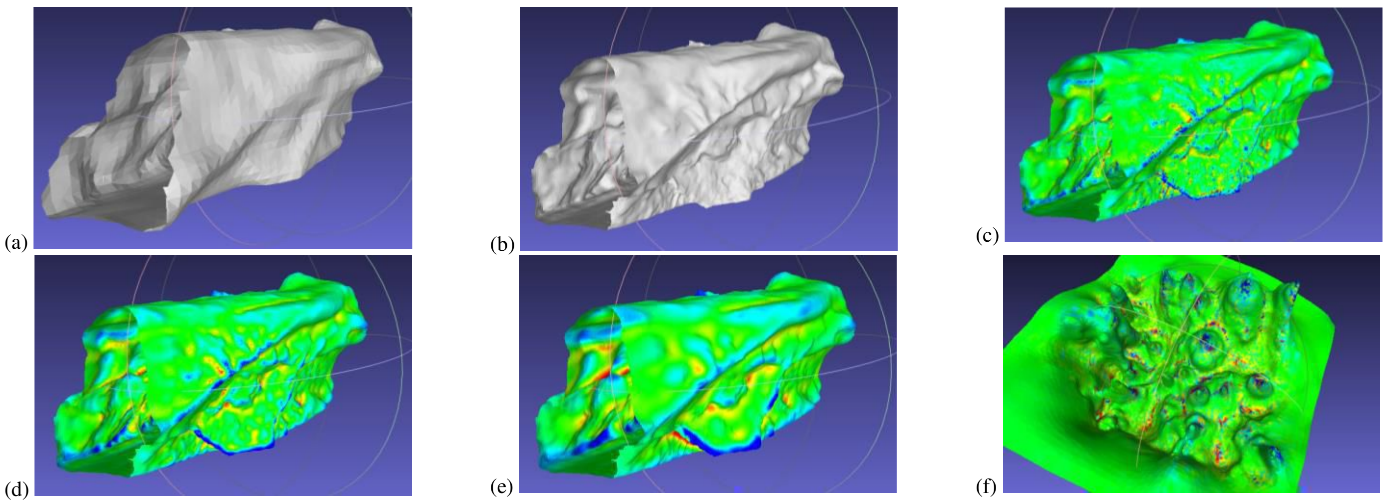

Figure 3. 3D cave surface reconstructed for a selected part of the Domica cave (10 meters long, 4 meters high) located in Fig. 2. Reconstructed 3D triangular mesh using the Poisson surface reconstruction with the octree depth of 6 containing 4,310 vertices (a), and with the depth of 9 containing 140,631 vertices (b). Mean surface curvature on multiple levels of scale was calculated for the surface (b) based on 5 neighbours (c), 10 neighbours (d), 20 neighbours (e). A part of the cave ceiling (1 m sq.) reconstructed with the octree depth of 12 rendered with the mean curvature based on 20 neighbours.

required for processing. Setting of the algorithm is user and data dependent. In order to reconstruct the surface of the corridor lower octree depths are sufficient while if more detail of the 3D surface model is required higher octree depths are needed, as in the case of the detailed model of the cave ceiling (Fig. 3f). The mean curvature of the model of the corridor analysed at multiple levels of scale distinguishes large and small features of the cave walls (Fig. 3a-e) and ceiling (Fig. 3f). Such a 3D approach provides means of quantification and parameterisation of speleoforms which was not possible with traditional 2.5D concept of contemporary tools used in geospatial analysis.

VI. CONCLUSION

This paper outlined a methodological approach of a 3D cave surface modelling in order to parameterise the 3D surface model. Such a task is analogous to the geomorphometric analysis of a 2.5 surfaces available in GIS software which is well suited for a more complex analysis of geographical data. However, tools for modelling 3D volumetric surfaces and their parameterisation do not exist in GIS. Therefore, combining the analysis of a 3D surface with 2.5 DEMs representing the land surface above the caves is a difficult task. We demonstrated the cave surface 3D modelling approach using a sample of the laser scanning point cloud of a cave section of the Domica Cave in Slovakia. The preliminary results show that Poisson surface reconstruction is a suitable approach. The level of detail controlled by the octree depth should be tested for particular modelling case and required level of detail. Scale-dependency of the resulting surface was explored with mean curvature. Further research will focus on efficient processing of much larger datasets to reconstruct a 3D model of the entire point cloud with on multiple-levels of scale. Such a model will be applicable for (i) studying relations between different parts of the cave system and also for (ii) inferring the relationship between environmental processes acting underground and on the above-surface.

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