Acta Montanistica Slovaca Volume **22** (2017), number **3**, 246-256

Comparison of non-contact surveying technologies for modelling underground morphological structures

***Katarína Pukanská*[1], *Karol Bartoš*[1], *Pavel Bella*[2], *Štefan Rákay ml.* [1] and *Janka Sabová*[1]**

Underground spaces are often characterised by complex morphology and, in some cases, also by a large area, and they often need to be surveyed and mapped with a sufficient accuracy. A 3D digitisation of such spaces is appropriate for more accurate mapping of complex morphology of underground spaces. It allows not only to, for example, identify dislocations, but also to obtain data on their direction and inclination in hardly accessible places (high walls, ceilings, etc.). More detailed data about structural and geological conditions and morphology of underground spaces are important in terms of completing and refining existing knowledge. Unlike traditional mapping methods of the underground, modern surveying technologies make it possible to determine various morphological structures and dislocations even in hardly accessible areas. Therefore, we can obtain clearer and comprehensive knowledge of structural and geological conditions. The objective of this paper is to present the current possibilities of modern digitisation of underground morphological structures, which primarily concerns terrestrial laser scanning and methods of digital close-range photogrammetry – Structure from Motion and Image Scanning, which belong to the most frequently used method of obtaining spatial data in recent years. The results indicate that taking data from laser scanning as the reference and most accurate data, the SfM photogrammetric method provides similar results in terms of accuracy, however with lower financial demands, less time consumption and better quality of photo-texture, but its use is significantly limited by lighting conditions in underground. On the other hand, Image Scanning provides worse results in terms of accuracy and overall quality, along with more severe limitations in the selection of imaging stations when compared to SfM method. According to results, terrestrial laser scanning appears to be the most appropriate technology for mapping underground spaces, while also SfM method can provide quality results under suitable lighting conditions.

Key words: *underground spaces, morphology, terrestrial laser scanning, digital close-range photogrammetry.*

Introduction

Underground spaces attracted people's attention by its mysteriousness in all periods of human history and many archaeological finds from the Stone Age to modern times testifies it. One of the most common and most interesting underground spaces are caves. Caves belong to the most important remarkable sites of nature; they are characterised by peculiar shapes of speleorelief (cave morphologies). Knowledge of the origin, morphology and morphometry of underground shapes belongs to fundamental data on caves. Due to the reconstruction of cave evolution and the protection of caves against insensitive human impacts, it is very important to know and map natural features and processes of cave surfaces as morphological structures.

So far, speleological mapping in the Slovak Republic does not have unified and accepted rules and standards. Therefore, the resulting maps differ in details, accuracies as well as in specifics and the way their content is displayed. When a speleologist (geologist, geomorphologist, etc.) realises mapping, the base map is usually inaccurate. However, the map content is generally greater in terms of morphology or practical speleology. Conversely, when a surveyor performs mapping, the base cave map is relatively accurate, but it does not correspond to the morphology, and there can often occur problems that hardly accessible cave areas are not surveyed at all (Hromas and Weigel, 1988; Hochmut, 1995).

However, it is always true that an accurate and quality survey of cave passages, domes and shape of their walls is a major priority before we will try to describe or understand the processes that take place underground based on acquired data, whether they relate to the origin and creation of caves or human activities that could take place therein (González-Aguilera et al., 2009). Nowadays, almost every scientific discipline has a modern surveying instrumentation. In recent years, technologies such as laser scanning and in some cases also digital photogrammetry are getting into the foreground for mapping cave structures. In particular, laser scanning represents a fast method of non-contact collection of accurate spatial data, whether for mapping whole caves or selected parts (Tsakiri et al., 2007; Lerma et al., 2009; Canevese et al., 2011; Gašinec et al., 2012; Amparo Núñez et al., 2013; Silvestre et al., 2013), and also digital close-range photogrammetry (to a lesser extent), which is, however, rather used for the collection of spatial and textural information about smaller cave objects and structures (Lerma et al., 2009; Favalli et al., 2011). However, in the Slovak Republic, these methods have not yet

---

[1] *Katarína Pukanská, Karol Bartoš, Štefan Rákay ml., Janka Sabová*, Institute of Geodesy, Cartography and GIS, Technical University of Košice, Park Komenského 19, 040 01 Košice, Slovakia, katarina.pukanska@tuke.sk, karol.bartos@tuke.sk, stefan.rakay@tuke.sk, janka.sabova@tuke.sk

[2] *Pavel Bella*, State Nature Conservancy of the Slovak Republic, Slovak Caves Administration, Hodžova 11, 031 01 Liptovský Mikuláš, Slovakia, Department of Geography, Faculty of Education, The Catholic University in Ružomberok, Hrabovská cesta 1, 034 01 Ružomberok, Slovakia, pavel.bella@ssj.sk

found a wider use for mapping cave spaces, only in some special cases and only with the use of terrestrial laser scanning (Bella et al., 2015; Gallay et al., 2015, 2016; Hofierka et al., 2016).

Another important type of underground spaces with a complex morphology are spaces created by mining activities. Accurate and fast mapping of these spaces is necessary, for example, to quickly assess potential hazards and work safety. As stated by Benton et al., 2016, the use of standard surveying instrumentation for underground deformation monitoring is not very efficient due to its financial and time requirements. Moreover, locations that can be effectively monitored are limited. Digital photogrammetry can be used as a more suitable and safer method when compared to standard geotechnical instrumentation. Use of digital photogrammetry can significantly improve worker safety, analysis of displacements and avoid damage to instrumentation.

According to Slaker and Mohamed, 2016, photogrammetry in underground spaces used for mining is also important to perform rib characterisation measurements. Since photogrammetry can be considered as a quick and accurate method when compared to conventional tape measures and laser range meters, it can be conveniently used to investigate coal mine rib behaviour to so we can understand pillar loading conditions and ensure the safety of miners.

Moreover, digital photogrammetry can be conveniently used for 3D modelling and monitoring in mining (Ristović and Vulić, 2014), geological logging in coal mines (Li et al., 2013), or monitoring and determination of geometric changes in support structures (Brent et al., 2016).

Even more widespread is the use of terrestrial laser scanning (TLS) in underground mining spaces. Since laser scanning can capture accurate data at an unprecedented rate, it is an essential technology in underground space utilisation to ensure the necessary alignment, void control, and efficiency of extraction operations (Eyre et al., 2016). TLS technology is also commonly used for mine roadway surface reconstruction (Guo et al., 2016). The very important issue in underground mining is inevitable results in land surface subsidence. Terrestrial laser scanning can be successfully used to quickly extract accurate information on land surface deformation in underground mining areas since conventional data acquisition techniques cannot always obtain information on whole subsidence area (Song et al., 2015). Another use of TLS technology in underground spaces can be seen in building underground constructions, where spatial parameters monitoring is essential due to safety and statuary reasons, and conventional approaches are time-consuming, and even with a combination of independent contractors, collected data is often deficient and corrupted with rough interpolations. (Novaković et al., 2014). Moreover, TLS technology can even be efficiently used to document underground wine cellars (Herrero et al., 2014).

The primary objective of this work is to highlight the use of these modern technologies so that all important morphologic features of the selected part of underground space can be captured in the best possible way not only in terms of accuracy but also of morphology; and subsequently compare these two technologies. A part of the Belianska Cave in Slovakia was selected as the best location to compare the given technologies/methods. The cave was selected for its morphological segmentation, relatively simple access, as well as due to the fact that our works on the selected part of this cave did not limit the standard operation in the cave spaces.

Characteristics of the location and conditions of survey

Selected parts of the Belianska Cave (Pipe Dome, Dome of Discoverers and Musical Hall), one of the most popular and visited show caves in Slovakia (Fig. 1a), were the main subjects of the survey. Besides bizarre rock sculpturing, the cave is well known by calcite fills (mostly flowstones and dripstones). The cave is located on the northern slope of the Kobylí Hill in the eastern part of the Belianske Tatras Mountains. The cave length is 3641 m with elevation range 160 m. Air temperature reaches 5,0 to 5,8 °C and relative humidity 90 to 97 %. The cave was formed in Mesozoic Middle Triassic dark grey Gutenstein limestone of the Krížna Nappe. The origin of the cave was conditioned by bedding planes, less tectonic faults, along which the waters penetrated and flowed into deeper parts of karst aquifer. The initial phreatic cavities were completely filled with water and sculptured by a solution of limestone as a result of water convection. Large cupolas and smaller kettle and pocket hollows were deepened into the ceiling (Droppa, 1957; Bella and Pavlarčík, 2002; Bella et al., 2011; Bella and Bosák, 2012 and others). The cave is protected as a national natural monument.

The Belianska Cave morphologically consists of two main, north descending branches, which are connected in its upper sub-horizontal part, and partially also in the lower, also predominantly sub-horizontal part. The eastern branch is in a higher position than the western one. The verticality of the cave is complemented by several abysses and shafts. The cave spaces are situated at an altitude of 865 to 1025 m a.s.l. The shaft, descending from the first discovered entrance located 82 metres above the current entrance for visitors, falls into the lower sub-horizontal part of the cave, which is accessible by the artificial tunnel with the surface opening at an altitude of 890 m a.s.l. (Bella and Pavlarčík, 2002; Bella et al., 2011).

For the purposes of this work and comparison of individual technologies, part of the karst cave decorations in the Musical Hall (Fig. 1b) was chosen as the subject of the survey.

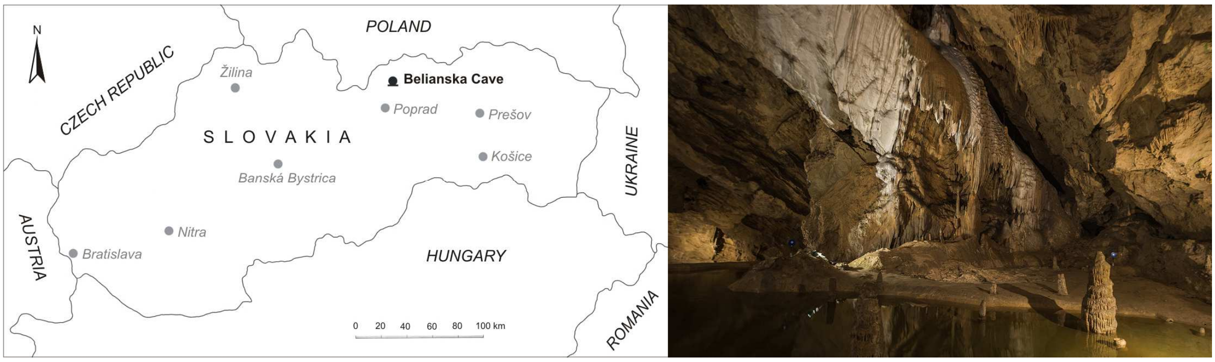


Fig. 1. Left - Location of the Belianska Cave in Slovakia; right – the selected detail in the cave (Musical Hall).

Geodetic survey of the selected object

It is necessary to consider each of the above conditions and facts when surveying and selecting the most suitable methods and procedures. The general measurement procedure involves field works related to the collection of spatial data such us terrain reconnaissance, selection of survey stations, targeting and measuring ground control points and the actual scanning and photogrammetric activities.

For photogrammetric imaging, an appropriate illumination of the measured object is an essential part. Due to the fact that Belianska Cave is a guided show cave, its accessible part is adequately illuminated by spotlights distributed along the guided route. These lights suitably illuminated the selected part of the cave and no additional lighting was needed. However, in the case of worse lighting conditions in underground spaces and the need for additional lighting, it is necessary that this lighting is constant and stable, in order to prevent variable lighting and shading on the surface. This could lead to problems in the image orientation of obtained images during photogrammetric processing.

Survey of the selected part by TLS technology

Terrestrial laser scanning is a technology based on the spatial polar method, in which the vertical angle, horizontal angle and slope distance are measured. The so-called "point cloud", i.e. a set of spatial points defined by Cartesian coordinates XYZ, is the result of laser scanning, and the value of the intensity of reflected signal *I* is assigned to every point as well as textural information in the form of RGB values in the case of using integrated or externally attached digital camera (Štroner and Smítka, 2013).

The TLS was carried out by using terrestrial high-speed pulse laser scanner with dual-axis compensator Leica ScanStation C10 together with Leica 6" circular tilt & turn targets (Fig. 2). The manufacturer guarantees the precision of modelled surface 2 mm and accuracy of single measurement 6 mm in position and 4 mm in the distance. The range of the scanner is 134 m for 18% albedo of the scanned surface.

Fig. 2. Leica ScanStation C10 at the survey station during orientation to 6" HDS target.

All geodetic activities were performed from points of the survey net, whose spatial coordinates were determined in the S-JTSK coordinate system (Datum of Uniform Trigonometric Cadastral Network) and Bpv vertical coordinate system (Baltic Vertical Datum - After Adjustment) by using terrestrial laser scanner Leica ScanStation C10. Points of geodetic point field monumented in the concrete footway of the guided tour (Fig. 3) were used as initial survey points, while all erroneous points were excluded from the adjustment of used survey net (Weiss et al., 2010; Braun et al., 2015; Štroner et al., 2017). Due to the elimination of error of centring of an instrument above the survey point of the survey net, the method of forced centring was used during the measurement. As a result of the high density of scanning (5x5 mm at a distance of 10 m), the total number of measured points reached approximately 6 million.

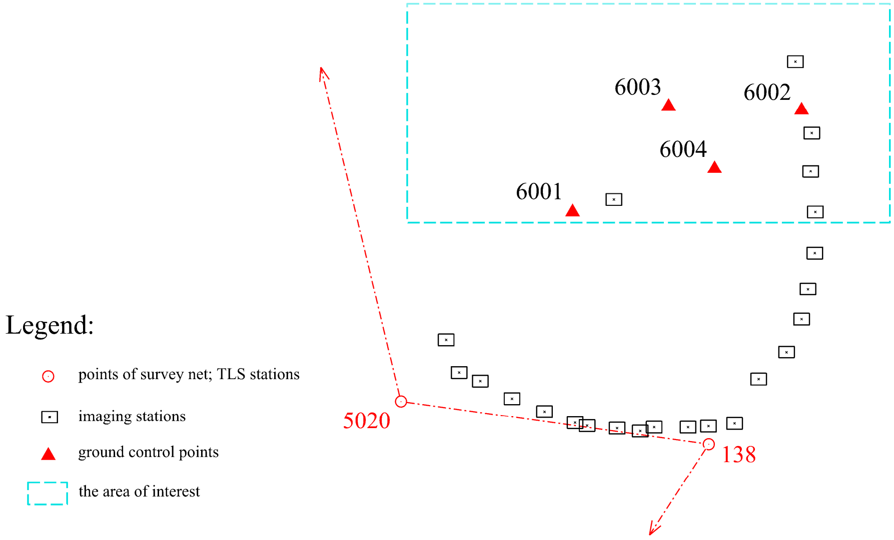


Fig. 3. General sketch of geodetic control and activities.

Leica Cyclone software was used for the processing of the final point cloud. In the first processing stage, individual scans (partial point clouds) are combined into a single final unit (point cloud). The implementation of this operation is based on the set of reference points, or identification of common points in the overlapping parts of adjacent scans. Thus, there is a spatial transformation of points of individual scans on the basis of coordinates of reference points in the local coordinate system of the scanner position and the local reference coordinate system of the final point cloud. In our case, the registration of scans into a single coordinate system as well as into the S-JTSK system was carried out directly in the Leica ScanStation C10 instrument by entering coordinates of survey stations and orientation points.

Imaging and image processing by photogrammetric methods

Two photogrammetric methods – Image Scanning (IS) and Structure from Motion (SfM) were chosen for the photogrammetric survey. In general, photogrammetric methods can achieve higher accuracy than laser scanning for shorter imaging distances (and also when optimal conditions of imaging are satisfied) (Luhmann et al., 2014).

The SfM method is based on the estimation of three-dimensional structure from two-dimensional image sequences, which are adherent to the movement of carrier – digital camera. As in the laser scanning, a point cloud is the result of the whole process (Fig. 5). The SfM method works on similar principles as stereophotogrammetry or intersection photogrammetry, i.e. a 3D structure can be reconstructed from a series of overlapping and mutually shifted and tilted images. However, it is different from a classic photogrammetry in the fact that the scene geometry, camera stations and its orientation are calculated automatically without necessity of ground control points usage, i.e. they are calculated simultaneously using an iterative method of bundle adjustment based on a set of characteristic points automatically selected in a series of multiple overlapping images (Westoby et al., 2012).

The method of Image Scanning can be methodologically understood as stereophotogrammetry by its accuracy and way of imaging, but the method of image evaluation is fundamentally different (Fraštia et al., 2006). Image points – pixels, or identical image elements, are measured fully automatically based on principles of digital image correlation using the epipolar geometry. However, objects of measurement should not be too rugged in depth, with no sharp edges and transitions, and they should provide sufficient variable texture of the surface.

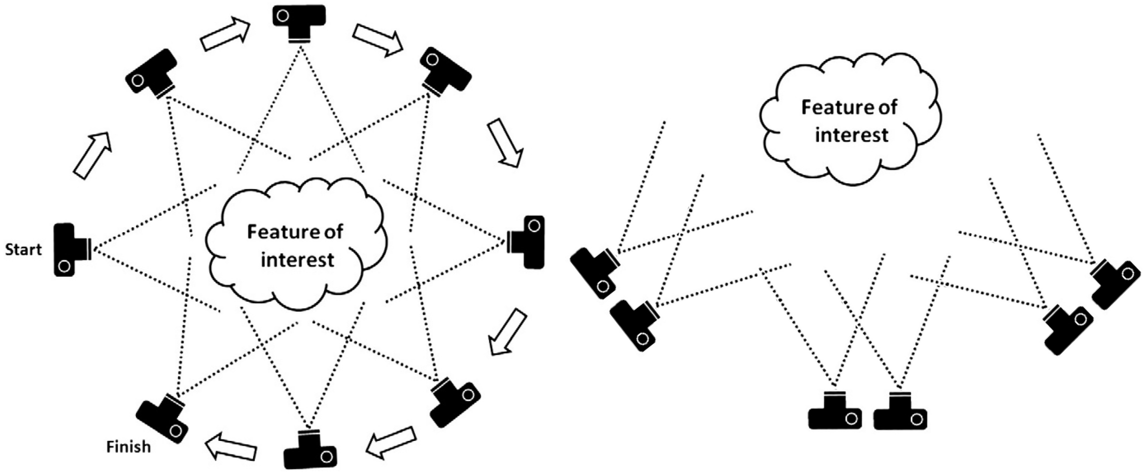


Fig. 4: A difference in imaging between the SfM method (left) and Image Scanning (right) (Westoby et al., 2012).

A selected part of the cave structures, which was the main objective of the survey, was imaged using 55 images so that all of its parts were well-captured (Fig. 3). Images were taken by DSLR Pentax K-5 with lens Pentax SMC DA 15mm f/4 ED AL Limited. All images were taken from the tripod using the 12 sec self-timer, ISO 100 and aperture f/13. The common imaging stations for both methods are shown in Figure 3. Imaging stations were selected with respect to the accessibility since a smaller pond was located in the immediate vicinity of the measured surface (Fig. 1 – right). However, imaging stations were selected so that a sufficient overlap between them was achieved together with convergent image axes. Due to the fact that images used in image scanning are limited by parallel image axes and appropriate distance between images at individual stereo-pairs (stereo base), the acquisition of images for image scanning is more difficult and in our case could potentially lead to missing data in obscured areas.

In the first step, images were processed in the RealityCapture (RC) software, and the point cloud of the selected part was created based on the SfM method. Software settings for highest quality were used for the automatic image processing to obtain final dense point cloud. 4 ground control points (Fig. 3) were selected for the transformation of resulting point cloud into the single coordinate system; 2 ground control points were targeted artificially using 6" HDS targets – 6001, 6002 and 2 ground control points were targeted by natural shapes – 6003, 6004. Coordinates of these points were surveyed and adapted from results of laser scanning.

In the second step, images were processed in the PhotoModeler Scanner 2010 (PMSC) software, so that 5 image stereo-pairs were chosen from 55 images. Using these image stereo-pairs, a point cloud of the area of interest was generated using the method of Image Scanning. The same 4 ground control points 6001 – 6004 were used for the transformation of the point cloud.

Parameters of imaging and subsequent image processing by both photogrammetric methods are shown in Tab. 1. In both cases, the method of field calibration, when calibration parameters are determined during the processing using the project images, was used.

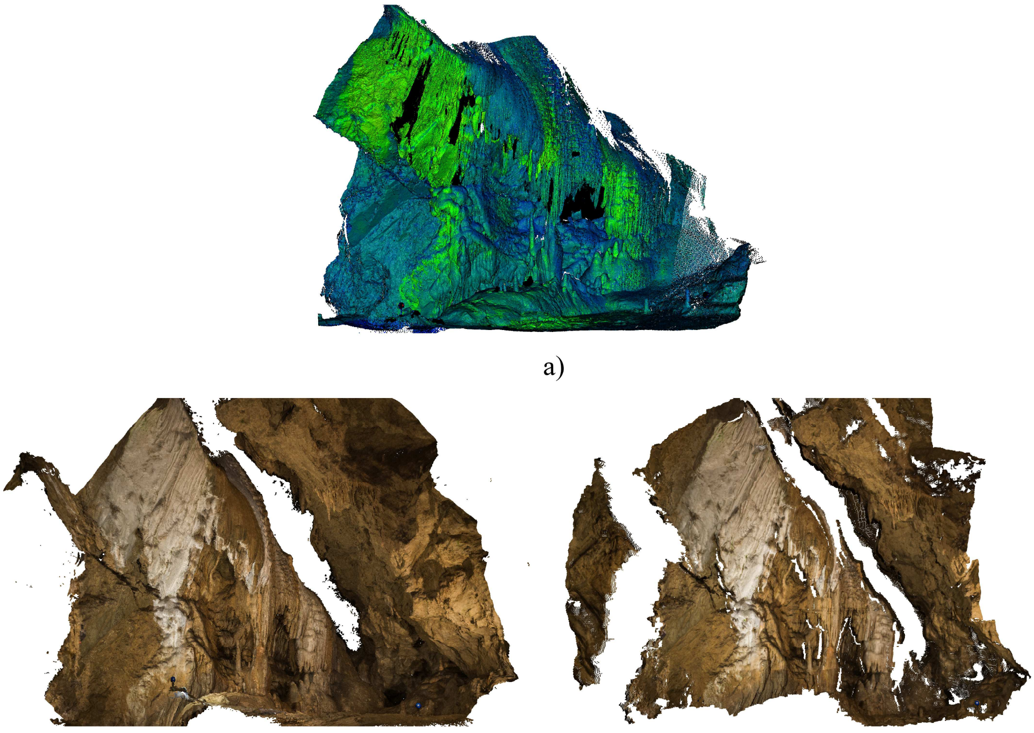
Tab. 1. Parameters of imaging and image processing by photogrammetric methods.

	SfM (RC)	**IS (PMSC)**
No. of used images	55	5 stero-pairs
Average imaging distances	10,16 m	
Length of baseline of image stereo-pairs	/	3,5 m
Time of software processing	20 hrs.	4 hrs.
No. of extracted characteristic features (image elements)	135 590	60 295
No. of reconstructed points	approx. 12 mil.	800 000
Ground Sampling Distance	2,9 mm/pix	
RMS of image orientation	0,412 pix	0,984 pix
Accuracy in the reference system (overall mean spatial error)	13,1 mm	54,4 mm

Analysis of results

In all three cases, a point cloud is the final result of individual surveys and subsequent processing. In the case of laser scanning, information on the intensity of the reflected signal is assigned to every point; in the case of digital photogrammetry, it is the textural information in the form of RGB values. Each technology (method, respectively) provides a different quality of outputs in terms of density and integrity of point cloud, noise level and quality of the photo-texture (Fig. 5).

Since the Leica ScanStation C10 laser scanner contains only an integrated digital camera with low resolution and considering light conditions in the cave (relatively low light, without possibility to adjust its direction and intensity), there were no images taken during laser scanning and the final point cloud does not contain colour information, in contrast to digital photogrammetry. At first sight, the point cloud obtained by the SfM method shows a high quality with a high level of integrity, low noise and quality photo-texture. On the other hand, data obtained by the method of Image Scanning have the same quality considering the photo-texture. However, the point cloud is "shattered", with a higher level of noise and more areas with missing data.



a)

b)

c)

Fig. 5. Final point clouds: a) TLS; b) RealityCapture; c) PhotoModeler Scanner.

Due to the scanning distance from individual scanning stations (and imaging distance) and dimensions of the area of interest, we can say that the data obtained by terrestrial laser scanning achieve the highest accuracy. However, we assume that the data obtained by digital photogrammetry can achieve similar accuracy if the correct conditions of imaging and subsequent image processing are respected. In order to measure deviations between data obtained by photogrammetry and data from laser scanning, all three point clouds were compared with each other by means of difference models generated in the 3D point cloud and mesh processing software CloudCompare 2.6.0 using the plugin "M3C2 distance" (Lague et al., 2013), which can be used to determine robust signed distances directly between two point clouds.

In the first step, a difference model between the point cloud obtained by laser scanning (reference data) and the point cloud generated by the SfM method using RC software (compared data) was created (Fig. 6). The frequency distribution graph of points and their deviations from the normal distribution represented by the Gaussian curve is shown in the Fig. 7. The mean value of real deviations reaches + 6 mm, which represents a minimum enlargement of compared data against reference data. All values of deviations range from -21,3 mm to +29,5 mm while the distribution of points is sharp, representing a low variability of deviations and high frequency of data in a narrow interval. The graph has only one peak. However, there is a systematic error regarding the size of the deviations (possibly a shift of the data).

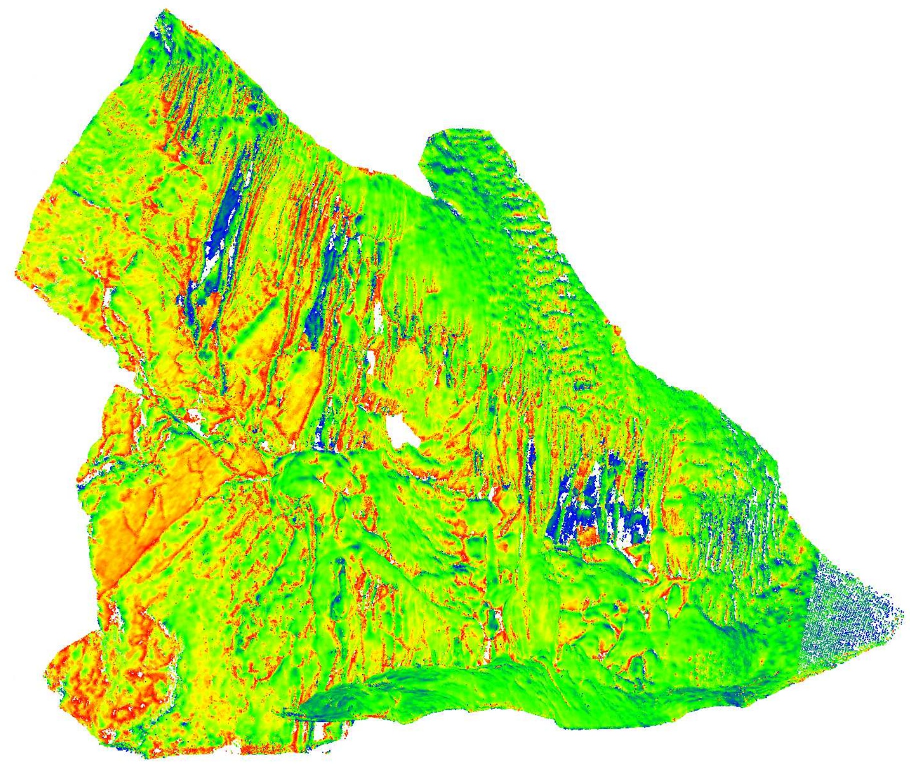


Fig. 6. The difference model between data from laser scanning and RealityCapture.

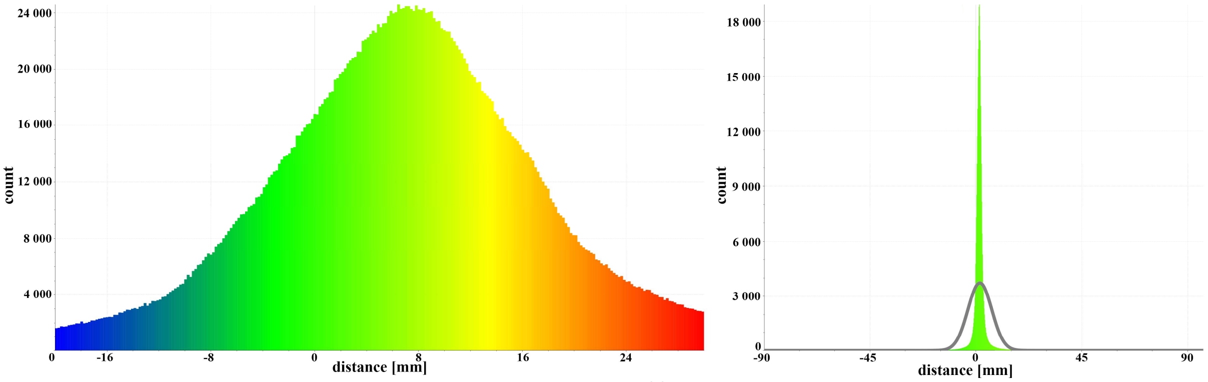


Fig. 7. The graphical analysis of frequency distribution.

The normality of histograms was tested using the Chi-square test with the following value of the test statistics:

$$\chi^2=\sum_{j=1}^{k_0}\frac{\left(n_j-n\pi_j\right)^2}{n\pi_j}, \tag{1}$$

with a critical range for the normality test at the level of significance α:

$$\chi^2>\chi^2_{1-\alpha}\left(k_0-c-1\right), \tag{2}$$

while $\chi^2_{1-\alpha}\left(k_0-c-1\right)$ represents the $\left(1-\alpha\right)$ -quantile of the χ^2 distribution for $v=k_0-c-1$ degrees of freedom.

In the second step, the difference model between the point cloud from laser scanning (reference data) and the point cloud generated by the method of Image Scanning using PMSC software (compared data) was created (Fig. 8). In this case, the mean value of real deviations reaches up to -47,5 mm (8-times more than in comparison with the model from SfM processing), corresponding to a significant reduction of compared data against the reference data. A small degree of graph skew and real values of deviations from the interval [-172,7 mm;

+41,3 mm] indicate the greater variability of deviations of individual points. Moreover, the graph has one main peak, but several partial peaks indicate the influence of systematic errors.

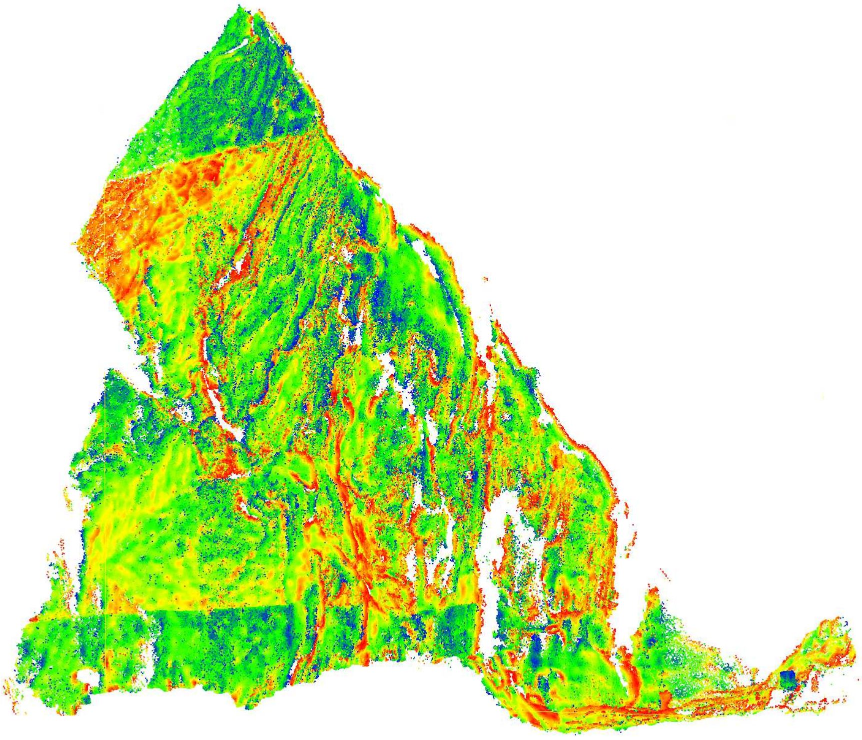


Fig. 8. The difference model between data from laser scanning and PhotoModeler Scaner and the graphical analysis of frequency distribution.

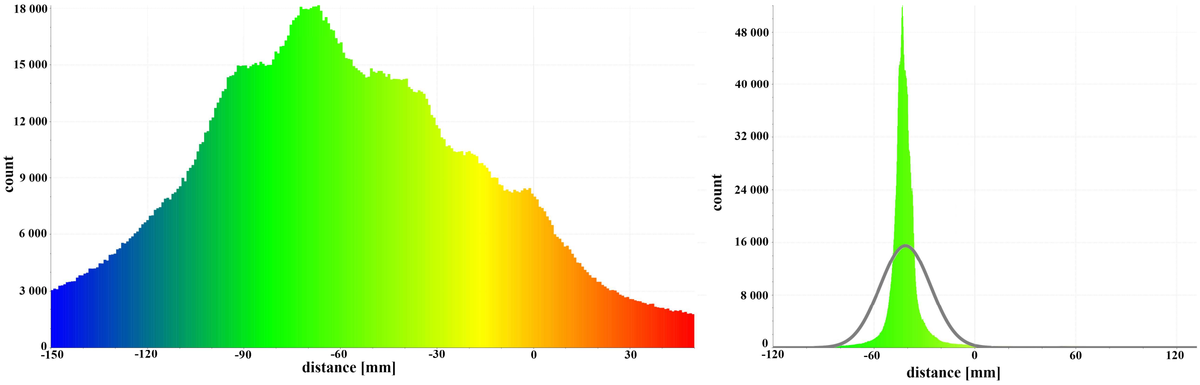


Fig. 9. The graphical analysis of frequency distribution.

Regarding the results in all three cases, a point cloud is the final result of individual surveys and subsequent processing. In the case of laser scanning, information on the intensity of the reflected signal is assigned to every point; in the case of digital photogrammetry, it is textural information in the form of RGB values. Each technology (resp. method) provides a different quality of outputs in terms of density and integrity of point cloud, noise level and quality of photo-texture (Fig. 5).

By comparing the resulting models, taking the point cloud from laser scanning as the reference data (since the data from laser scanner are considered as the most precise), the expected results were obtained – the SfM method provides more reliable results. The point cloud created by SfM method is more precise than the point cloud from IS (it also depends on the imaging/scanning distance). However, it is clearly evident that the IS method is not suitable at all. Based on these results, it is not possible to clearly determine which technology/method (TLS/SfM) is more suitable to survey and model morphologic underground structures – each of them provides certain advantages and disadvantages. Whether considering financial demands, availability, lighting options, the need to get also photo-texture of the surface, and so on.

Conclusion

Underground spaces are an important part contributing to the morphology of the area – whether created naturally or by human activities. Knowledge of their spatial conditions in the underground and connection with surface allows to determine the overall morphology of these spaces and surrounding area as well as to support the operation of mining works and ensure the higher safety of workers. For this reasons, it is necessary to obtain the mentioned spatial data in the shortest possible time and as accurate as possible, often requiring minimisation of costs.

The aim of this paper was to highlight the use of modern surveying technologies in underground spaces, with a focus on morphology in cave spaces. Caves belong to the unusual natural phenomenon, which appeals to the general public and professionals with different specialisation by their remarkableness. In comparison with other natural phenomena, they are characterised by many peculiar and unique features that enhance the mysteriousness of underground. The uniqueness of shapes of stalactite decoration with varying colour and fragile beauty, massive underground domes and stalactite or ice formations document the great power of nature. For the comprehensive capture of all of those complex features, it is the responsibility of surveyors to choose such technology and methods of measurement, so that underground structures are captured in the most detailed and accurate way.

In the recent years, two technologies – terrestrial laser scanning and digital close-range photogrammetry got into the foreground, mainly due to their speed, efficiency, accuracy, a high number of captured data and non-contact method of measurement. However, the specific conditions of measurement, such as the size and surface of the surveyed object, lighting, etc., must be considered when they are used.

To find a definitive answer to which technology/method is better for the underground survey, it should be stated that each of them has (in certain conditions) its advantages as well as disadvantages (including mainly time and financial requirements) that should be considered for each specific underground survey. Their mutual comparison based on the survey of selected part of the Belianska Cave in Slovakia reveals that the SfM method of digital photogrammetry gives the same quality of outputs as terrestrial laser scanning in terms of accuracy and quality of acquired data. On the other hand, the method of Image Scanning shows significant deviations in comparison with data obtained by laser scanning and generally also a lower quality of the final point cloud against the SfM method (in terms of compactness, density and quality of photo-texture), therefore, it is not a suitable photogrammetric method for modelling complex underground structures.

The great advantage of TLS is its speed and accuracy (in the case of used Leica ScanStation C10 scanner - the precision of modelled surface 2 mm and maximum speed 50 000 points/sec. are guaranteed by manufacturer) and the fact that measurements realized by laser scanner are independent of the illumination of the measured surface (in fact, the laser scanning can be carried out in complete darkness). However, financial requirements for scanning are relatively high, especially when compared to photogrammetry. Another disadvantage can be a difficult handling and higher vulnerability to damage in often narrow cave spaces. Also, the obtained data does not have any photo-texture information, only assigned colour information about the intensity of reflected signal (in some cases, the point cloud can have the RGB information if the laser scanner has some integrated camera, but the quality will never be the same as in the case of digital photogrammetry). On the other hand, digital photogrammetry (namely the SfM method) does not have such high financial demands on the used equipment and accessories and handling with a digital camera is easier and more accessible even to hardly accessible cave spaces. Moreover, data obtained by digital camera and processed by SfM method can have a high-quality photo-texture (however, this is conditioned by sufficient illumination of the measured surface, which can often be difficult in underground spaces and therefore can be considered a disadvantage of digital photogrammetry). Moreover, finally, the accuracy of digital photogrammetry significantly decreases with increasing imaging distance, as in our case, the data obtained from digital photogrammetry are less precise than data obtained from laser scanning for the imaging/scanning distance approximately 10 m. Regarding the accuracy of the obtained data, it strongly depends on the requirements specified for each project that is currently being solved. For example, in the case of caves, there can be different required accuracy for a common map output like planimetry, hypsography, etc. (with a centimetre accuracy) and detailed modelling of specific morphological features (with a millimetre accuracy).

References

Bella, P., Bosák, P.: Speleogenesis along deep regional faults by ascending waters: case studies from Slovakia and Czech Republic. *Acta Carsologica, Vol. 41, No. 2-3, 2012. pp. 169-192. ISSN 0583-6050. doi: 10.3986/ac.v41i2-3.556.*

Bella, P., Bosák, P., Pruner, P., Głazek, J., Hercman, H.: The development of the River Biela Valley in relation to the genesis of the Belianska Cave. *Geografický časopis / Geographical Journal, Vol. 63, No. 4, 2011. pp. 369-387. ISSN 0016-7193.*

Bella, P., Littva, J., Pukanská, K., Gašinec, J., Bartoš, K.: Use of terrestrial laser scanning for the investigation of structural geological discontinuities and morphology of caves: the example of the Dúpnica Cave, Západné Tatry Mts., Slovakia. *Acta Geologica Slovaca, Vol. 7, No. 2, 2015. pp. 92-102. ISSN 1338-5674.*

Bella, P., Pavlarčík, S.: Morfológia a problémy genézy Belianskej jaskyne. In Bella, P. Ed. Výskum využívanie a ochrana jaskýň. Zborník referátov z 3. vedeckej konferencie (Stará Lesná, 14. – 16. 11. 2001). Liptovský Mikuláš, *Správa slovenských jaskýň, 2002. pp. 22-35. ISBN 80-8064-145-5.*

Benton, D. J., Chambers, A. J., Raffaldi, M. J., Finley, S. A., Powers, M. J.: Close-Range Photogrammetry in Underground Mining Ground Control. Proc. SPIE 9977, *Remote Sensing System Engineering VI, 997707 (September 19, 2016); 13 p. doi:10.1117/12.2236691.*

Braun, J., Štroner, M., Urban, R., Dvořáček, F.: Suppression of Systematic Errors of Electronic Distance Meters for Measurement of Short Distances. *Sensors. Vol. 15, Issue 8, 2015. Pp. 19264-19301. ISSN 1424-8220. DOI 10.3390/s150819264.*

Brent, S., Erik, W., John, E., Michael, M.: Determination of volumetric changes at an underground stone mine: a photogrammetry case study. *International Journal of Mining Science and Technology. Vol. 26, 2016. pp. 149-154. ISSN 2095-2686.*

Canevese, E. P., et al.: Laser scanning technology for the hypogean survey: the case of Santa Barbara karst system (Sardinia, Italy). *Acta Carsologica, Vol. 40, No. 1, 2011. pp. 65-77. ISSN 0583-6050.*

CloudCompare (version 2.6.0) [GPL software]. *EDF R&D, Telecom ParisTech (2015). Retrieved from* http://www.cloudcompare.org/ .

Droppa, A.: Belanská jaskyňa a jej kras. *Bratislava, Šport 1959. 136 p.*

Eyre, M., Wetherelt, A., Coggan, J.: Evaluation of automated underground mapping solutions for mining and civil engineering applications. *Journal of Applied Remote Sensing. Vol. 10, Issue 4, 2016. 19 p. ISSN 1931-3195.*

Favalli, M., et al.: Multiview 3D reconstruction in geosciences, 2012. *Computers & Geosciences, Vol. 44. pp. 168-176. ISSN 0098-3004.*

Fraštia, M., Bartoš, P., Matyšáková, A., Chlepková, M.: Inžinierske aplikácie digitálnej blízkej fotogrametrie. Progresívne technológie v inžinierskej geodézii: Zborník prednášok z odborného seminára. *Bratislava STU v Bratislave SvF, 2006. pp. 95-102. ISBN 80-227-2380-0.*

Gallay, M., Kaňuk, J., Hochmuth, Z., Meneely, J., Hofierka, J., Sedlák. V.: Large-scale and high-resolution 3-D cave mapping by terrestrial laser scanning: a case study of the Domica Cave, Slovakia. *International Journal of Speleology, Vol. 44, No. 3, 2015. pp. 277-291. ISSN 1827-806X. doi:10.5038/1827-806X.44.3.6.*

Gallay, M., Hochmuth, Z., Kaňuk, J., Hofierka, J.: Geomorphometric analysis of cave ceiling channels mapped with 3-D terrestrial laser scanning. *Hydrology and Earth System Sciences, Vol. 20, 2016. pp. 1827-1849. doi:10.5194/hess-20-1827-2016.*

Gašinec, J., Gašincová, S., Černota, P., Staňková, H.: Zastosowanie naziemnego skaningu laserowego do monitorowania logu gruntowego w Dobszyńskiej Jaskini Lodowej. *Inžinieria Mineralna, 2012, Vol. 13, No. 2. pp. 31-42. ISSN 1640-4920.*

González-Aguilera, D., et al.: 3D Digital Surveying and Modelling of Cave Geometry: Application to Paleolithic Rock Art. *Sensors, 2009, Vol. 9, Issue 2. ISSN 1424-8220.*

Guo, J., Jiang, J., Wu, L., Zhou, W., Wei, L.: 3D modelling for mine roadway from laser scanning point cloud. Geoscience and Remote Sensing Symposium (IGARSS), *2016 IEEE International. 4 p. ISSN 2153-7003.*

Herrero, T., Pérez-Martín, E., Conejo-Martín, M. A., L. de Herrera, J., Ezquerra-Canalejo, A., Velasco-Gómez, J.: Assessment of underground wine cellars using geographic information technologies. *Survey Review, Vol. 47, 2014. pp. 202-210. ISSN 1752-2706.*

Hofierka, J., Hochmuth, Z., Kaňuk, J., Gallay, M., Gessert, A.: Mapovanie jaskyne Domica pomocou terestrického laserového skenovania. *Geografický časopis / Geographical Journal, Vol. 68, No. 1, 2016. pp. 25-38. ISSN 0016-7193.*

Hochmut, Z.: Mapovanie jaskýň. *Slovenská Speleologická Spoločnosť. Liptovský Mikuláš, 1995. ISBN 80-966963-1-9.*

Hromas, J., Weigel, J.: Základy speleologického mapování. *Praha: Česká speleologická spoločnosť 1988. 135p.*

Lague, D., Brodu, N., Leroux, J.: Accurate 3D comparison of complex topography with terrestrial laser scanner: application to the Rangitikei canyon (N-Z). *ISPRS Journal of Photogrammetry and Remote Sensing. Vol. 82, August 201, pp. 10-26. ISSN 0924-2716.*

Lerma, J. L., et al.: Terrestrial laser scanning and close range photogrammetry for 3D archaeological documentation: the Upper Palaeolithic Cave of Parpallo´ as a case study. *Journal of Archaeological Science, 2010, Vol. 37, Issue 3. pp. 499-507. ISSN 0305-4403.*

Li, H., Cai, Y., Yang, B., Wu, M.: A Fast Geological Logging Technique of Underground Coal Mines Based on Photogrammetry. *Advanced Materials Research, Vol. 663, 2013. Pp. 661-667. ISSN 1662-8985*.

Novaković, G., Lazar, A., Kovačič, S., Vulić, M.: The Usability of Terrestrial 3D Laser Scanning Technology for Tunnel Clearance Analysis Application. *Applied Mechanics and Materials. Vol. 683, 2014. pp. 219-224. ISSN 1662-7482.*

Luhmann, T., Robson, S., Kyle, S., Boehm, J.: Close-Range Photogrammetry and 3D Imaging, 2nd ed. *Walter de Gruyter GmbH, Berlin/Boston, 2014. ISBN 978-3-11-030269-1.*

Núñez, A. M., Buill, F., Edo, M.: 3D model of the Can Sadurní cave. *Journal of Archaeological Science, 2013, Vol. 40, Issue 12. pp. 4420-4428. ISSN 0305-4403.*

Ristović, I., Vulić, M.: Affordable Photogrammetry as Applied in the 3D modelling and Monitoring of Underground Mining Exploitation and Transport. *Applied Mechanics and Materials. Vol. 683, 2014. Pp. 251-256. ISSN 1662-8985.*

Silvestre, I., et al.: Framework for 3D data modeling and Web visualization of underground caves using open source tools. Proceedings of the 18th International Conference on 3D Web Technology, 2013. *ACM New York, NY, USA. Pp. 121-128. ISBN: 978-1-4503-2133-4.*

Slaker, B. A., Mohamed, K. M.: A practical application of photogrammetry to performing rib characterization measurements in an underground coal mine using a DSLR camera. *International Journal of Mining Science and Technology. Vol. 27, Issue 1, 2017. pp. 83-90. ISSN 2095-2686.*

Song, B., Zheng, N., Li, D., Chen, R., Li L.: Reconstructing DEM using TLS point cloud data and NURBS surface. *Transactions of Nonferrous Metals Society of China. Vol. 25, Issue 9, 2015. pp. 3165-3172. ISSN 1003-6326*.

Štroner, M., Smítka, V.: 3D scanner point cloud denoising by near points surface fitting. Videometrics, Range Imaging, and Applications XIII; and Automated Visual Inspection, *Proceedings of SPIE. Vol. 8971, 2013. DOI 10.1117/12.2020254.*

Štroner, M., Michal, O., Urban, R.: Maximal precision increment method utilization for underground geodetic height network optimization. *Acta Montanistica Slovaca, Vol. 22, No. 1, 2017. pp. 32-42. ISSN 1335-1788.*

Tsakiri, M., et al.: 3D Laser Scanning for the Documentation of Cave Environments. 11th ACUUS Conference: "Underground Space: Expanding the Frontiers", *September 10-13 2007, Athens - Greece*.

Weiss, G., Labant, S., Weiss, E., Mixtaj, L.: Detection of erroneous values in the measurement of local geodetic networks. *Acta Montanistica Slovaca, 2010, Vol. 15, No. 1. pp. 62-70. ISSN 1335-1788*.

Westoby, M. J., et al.: ’Structure-from-motion’ photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology, 2012, Vol. 179. pp. 300-314. ISSN 0169-555X.*