UDC 528.18:629.783

Ihor BUBNIAK[1], Mariia OLIINYK[1], Serhiy TSIKHON[2], Yuriy GOLUBINKA[3], Taras MARKO[1]

[1] Department of Engineering Geodesy, Lviv Polytechnic National University, 12, Bandery str., Lviv, 79013, Ukraine, e-mail: пошта ihor.m.bubniak@lpnu.ua, mariia.a.oliinyk@lpnu.ua, * https://orcid.org/0000-0002-3548-8785
[2] Geological faculty, Ivan Franko National University of Lviv, 1, Universytetska str., Lviv, 79000, Ukraine, e-mail: serhii.tsikhon@lnu.edu.ua
[3] General Commission of Survey, Saudi Arabia, ел. пошта iurii.golubinka@gmail.com

https://doi.org/10.23939/istcgcap2023.98.032

3D MODEL OF MEDOVA CAVE, LVIV

The purpose of this article is to present and provide a detailed analysis of the 3D model of the Medova Cave in Lviv, created using laser scanning technology. The main objectives include revealing the accuracy and detailing the obtained model, as well as determining its potential applications in various fields such as geological research, scientific exploration, cultural heritage, and tourism. Additionally, the article aims to emphasize the importance and advantages of using laser scanning for creating precise and realistic 3D cave models, opening new possibilities for the study and preservation of natural unique formations. Method. The article describes the methodology used to create a 3D model of the Medova Cave, which involves several key steps. Firstly, a thorough reconnaissance of the cave is conducted to identify technical and logistical aspects such as temperature, humidity, movement restrictions, and lighting that are necessary for the scan. Next, ground-based laser scanning is employed, proving effective in conditions of complete darkness and limited space, to ensure accurate data collection regarding the cave's geometry. Reflective markers are strategically placed inside the cave before scanning, facilitating efficient scanning and alignment of scans. Specialized equipment such as GNSS receivers (Trimble R7) and ground-based laser scanners (Faro Focus 3D 120) are utilized for data collection. Software tools like Faro Scene are used for stitching together scans into a unified 3D point cloud model during data processing. Finally, the accuracy of marker connections is analyzed to ensure high-quality registration, and the 3D model is constructed. Detailed 3D models, including textured models and cross-sections for visualizing the internal structure of the cave, were constructed using software such as Move. Results. The research on the Medova Cave, employing ground-based laser scanning, yielded an accurate and detailed 3D model of the cave. This model opens new perspectives for geological and geomorphological studies, tourism development, and cultural heritage preservation. The use of advanced scanning technologies allowed for a comprehensive representation of the cave's geometric features, considering its complex structure and varied dimensions. Scientific novelty and practical significance. The creation of the 3D model of the Medova cave using laser scanning signifies progress in cave geometry studies. The innovation lies in the utilization of advanced laser scanning technologies to ensure a detailed representation of the cave's geometric features, accounting for its complex structure and diverse dimensions. The novelty also lies in the development of a data collection and processing strategy in conditions of complete darkness and limited cave space, resulting in an accurate and realistic 3D model. Practically, the 3D model of the Medova Cave serves as a crucial tool for geological and geomorphological research and the exploration of unique natural formations. The model opens new opportunities for tourism development, where virtual cave exploration can provide a unique experience for visitors. Creating this 3D model is a significant step in preserving and documenting cultural heritage, contributing to the scientific and cultural development of the region, and providing access to unique objects for researchers and the public.

Key words: laser scanning, 3D modeling, research, Medova cave, geometry caves, geodetic technologies, tourism, geomorphology, digital documentation of the cave

Introduction

Over the past two decades, there has been a technological breakthrough in obtaining spatially-coordinated information, which finds wide application in various scientific fields, including geology, geography, and applied sciences. The application of cutting-edge technologies is evident in the study of geomorphological features of the Earth's surface, sedimentological processes, and structural elements of the Earth's crust at various scales. New terms such as "vertical geology" and "virtual geological exposure" are emerging, reflecting new approaches to the analysis of geological phenomena.

Laser scanning is used for objects that rapidly change their parameters, such as volcanoes, making it an effective tool for studying the dynamics of such objects. Particularly significant is the use of these advanced technologies in monitoring the processes of landslide-prone areas, opening up opportunities for more precise and predictable management of these phenomena. Laser scanning methods have become an integral part of glacier research, where their use allows for a detailed study of the structure and dynamics of these important components of the Earth's system.

The application of laser scanning in geological research significantly accelerates data collection and processing. The quality of the obtained data has improved, and the speed of their collection and analysis has greatly increased. Modern computer technologies provide new opportunities for visualizing processing results and exchanging large volumes of information.

Recently, laser scanning and digital photogrammetry have also been used for the study of caves, allowing for a detailed examination of their internal structure and features. This has led to the creation of accurate three-dimensional models of caves in different regions of the world. Such models are beneficial to various scientific fields, including speleology, geomorphology, geology, and biology. Additionally, representatives of geotourism actively utilize 3D models and maps in their daily activities.

At Lviv Polytechnic National University in the Institute of Geodesy, a group of researchers is engaged in the study of both architectural and natural objects using laser scanning and digital photogrammetry methods. The results of these studies are widely presented in a series of scientific publications [Bubniak et al, 2021; Bubniak et al, 2019; Malitskyi & Bubniak, Kuzik et al., 2017; Marusazh, 2021; Savchyn et al, 2019].

In western Ukraine, caves are quite common, but none of them have corresponding three-dimensional models, and the plans are usually not accurate enough. To fill this gap, we conducted research using laser scanning to create detailed three-dimensional models of caves. The Medova Cave, located in the vicinity of Mayoryvka in the Lychakiv district of Lviv, was chosen as the research object. This cave is considered one of the most visited natural tourist attractions in the city of Lviv. Additionally, active construction is taking place near the cave, creating the need for continuous monitoring of its condition.

Previous research on cave scanning

In the early works of Edward Alfred Martel, the founder of modern speleology [Shaw, 2004], surveying activities in caves were extensively employed, leading to the emergence of speleology in the early 20th century.

In the initial stages of research, scientists used hand-drawn sketches to document their discoveries, which was considered a straightforward method. [Fryer et al., 2005].

The next step involved the use of standard surveying instruments, such as compasses, tapes, and clinometers [Tsakiri et al., 2007]. As reflected in the work [Zorin, 2008], these tools helped create plans (maps) of all discovered caves in the territory of Ukraine. The use of theodolites represented significant progress in conducting underground research in terms of methodology and accuracy. However, these methods are not optimal for obtaining data on irregular geometry, such as cave geometry [Haddad, 2011]. The application of terrestrial laser scanning technology has revolutionized cave surveying and led to significant advancements in their exploration.

Between 1988 and 2001, the first attempts at reconstructing the geometry of the Altamira Cave in northern Spain took place using the Minolta VI-700 scanner. The project lasted a significant period due to scanner limitations (0.7-1.1 m range), large volumes of CAD models, and the need for manual processing [Blais, 2004]. Almost 10 years after the completion of the "Altamira" project, another team of researchers decided to explore 3D mapping in the Upper Paleolithic Cave of Cap Blanc in the southwest of France in March 1999 [Robson et al., 2001]. They used the Autoscanning Surveyor (Surveyor ALS) laser system to create a detailed 3D model of the cave. However, both projects have two main drawbacks: one of the methods used is not empirically justified, and the other is limited by memory capacity. Nevertheless, both projects marked a new era in cave geodetic research.

Thematic studies have been conducted in various countries, including Australia [El-Hakim et al., 2004], Austria [Buchroithner & Gaisecker, 2009], the United States [Perperidoy et al., 2010], Italy [Beraldin et al., 2006], [Caprioli et al., 2003], France [Chandelier & Roche, 2009], Greece [Tsakiri et al., 2007], Portugal [Silvestre et al., 2013], Croatia [Kordic et al., 2012], and Malaysia [McFarlane et al., 2013]. Only in two African countries, South Africa and Egypt, Terrestrial laser scanning (TLS) was used for cave research. The Wonderwerk Cave in South Africa was fully scanned using Leica HDS3000 to construct a 3D model as part of a documentation project for African cultural heritage sites [Rüther et al., 2009].

A general overview of the conducted research indicates significantly less activity in the study of caves outside the European Union. However, this does not imply that Europe has more caves compared to other regions of the world. It is likely related to several factors, such as societal understanding of cultural heritage, the influence of educational institutions, economic conditions, and access to research tools. Another important factor is that most manufacturers of modern laser scanners are based in Europe. Among our neighbors, cave research using TLS is conducted in Poland. Ukraine is home to numerous globally significant caves that have been studied for over two hundred years. Unfortunately, until today, TLS has not been utilized in their exploration. Only a few works, closely aligned with TLS approaches to cave study, have been conducted in the Near caves of the Kyiv Pechersk Lavra [Shultz, 2016].

The geological position of the Medova Cave

The Medova Cave is located at the end of the street with the same name, in the Maiorivka area of the city of Lviv (Fig. 1). Figure 2 shows the outline of Medova Cave along the horizon of 380 meters.

In tectonic terms, the cave is situated on the Lviv Plateau, the southwestern part of the East European Platform, known as the Podolian Plate. The sedimentary cover of this structure consists of Paleozoic rocks (Cambrian-Lower Silurian, Upper Silurian, Devonian, Lower and Middle Carboniferous), which gently dip to the southwest beneath the Carpathian orogen. The Main European Watershed runs through this area, between the Baltic and Black Sea basins. The cave is located within the deposits of the Neogene period, specifically within the Ratyn Limestone. These are light-gray to yellowish cavernous limestones containing a significant amount of fauna. The surrounding area of the cave is covered by beech and beech-pine trees. Chernozem, eluvial, and peat-bog soils are prevalent. The region has a moderately continental climate with mild winters and warm summers. The average monthly air temperature is -4°C in January and +18°C in July. The average air humidity is around 80%. Westerly winds prevail, occasionally shifting to the northeast.

Fig. 1. Location of the Medova cave, Lviv.

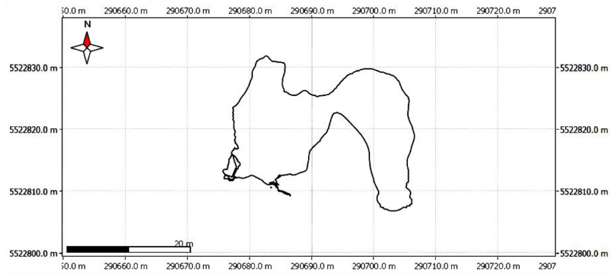

Fig. 2. Contour of the Medova Cave at the elevation of 380 m, Lviv

The aim

The purpose of this article is a thorough analysis and presentation of the 3D model of the Medova Cave in Lviv, successfully created using laser scanning technology. We aim to highlight crucial aspects of this project, focusing on the accuracy and detailing of the obtained model. Additionally, our efforts are directed toward exploring the potential use of this 3D model in various fields such as geological research, science, cultural heritage exploration, and tourism development. Specific objectives include analyzing the possibilities of using the model to study geomorphological features, structural elements, and other aspects of the cave. We also examine the prospects of using the obtained 3D model for scientific research, increasing interest in cultural heritage, and stimulating tourism development in the region. The overall goal is to showcase and popularize advanced methods of cave geometry research through the application of laser scanning, which can open new perspectives in studying natural formations and contribute to their preservation for future generations.

Research Methodology and Data

Capturing data in caves using Terrestrial Laser Scanning (TLS) occurs conventionally similarly to surface scanning. Caves typically have complex shapes and various dimensions, and they are subject to challenges of the surrounding environment, such as narrow passages and complete darkness. However, the total darkness and orientation challenges in the confined spaces of caves are key distinctions between these environments, significantly affecting the logistics of capturing more than the scanning process itself. While the absence of light does not hinder the collection of point data, it limits the ability to obtain color data and photographs. This may not be an issue for applications like 3D modeling and geomorphological analysis, but for applications where photorealism is crucial (e.g., documenting cave paintings, and petroglyphs), external lighting is necessary. Considering this, it is important to use a systematic and efficient strategy that ensures the effective collection and processing of data for accurate capturing of the geometry and orientation of cave voids and, where needed, provides appropriate illumination for photography.

The standard practice in the field of surveying, conducted before data collection, is reconnaissance. However, in cave surveying, this stage is much more critical because caves pose various challenges, such as high temperature and humidity, restricted movement, and darkness. Thus, cave surveying requires detailed planning to ensure the selection of appropriate methods and the development of an effective data processing scheme. On the other hand, proper planning will ensure the quality of the collected data and the 3D model.

The first task in the planning stage is to define the project goals and ensure a clear understanding of the purpose of the task and user needs. Next is a visit to the site to identify technical and logistical issues that need to be addressed before data collection. The planning stage should take into account the cave's unique features, such as its shape, coverage, and other characteristics like lighting and temperature. In most cases, the cave's structure may lead to obtaining an insufficient number of point clouds. The scanner's location should be chosen so that successive scans have sufficient overlap, facilitating the merging of point clouds from different scanning positions. It is important to note that the choice of scanner should be based on its technical specifications and its adaptation to the cave's conditions.

A determining factor in cave 3D scanning is obtaining accurate three-dimensional data that ensures detailed and high-quality morphometric data as the foundation on which other cave information can be integrated and spatially analyzed. However, this requires a certain level of expertise on the operator's part. There are two possible approaches to creating ground-based laser scans during data collection. The first procedure is analogous to using an electronic theodolite, where the instrument is aligned with a ground control point, the coordinates of which are known. It then "backsights" to another visible control point to calculate the correct azimuth and angle. However, the uneven surface and perpetual darkness inside the cave make this orientation setup unfeasible. As a result, an alternative approach was specifically developed for cave exploration. It allows placing the scanner anywhere, ensuring optimal scanning coverage. Markers made from reflective materials that are easily identifiable are used; however, the accuracy of automatic registration improves with increasing scanning resolution.

The common practice is to place markers in the cave before the scanning begins, ensuring that at least three (preferably more) markers are visible at any time on two adjacent scanners, and their global positions are precisely measured using a theodolite, electronic theodolite, or a combination of GPS and electronic theodolite. The presence of alternative scanning registration procedures, such as cloud-to-cloud and automated targetless registration, gradually diminishes the use of artificial markers. For cave scanning, the overlap must be well-planned before the data collection process. A general rule is that approximately 25 percent overlap between two adjacent scans will yield high-quality registration. Points scanned from different stations are in different local coordinate systems. Therefore, registration is necessary to align these individual point clouds into a unified rectangular coordinate system. Additionally, for accurate data processing and comprehensive cave information, it must be tied to a global coordinate system. This is usually achieved through geodetic methods (GPS and electronic theodolite or theodolite). As GPS is ineffective inside caves, a common practice is to establish control points on the surface before entering the cave and use an electronic theodolite to transfer coordinates underground through a network of survey points. Point processing packages are designed to automatically determine the coordinates of markers used during registration, stitch point clouds obtained from different scans, and transform the scanner's Cartesian coordinate system into the local or global reference system.

To conduct terrestrial laser scanning research on Medova Cave, the following equipment was used:

1. Set of GNSS receivers Trimble R7 (Fig. 3).
2. Ground-based laser scanner Faro Focus 3D 120 (Fig. 4).

Fig. 3. Trimble R7 GNSS Receiver Set

Fig. 4. Faro Focus 3D 120 Terrestrial Laser Scanner

Measurements were taken from 4 points using 6 reflector marks (Fig. 5) to merge individual scans into a unified point cloud. Additionally, the coordinates of some marks were determined in the global coordinate system, allowing the transformation of the obtained 3D model of Medova Cave into this coordinate system.

Fig. 5. Volumetric reflector targets

Further processing of the data obtained from laser scanning of the cave was conducted using software. To stitch the acquired scans, we utilized Faro Scene 5.0 software, following these steps:

- Load object scans.
- Mark flat targets and spheres.
- Register scans based on defined points.

During registration, the program automatically connects the marked targets. As a result, we obtain point clouds in a unified coordinate system, forming a 3D model of the researched object (Fig. 7). To achieve the best accuracy in scan alignment, it is advisable to analyze the precision of their merging for each mark (Fig.6).

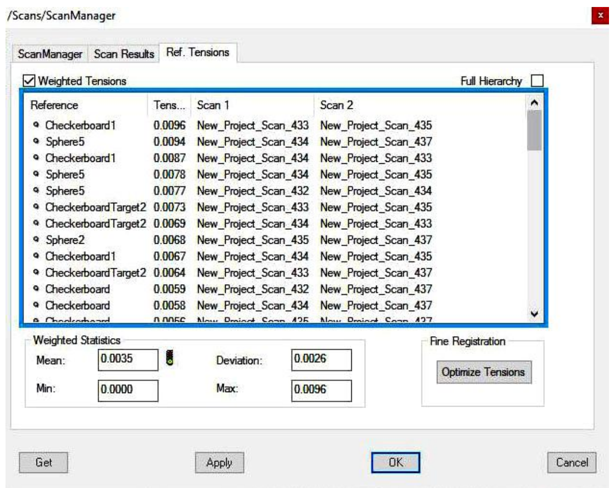

Fig. 6. Results of the accuracy analysis of marker alignment

The obtained accuracy of scan registration is 0.0035 m. The maximum deviation between flat markers is 0.0096 m, and the minimum is 0.0012 m. The maximum deviation between volumetric markers is 0.0086 m, and the minimum is 0.0005 m.

Fig. 7. Point cloud model of the Medova cave showing the location of markers

Results of the Research. Processing of laser scanning data and construction of a 3D model of the Medova Cave using Move software.

Subsequent construction of models of the Medova Cave was carried out using Move software, developed by Midland Valley, a global leader in creating programs for structural geology and geological mapping. Among the numerous functional capabilities, we utilized the 3D block and the block for constructing cross-sections. First, we imported the point cloud model created from laser scanning results. The model can be represented in various formats, and we chose *.obj, presenting it as a textured model. It is important to note that the new project should have the same coordinate system as the model. Since we are exploring a cave, it is practical to divide the model into two parts, upper and lower (Figs. 8, 9). This will be convenient for visualization as well.

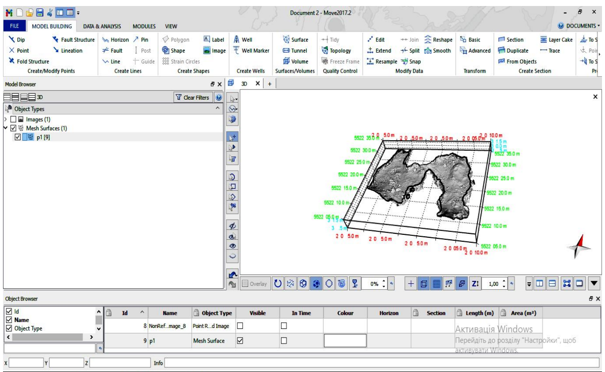

Fig. 8. The lower part of the Medova cave model loaded into the 3D module of the Move program

As we can see, these models represent only the surface of the cave. To visualize the internal structure, we use two approaches. The first one is to "slice the model" into two parts. See Fig. 10.

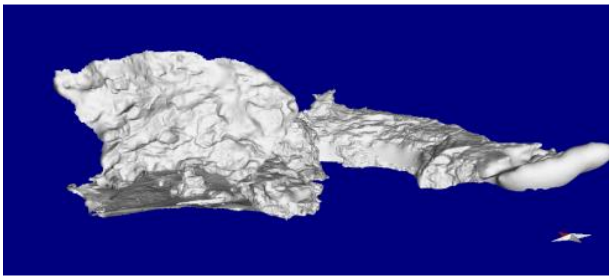

Fig. 9. The upper part of the Medova cave loaded into the Move program

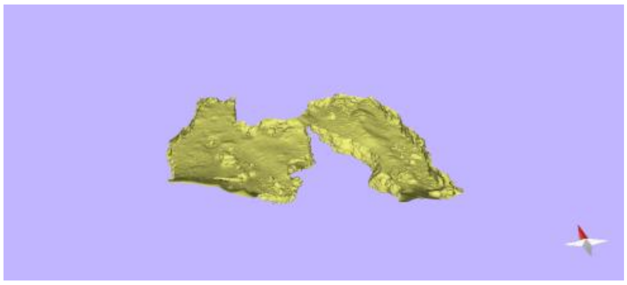

Fig. 10. Structure of the bottom of the Medova cave

The second way to represent the internal structure of the cave is by constructing a cross-section (Fig. 11 a,b). For this, the Section tool in the 3D module was utilized.

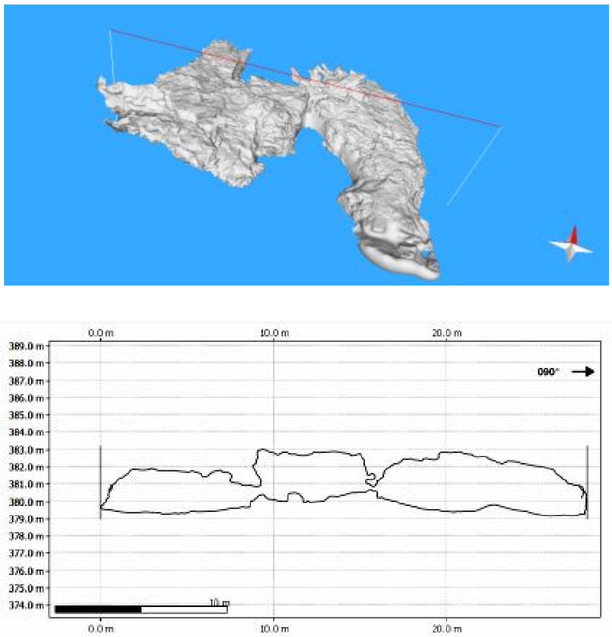

Fig. 11(a,b). Cross-section through Medova Cave along the selected direction

We use the "Creation Multiply Sections" function to demonstrate the internal structure, allowing us to build a series of cross-sections along selected directions simultaneously. In this process, we can choose not only the number and location of the sections but also the distance between them. Typically, these section planes are oriented vertically, but if necessary, they can be placed at any angle. Fig. 12 shows the arrangement of sections in Medova Cave, and Fig. 13 displays the actual sections.

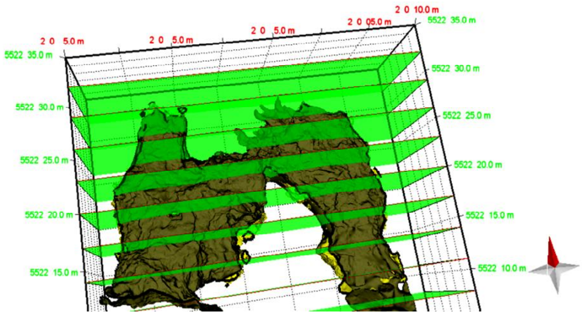

Fig. 12: Arrangement of cross-sections in Medova cave

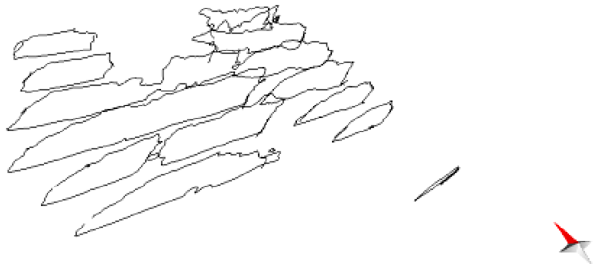

Fig. 13: Internal structure of Medova Cave shown as a series of cross-sections

Fig. 14: A detailed plan of the cave was constructed based on the obtained model, using the Map module. This module offers a wide range of tools for cartographic purposes, allowing the selection of contour intervals and other parameters.

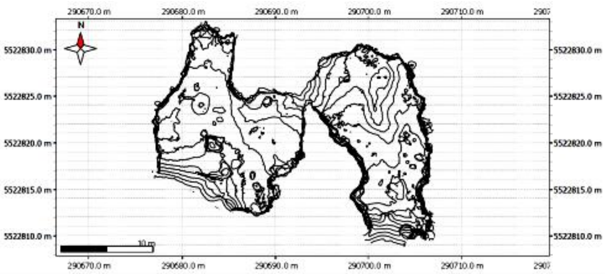

Fig. 14: Plan of the Medova Cave

The described model above will not be complete without showing the surface above which the cave is located. To display the surface, the results of aerial photography conducted by a group of researchers from the Institute of Geodesy were used. The obtained surface model was loaded into the Move software to the existing model of the Medova Cave. Based on these models, a cross-section was again constructed, on which both the cave and the surface above it are shown, as in Fig. 15.

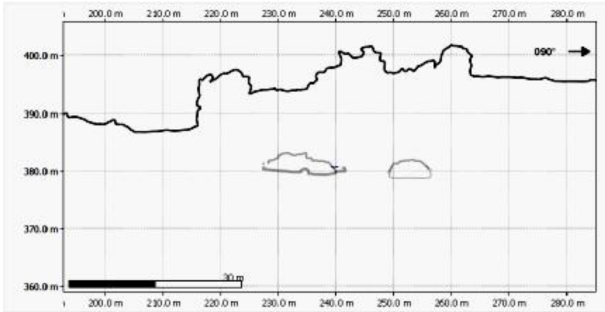

Fig. 15. Cross-section through the Medova cave and the surface beneath it

The result of the research is the obtained virtual model of the Medova Cave.

Scientific novelty and practical significance

The presentation of the 3D model of the Medova Cave in Lviv created through laser scanning, is characterized by significant scientific novelty in the context of cave geometry study and its utilization for further scientific research. One of the key innovations is the application of advanced laser scanning technology for comprehensive coverage of the cave's geometric features, considering its complex shape and diverse dimensions. Additionally, the novelty lies in the development of a data collection and processing strategy under conditions of complete darkness and limited spatial constraints within the cave. Accounting for these features enables the creation of an accurate and realistic 3D model, serving as the foundation for subsequent scientific investigations.

The practical significance of the obtained 3D model of the Medova cave lies in its practical applications. It can serve as a crucial tool for geological and geomorphological research, as well as for studying unique natural formations within caves. Additionally, this model opens up opportunities for tourism development, where virtual exploration of the cave can provide a distinctive experience for visitors.Furthermore, the creation of the 3D model represents a significant step in preserving and documenting the cultural heritage of the cave. This is essential for the further scientific and cultural development of the region, as well as for providing access to unique objects for researchers and the general public**.**

Conclusions

The result of the work demonstrates the suitability of using terrestrial laser scanning for the exploration of caves, including the construction of their models and plans. The findings of this study can be valuable for geologists, geomorphologists, and speleologists in conducting further research. The efficiency of surveying operations, the speed of data processing, and the high quality of the obtained data have been highlighted in the course of the work. We recommend employing this approach for studying other caves in Ukraine. The outcomes of this work can also be utilized in organizing excursions and in the educational process for students in higher education institutions specializing in Earth sciences.

This study highlights the significance and effectiveness of using terrestrial laser scanning (TLS) for creating detailed three-dimensional models of caves, as demonstrated by the example of the Medova Cave in Lviv. Thanks to this technology, we obtained an accurate and realistic 3D model of the cave, opening new perspectives for geological research, science, cultural heritage exploration, and tourism development.

TLS allowed us to better understand the geomorphological features and structural elements of the Medova Cave, which is of great significance for scientific research and the preservation of natural unique formations. Additionally, creating this model is a crucial step in documenting and preserving the cultural heritage of the region, providing valuable data access for researchers and the wider public.

Based on the results of this study, we recommend the application of TLS for studying other caves in Ukraine and believe that this technology can play a key role in enhancing the quality of cave surveying.

REFERENCES

Beraldin, J. A., Blais, F., Cournoyer, L., Picard, M., Gamache, D., Valzano, V., ... & Gorgoglione, M. A. (2006, October). Multi-Resolution Digital 3D Imaging System Applied to the Recording of Grotto Sites: the Case of the Grotta dei Cervi. In The *7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST* (pp. 45-52).

Blais, F., (2004). Review of 20 years of range sensor development. *Journal of Electronic Imaging*, 13 (1): 231-240. http://dx.doi.org/10.1117/1.1631921

Buchroithner, M. F. & Gaisecker, T. (2009). Terrestrial laser scanning for the visualization of a complex dome in an extreme alpine cave system. *Photogrammetrie - Fernerkundung - Geoinformation,* 4: 329–339. http://dx.doi.org/10.1127/1432-8364/2009/0025

Bubniak, I., Bubniak, A., Shylo, E., Oliinyk, M., & Bihun, M. (2021, November). Virtual otcrop of Eocene rocks of the Sokilskyi ridge (Outer Ukrainian Carpathians, Ivano-Frankivsk Region). In *15th International Conference Monitoring of Geological Processes and Ecological Condition of the Environment* (Vol. 2021, No. 1, pp. 1-5). European Association of Geoscientists & Engineers. https://doi.org/10.3997/2214-4609.20215K2077

Bubniak, I. M., Bubniak, A. M., Gavrilenko, O. D., Nikulishyn, V. I., & Golubinka, I. I. (2019, May). Using laser scanning and digital photogrammetry for creation of virtual geological *outcrops: Case studies from the west of Ukraine. In 18th International Conference on Geoinformatics-Theoretical and Applied Aspects* (Vol. 2019, No. 1, pp. 1-5). European Association of Geoscientists & Engineers. https://doi.org/10.3997/2214-4609.201902078

Caprioli, M., Minchilli, M., Scognamiglio, A. & Strisciuglio, G. (2003). Architectural and natural heritage: virtual reality with photogrammetry and laser scanning. In: *Proceedings of XIXth International Symposium CIPA,* Antalya, Turkey, p. 1–5.

Chandelier, L. & Roche, F. (2009). Terrestrial laser scanning for paleontologists: the Tautavel Cave. In: *XXII CIPA Symposium: Digital Documentation, Interpretation & Presentation of Cultural Heritage*, Kyoto, Japan, 11-15 October, 2009, p. 1–5

El-Hakim, S.F., Fryer, J. & Picard, M. (2004). Modeling and visualization of aboriginal rock art in the Baiame Cave. In: *Proceedings of the XXth Congress of the International Society for Photogrammetry and Remote Sensing:* 12-23 July 2004, Istanbul, Turkey. Commission V, Working Group V/2, p. 990–995.

Fryer, J. G., Chandler, J. H. & El-hakim, S. F., (2005). Recording and modelling an aboriginal cave painting: with or without laser scanning? *International Society for Photogrammetry and Remote Sensing*, 2: 1-8.

Haddad, N. A. (2011). From ground surveying to 3D laser scanner: A review of techniques used for spatial documentation of historic sites. *Journal of King Saud University of Engineering Sciences*, 23 (2): 109–118. https://doi.org/10.1016/j.jksues.2011.03.001

Kordic, B., Dapo, A. & Pribicevic, B. (2012). Application of terrestrial laser scanning in the preservation of fortified caves. In: FIG Working Week 2012. Knowing to manage the territory, protect the environment, evaluate the cultural heritage, Rome, Italy, 7 p.

Kuzik, Z., Stavovyi, A., & Ilkiv, T. (2017). Documentation and modeling of archaeological objects using digital photogrammetry. *Modern Achievements of Geodetic Science and Production*, (1), 125-130. (in Ukrainian).

Malitskyi, A., & Bubniak, I. (2017). Geological researches of Dyravets rock with using of land laser scanning. (in Ukrainian).

Marusazh, K. I. (2021). Development of a methodology for comprehensive research of changes in surface volumes of island glaciers on the Antarctic coast (Doctoral dissertation, National University "Lviv Polytechnic"). (in Ukrainian).

McFarlane, D. A., Buchroithner, M., Lundberg, J., Petters, C., Roberts, W. & Rentergen G. V. (2013). Integrated three-dimensional laser scanning and autonomous drone surface-photogrammetry at Gomantong Caves, Sabah, Malaysia. In: Proceedings of the *16th International Congress of Speleology*, Brno, 1: 317–319.

Perperidoy, D. G., Tzortzioti, E. & Sigizis, K., (2010). A new methodology for surveying and exploring complex environments using 3D scanning. In: *FIG Congress 2010 - Facing the Challenges - Building the Capacity*, Sydney, 11-16 April 2010, p. 1–14.

Robson-Brown, K. A., Chalmers A., Saigol T., Green C. & D'Errico F. (2001). An automated laser scan survey of the Upper Palaeolithic rock shelter of Cap Blanc. *Journal of Archaeological Science*, 28:283–289. http://dx.doi.org/10.1006/jasc.2000.0574

Rüther, H., Chazan, M., Schroeder, R., Neeser, R., Held, C., Walker, S. J. & Horwitz, L. K. (2009). Laser scanning for conservation and research of African cultural heritage sites: the case study of Wonderwerk Cave, South Africa. *Journal of Archaeological Science,* 36: 1847–1856. https://doi.org/10.1016/j.jas.2009.04.012

Savchyn, I., Shylo, Y., Bubniak, I., & Bubniak, A. (2019, November). Creation of the geological virtual govoruha dome outcrop (galindez island, western antartica). In Monitoring 2019 (Vol. 2019, No. 1, pp. 1-5). European Association of Geoscientists & Engineers. (in Ukrainian). https://doi.org/10.3997/2214-4609.201903270

Shaw, T. (2004). Speleologist. In: Gunn J. (Ed.), Encyclopedia of caves and karst science. Fitzroy Dearborn, New York, p. 686-689.

Shultz, R. V., Bilous, B., & Honcheriuk, O. M. (2016). Monitoring architectural monuments using terrestrial laser scanning. *Modern Problems of Architecture and Urban Planning,* 46, 202-207. (in Ukrainian).

Silvestre, I., Rodrigues, J. I., Figueiredo, M. J. G. & VeigaPires, C. (2013). Cave chamber data modeling and 3D web visualization. In: *Proceedings of the International Conference on Information Visualisation*, p. 468–473. http://dx.doi.org/10.1109/IV.2013.103

Tsakiri, M., Sigizis, K., Billiris, H. & Dogouris, S., (2007). 3D laser scanning for the documentation of cave environments. In: *11th ACUUS Conference: Underground Space, Expanding the Frontiers*, 10-13 September 2007, Athens, p. 403–408.

Zorin, D. O. (2008). Geological environment disturbances in Transnistria caused by karst processes. Environmental Safety and Rational Nature Management. *Scientific Bulletin of IFNTUNG*, 1(17), 150-155. (in Ukrainian).

Ігор БУБНЯК[1*], Марія ОЛІЙНИК[1], Сергій ЦІХОНЬ[2], Юрій ГОЛУБІНКА[3]

[1] Кафедра інженерної геодезії, Національний університет «Львівська політехніка», вул. С. Бандери 12, Львів, Україна, 79013, ел. пошта: ihor.m.bubniak@lpnu.ua, mariia.a.oliinyk@lpnu.ua, [*] https://orcid.org/0000-0002-3548-8785

[2] Геологічний факультет, Львівський національний університет ім. Івана Франка, вул. Університетська 1, Львів, Україна, 79000, ел. пошта: serhii.tsikhon@lnu.edu.ua

[3] General Commission of Survey, Saudi Arabia, ел. пошта iurii.golubinka@gmail.com

3Д МОДЕЛЬ МЕДОВОЇ ПЕЧЕРИ, М. ЛЬВІВ

Мета даної статті – представлення та детальний аналіз 3D-моделі Медової печери у Львові, яка була створена за допомогою технології лазерного сканування. Основні цілі включають розкриття точності та деталізації отриманої моделі, а також визначення можливостей її використання в різних сферах, таких як: геологічні дослідження, археологія, культурна спадщина та туризм. Крім того, мета статті – підкреслити важливість та переваги використання лазерного сканування для створення точних та реалістичних 3D-моделей печер, які відкривають нові можливості для вивчення та збереження природних унікальних формацій. Методика, використана в статті для створення 3D моделі Медової печери, охоплює декілька кроків: Підготовка та рекогносцирування, що включає проведення рекогносцирування печери для виявлення технічних та логістичних аспектів, такі як: температура, вологість, обмеження у русі та освітлення, необхідні для зйомки. Зйомка здійснюється за допомогою наземного лазерного сканування, яке є ефективним в умовах повної темряви та обмеженого простору. Наземне лазерне сканування забезпечує точний збір даних про геометрію печери. Для ефективного сканування та зшивання сканів використовуються маркери-рефлектори. Ці маркери розміщуються всередині печери перед початком сканування. При дослідженнях використовували спеціалізоване обладнання, як-от GNSS-приймачі Trimble R7 та наземний лазерний сканер Faro Focus 3D 120. Вимірювання проводили з різних точок для створення детальної хмари координованих точок, яка є основою для 3D моделі. Для зшивання отриманих сканів і створення єдиної точкової 3D моделі використовували програмне забезпечення, таке як Faro Scene. Під час реєстрації автоматично з'єднуються позначені марки. Проводили аналіз точності з'єднання марок для забезпечення високої якості реєстрації. Використовуючи програмне забезпечення Move, побудували детальні 3D моделі, включаючи текстуровані моделі та перетини для візуалізації внутрішньої структури печери. В результаті дослідження Медової печери за допомогою наземного лазерного сканування створена точна та деталізована тривимірна модель печери. Ця модель відкриває нові перспективи для геологічних досліджень, наукового вивчення, культурної спадщини та туризму. Особливість цього дослідження полягає у використанні передових технологій сканування, які дозволяють детально відтворити геометричні особливості печери, враховуючи її складну форму та різноманітні розміри. Отримана модель стала важливим інструментом для геологічних та геоморфологічних досліджень, а також для розвитку туризму та збереження культурної спадщини. Наукова новизна. Створення 3D-моделі Медової печери у Львові за допомогою лазерного сканування представляє собою значний прогрес у вивченні геометрії печер. Основною інновацією є використання передових технологій лазерного сканування для забезпечення детального відображення геометричних особливостей печери, враховуючи її складну структуру та різноманітність розмірів. Новизна полягає також у розробці стратегії збору та обробки даних в умовах повної темряви та обмеженого простору печери, що дозволило отримати точну та реалістичну 3D-модель. Практична значущість: 3D-модель Медової печери стає важливим інструментом для геологічних, геоморфологічних досліджень та вивчення унікальних природних формацій. Модель відкриває нові можливості для розвитку туризму, де віртуальне вивчення печери може забезпечити унікальний досвід для відвідувачів. Створення цієї 3D-моделі є важливим кроком у збереженні та документуванні культурної спадщини, сприяючи науковому та культурному розвитку регіону, а також забезпечуючи доступ до унікальних об'єктів для науковців та громадськості.

Ключові слова: лазерне сканування, 3D моделювання, геологічні дослідження, Медова печера, геометрія печер, геодезичні технології, туризм, геоморфологія, цифрова документація печер.

Received 15.10.2023