UDC 528.44; 528.88

Maksim BILIAVSKYI[1*], Nazarii DANYLIV[2*]

[1] Department of Engineering Geodesy of Lviv Polytechnic National University, 12, S. Bandery str., Lviv, 79013, Ukraine, e-mail: maksim.o.biliavskyi@lpnu.ua, https://orcid.org/0009-0008-9270-5142
[2] Department of Higher Geodesy and Astronomy of Lviv Polytechnic National University, 12, S. Bandery str., Lviv, 79013, Ukraine, e-mail: nazarii.v.danyliv@lpnu.ua

https://doi.org/10.23939/istcgcap2025.101.005

DIGITAL MAPPING OF TERRITORIES USING SLAM TECHNOLOGY: ANALYSIS OF THE ACCURACY OF THE RESULTS OBTAINED

The article addresses the issues of digital mapping of territories using modern equipment and innovative methods for performing topographic and geodetic work. *Objective.* To study modern territorial mapping methods and justify mapping approaches using SLAM technology. *Methods and results.* The study employed a territorial mapping method using handheld laser scanners with SLAM technology. Terrain reconnaissance was conducted, control geodetic points were established, and fieldwork was performed using a Stonex X120GO scanner. The acquired point clouds were compared with the tacheometric survey results. Analysis of mean square errors confirmed that the accuracy met regulatory requirements. *Scientific novelty and practical significance.* This study enables the evaluation of SLAM technology in ground-based handheld laser scanners as an alternative to traditional topographic surveying methods. When used correctly, this type of equipment fully meets the accuracy requirements for topographic plans at a scale of 1:500 and, in some cases, even 1:200. This, in turn, creates opportunities for the broader implementation of SLAM in topographic and geodetic practices. Applying SLAM technology and modern handheld laser scanners for topographic, geodetic, and mapping tasks can significantly reduce costs, resource consumption, and labor efforts while requiring fewer personnel and pieces of equipment. The study evaluates the possibilities of using SLAM technology and its accuracy. The article proves that using SLAM technology and handheld 3D scanners is an accurate and reliable tool for performing work in modern realities.

Keywords: SLAM (Simultaneous Localization and Mapping), Digitals software, territory mapping, laser scanning, software product, LIDAR, topographic plan, integration of modern approaches, GNSS receiver, point cloud, handheld scanner, topographic and geodetic works.

Introduction

Currently, the automation of task execution and the adoption of new advanced technologies, methods, and tools play a decisive role. Automation is also being widely implemented in classical geodesy and mapping. In the classical sense, territorial mapping is a labor-intensive process. It typically involves a team of two surveyors and geodetic equipment, usually a combination of GNSS receivers and an electronic total station.

This process requires establishing a temporary geodetic network for tacheometric surveying. Subsequent stages require measurement adjustments. At least two people are involved: one operates the total station, and the other manages the reflector to ensure reliable terrain element surveying [Khairuddin et al., 2015].

One of the most advanced and efficient approaches to significantly reducing fieldwork time is the use of ground laser scanners in classical geodesy. To better understand how these scanners work, it is necessary to examine their technology and data collection methods. Various types of ground scanners are available. Most 3D laser scanners on the market are static. They are mounted on a tripod and function as fixed stations during the scanning process. Recently, handheld laser scanners have gained popularity. Unlike static scanners, they do not require a fixed position and can be used while in motion.

3D laser scanners are potent tools for collecting vast amounts of environmental data using LiDAR technology [Shan & Toth, 2018]. This active sensor emits laser beams that reflect off surfaces and return to the sensor. The system determines spatial positions of points in 3D space and merges them to form a detailed point cloud. To enhance this data, color information from area photographs is used [Palomer et al., 2019]. These photos are typically captured with panoramic cameras. As a result, the RGB components are added to the point cloud during processing and export. A colorized point cloud is called a textured point cloud. A grayscale version is called an intensity point cloud.

3D scanners are used in digital mapping [Alsadik & Karam, 2021] and modeling for tasks such as deformation monitoring, architectural modeling, and other topographic or engineering projects. Scanner localization and orientation are based on integrating GNSS and IMU data. Therefore, accuracy depends on the scanner's laser sensor, the IMU's performance [Chen et al., 2017], and the quality of GNSS observations at reference points. These control points enable alignment of the point cloud with the correct coordinate and height systems [Taheri & Xia, 2021].

The final coordinate system depends on the operator's choice, which is convenient for global users. However, to ensure accuracy, several factors must be considered – including the selected coordinate system and external influences.

Even ground-based laser scanners are not flawless. Accuracy may be affected by equipment characteristics and external factors. One key factor is the scanner's angle relative to the ground. The optimal angle is close to 180 degrees. Reflectivity of surfaces also affects scanning. Mirror-like or dark objects absorb more laser energy and reflect less. Thus, material properties such as color, texture, gloss, or transparency influence signal intensity.

Weather conditions are also critical. They may strongly affect results and sometimes render data unusable. Heavy rain or snow introduces noise and distorts point cloud accuracy [Ridao & Ribas, 2019]. Therefore, proper timing of field scanning is essential.

Using handheld scanners with SLAM technology [Taheri & Xia, 2021] allows for comprehensive terrain representation. Unlike total stations, which capture only discrete measured points, SLAM scanners generate point clouds of the entire surveyed area along the operator's route.

This results in a detailed model of the terrain, including geometry, coordinates, and elevation. Operators can return to the point cloud at any stage of mapping and obtain real-time information about object dimensions or configurations [Zhang et al., 2021].

This is not possible with traditional methods and incurs no extra cost, making it highly efficient [Kazerouni et al., 2022; Zhang et al., 2024].

SLAM-based mapping is therefore a fast, resource-efficient, and accurate method. It meets topographic requirements at appropriate scales. Its accuracy is comparable to traditional geodetic equipment and survey methods [Kim et al., 2018; Yue et al., 2024].

Methods and techniques

The article is based on the results of a detailed analysis of the capabilities of territory mapping using handheld laser scanners equipped with SLAM technology, as well as an accuracy assessment of SLAM-based mapping through the calculation of the root mean square errors (RMSE) of coordinates obtained from SLAM surveys compared to the results of total station surveys conducted in previous years.

As part of the study, a sequence of activities was performed to collect and analyze spatial data to create a cartographic base for the study area. Initially, a preliminary analysis of the technical assignment was conducted, allowing the main mapping requirements to be defined and an action plan to be developed [Zhang et al., 2024], where the preliminary data acquisition approach is described in detail. Subsequently, a reconnaissance survey of the area was conducted to identify the most suitable locations for placing temporary geodetic points. Their coordination was performed following modern methodologies, similar to the approaches described by [Huang, 2021]. The following technical stages were implemented: securing control points in the field, based on which the root mean square errors (RMSE) of the measurements were calculated; Collection of spatial data using a mobile laser scanner employing SLAM technology, which has demonstrated its effectiveness under challenging conditions, as shown in the study by [Alsadik and Karam, 2021]; Processing and analysis of the SLAM mapping results, including the calculation of the RMSE of the obtained data according to the methodologies proposed by [Jia, et al., 2021]; Comparison of the newly created cartographic materials with data from previous topographic surveys, allowing for the assessment of deviations in elevation and planimetric coordinates. A similar approach was demonstrated by [Droeschel and Behnke, 2018]; Identification of factors influencing the accuracy of SLAM mapping, including sensor quality, equipment parameters, and specific survey conditions [Pierzchała et al., 2018]. Completing these technical stages provides a comprehensive understanding of the study object. It ensures the production of high-quality cartographic materials for further practical analysis of the proposed methodologies and approaches, as well as a qualitative evaluation of the project workflow.

The tacheometric method is considered to be one of the most accurate in classical geodesy. Its high level of detail and minimal measurement errors are achieved through “reflectorless” mode, which enables measurements to be taken directly on an object or terrain feature [Chong et al., 2015]. Thus, it can be noted that using materials generated based on tacheometric surveying is a highly accurate and significant element for conducting a comparative analysis of the accuracy of digital mapping of territories. The paper details the process of conducting fieldwork with a handheld laser scanner using SLAM technology and the subsequent desktop data processing. The paper also provides examples of software products that can perform digital territory mapping and their application.

The process of work execution and the results obtained

To achieve the research objective, field studies were conducted at designated engineering and technical sites.. Before commencing work, we analyzed the terms of reference for preparing a topographic plan of a critical infrastructure facility – specifically, a 330 kV power substation in the Lviv region. The task involved conducting geodetic surveys in two zones: the 35 kV switchgear and the 110 kV switchgear. A team of two surveyors conducted the topographic and geodetic surveys of the 35 kV switchgear area – the authors of this article. Regarding the 110 kV area, geodetic surveys had already been conducted earlier, and cartographic materials were available as a 1:500 scale topographic plan. Therefore, the task involved reconnaissance and site inspection to identify changes. These mapping materials were subsequently used as an additional tool to compare the accuracy of mapping derived from the point cloud obtained via SLAM technology.

First, the site was reconnoitered, and the locations of temporary control geodetic points were determined. The 110 kV switchgear area was also inspected, confirming no visual changes. A more detailed site analysis was conducted after obtaining the fieldwork results. Temporary reference points were established by marking them with paint and determining their coordinates using a Stonex S700A GNSS receiver in real-time kinematic (RTK) mode at a fixed resolution, achieving an accuracy of (8 mm + 1 ppm) in plan and (15 mm + 1 ppm) in height (Fig. 1–3).

Fig. 1. Marking control points with paint

Fig. 2. Recording the coordinates of control points – item 14

After marking the points on the ground, the same points were recorded using a Stonex X120GO laser scanner. For this purpose, we used the scanner’s centering platform-stand, aligning it precisely on the designated points, as shown in Figs. 4–7. After setting up the stand with the scanner at the point, we entered the control point with the corresponding point number into the controller. These processes are carried out to balance the point cloud further and establish the appropriate coordinate and height system. The SK-63 coordinate system and the Baltic height system were used in our case. This was because the 110 kV switchgear area survey was conducted using this coordinate system and was transferred electronically.

Fig. 3. Recording the coordinates of control points – item 2

Fig. 4. Control point No. 5 in the field

Fig. 5. Capturing the point with a scanner

Fig. 6. Setting up the scanner on the control point

Fig. 7. Control point No. 13 in the field

During the point cloud registration process, 15 points were established and used. During the work, one path (route) was created that covers the entire work area. We also calculated the mean square error for the coordinates determined from the point cloud for track, as shown in Table 1. Fig. 8 shows the location of control. The mean square errors for determining the planned elevation position from the point cloud are as follows: DX = 0.037 m, DY = –0.039 m, DXY = = 0.047 m, DZ = 0.018 m. In this context, the DZ

value represents the elevation deviation in the Baltic Height System relative to control points. This notation was chosen to preserve the original structure of the software-generated report and maintain data integrity. The software used with the scanner is a new development, in which the *DZ* value is applied to denote elevation deviations regardless of the height reference system in use.

The obtained level of accuracy fully meets the requirements for creating a cartographic product, defined by the current legislation of Ukraine and the rules of topographic surveying. In particular, for a plot plan at a scale of 1:500, the permissible error should not exceed 0.1 mm on the plan, which corresponds to 5 cm on the ground, according to the scale of the topographic plan. The results of the UCP calculation are presented in Table.

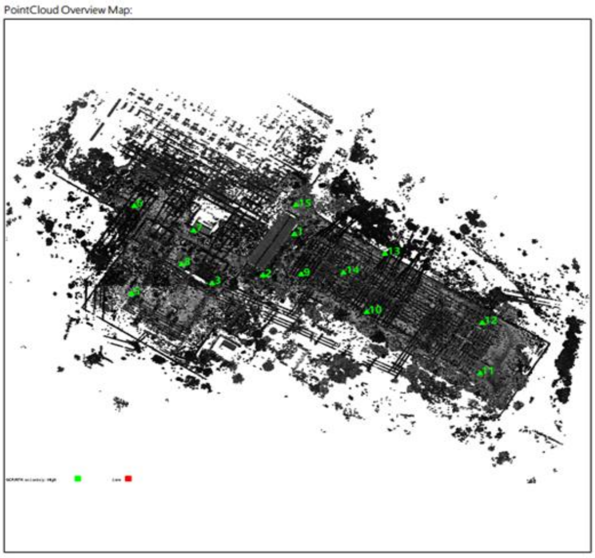

Fig. 8. Scheme of control point placement for track on the point cloud

Report on the determination of RMS of measurements for track

No.	East *X*	North *Y*	Up *Z*	Measure *x*	Measure *y*	Measure *z*	*DX*	*DY*	*DXY*	*DZ*
5	1 321 473,628	5 518 000,262	282,586	1 321 473,591	5 518 000,289	282,585	0.037	–0.027	0.046	0.001
3	1 321 534,263	5 518 009,339	283,81	1 321 534,232	5 518 009,335	283,824	0.031	0.004	0.031	–0.014
8	1 321 511,17	5 518 025,398	283,698	1 321 511,124	5 518 025,397	283,713	0.046	0.001	0.046	–0.015
6	1 321 474,737	5 518 075,238	282,996	1 321 474,775	5 518 075,189	283,01	–0.038	0.049	0.062	–0.014
7	1 321 520,31	5 518 054,248	284,277	1 321 520,271	5 518 054,251	284,302	0.039	–0.003	0.039	–0.025
8	1 321 511,166	5 518 025,398	283,728	1 321 511,124	5 518 025,357	283,723	0.042	0.041	0.059	0.005
3	1 321 534,223	5 518 009,339	283,81	1 321 534,232	5 518 009,335	283,834	–0.009	0.004	0.01	–0.024
2	1 321 572,577	5 518 015,923	284,599	1 321 572,546	5 518 015,981	284,555	0.031	–0.058	0.066	0.044
10	1 321 650,699	5 517 984,79	284,934	1 321 650,732	5 517 984,765	284,916	–0.033	0.025	0.041	0.018
11	1 321 766,046	5 517 927,488	284,691	1 321 766,085	5 517 927,482	284,706	–0.039	0.006	0.039	–0.015
9	1 321 601,303	5 518 016,991	284,914	1 321 601,351	5 518 016,959	284,898	–0.048	0.032	0.058	0.016
14	1 321 633,192	5 518 018,399	284,934	1 321 633,245	5 518 018,401	284,92	–0.053	–0.002	0.053	0.014
12	1 321 737,688	5 517 975,466	284,696	1 321 737,704	5 517 975,452	284,711	–0.016	0.014	0.021	–0.015
13	1 321 664,488	5 518 034,511	284,372	1 321 664,435	5 518 034,518	284,363	0.053	–0.007	0.053	0.009
15	1 321 697,281	5 518 075,365	284,705	1 321 697,297	5 518 075,335	284,716	–0.016	0.03	0.034	–0.011
1	1 321 596,149	5 518 051,169	285,034	1321596 161	5 518 051,239	285,016	–0.012	–0.07	0.071	0.018
2	1 321 572,577	5 518 015,929	284,559	1 321 572,546	5 518 015,918	284,555	0.031	0.011	0.033	0.004
9	1 321 601,303	5 518 016,891	284,904	1 321 601,351	5 518 016,939	284,898	–0.048	–0.048	0.068	0.006
	Mean	Error					–0.002	0.002	0.044	0.002
	RMSE	(m.)					0.037	0.039	0.047	0.018

A visual inspection of Table 1 may suggest the presence of a potential systematic shift, particularly based on certain values. Specifically, the table presents 11 positive differences in the *DY* column out of 15 listed values. Therefore, to verify the statistical consistency of the results, a hypothesis test for normal distribution was performed.

To assess the statistical distribution of coordinate deviations, the Shapiro – Wilk test was applied to the residuals in the *X*, *Y*, and *Z* directions (*DX, DY, DZ*) from the first track. The obtained *p*-values were as follows: *DX* ($p = 0.0226$), *DY* ($p = 0.1977$), and *DZ* ($p = 0.1739$). These results indicate that the *DY* and *DZ* components follow a normal distribution ($p > 0.05$), while the *p*-value for *DX* suggests a deviation from normality ($p < 0.05$).

This deviation in *DX* is likely due to the geometric characteristics of the scanning trajectory. In particular, the track exhibited greater width than length, which made the *X* component more sensitive to localized drift and loop closure effects inherent in SLAM-based scanning. Nevertheless, the root mean square error for *DX* (*RMSE* = 0.037 m) remains within the acceptable limits for a 1:500 scale topographic plan, thus confirming the reliability of the measurements.

To further verify the presence of potential bias, a comparative analysis was performed between cartographic products obtained from different equipment and methods, based on fieldwork conducted at the same site.

The key feature of SLAM technology in handheld electronic scanners is that the point cloud stitching occurs in real time. This is illustrated in the controller image (Fig. 9), which shows how the sectors of the data set are displayed, within which the position of terrain objects is recorded at a specific point in time (indicated by the white cone-shaped contours on the controller). Additionally, in Fig. 10, you can observe how the process of fixing the route in the point environment occurs, as well as how the point cloud is populated with terrain elements.

Analyzing this information, it is evident that this is a highly positive aspect, as it eliminates the need for additional expensive software packages used with some types of scanners to stitch the point cloud, and also reduces the potential for user errors that can occur during manual stitching, as is the case with data from stationary ground laser scanners. After completing the fieldwork, we obtained a ready-made point cloud, which we imported from the controller to a computer and loaded it into the SLAM GOpost software environment, as shown in Fig. 11. You can now additionally colorize the point cloud by combining the point set with images taken synchronously and automatically by the handheld scanner camera. In the SLAM GOpost software environment, the point cloud can be combined with LiDAR data and photos of the terrain object, which can be used to colorize the point cloud to match natural colors. The visualization of the point cloud after processing the results in the SLAM GOpost software environment is shown in Figs. 12, 13. The gradient color represents terrain heights, and it also displays the route of the operator's movement during fieldwork, which is visually marked with a continuous white line.

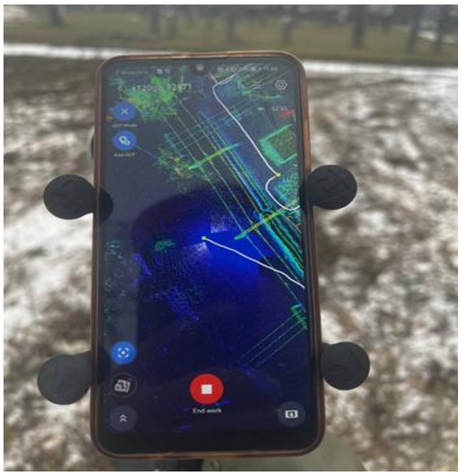

Fig. 9. Display of a dataset sector on the controller

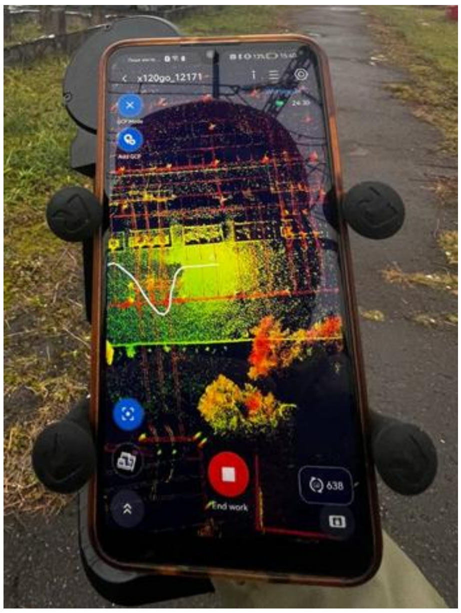

Fig. 10. Process of recording the route on the controller

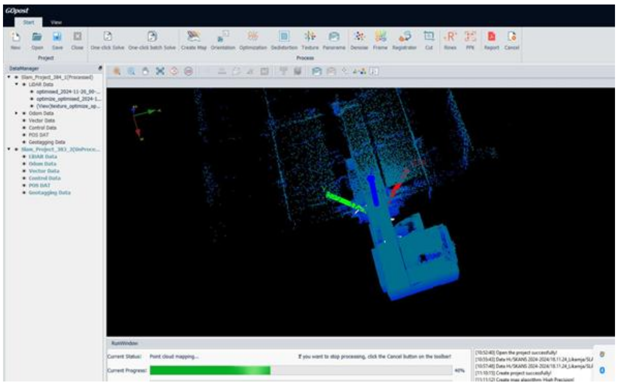

Fig. 11. Data upload into the SLAM GOpost

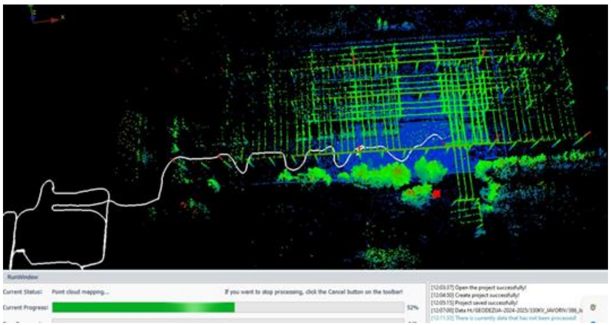

Fig. 12. Route visualization

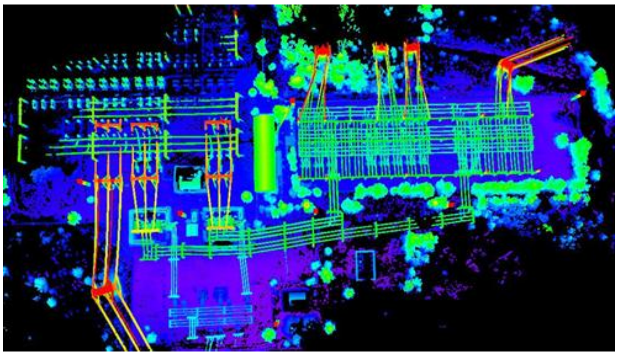

Fig. 13. Point cloud visualization following data processing in the SLAM GOpost software environment

Electronic digital maps in Ukraine are predominantly created using the Digitals software package. This program is unique in our country and is highly convenient for solving issues related to creating electronic digital plans and maps due to its user-friendly interface, ease of use, affordability, and the ability to integrate different symbol sets and edit existing ones. Additionally, this software product can be easily combined with other programs; it allows for importing data obtained from other software products, such as orthophotos, plans, images, or point clouds. To integrate our point cloud into the Digitals software package, several options for further development and data import methods can be used, each of which is viable. However, we will focus on the method used to solve this problem.

The first option is to import a point cloud with a .las extension directly into the workspace, which can be done using the File – Open – LAS format – Open menu. The second option, which we used, involves using an additional software package that allows for qualitative inspection, rotation, and trimming of the point cloud in the desired areas and shapes – we are referring to the 3DSurvey software product. This program is excellent for working with point clouds. Furthermore, the working environment allows for the immediate creation of layers (Fig. 14) with the ability to specify the layer name, symbols, and the color of linear elements. Among the program's disadvantages, it isessential to highlight that the primary drawing elements available in this software package are lines and points. Thus, we process the materials by selecting the primary components and contours of the terrain directly from the point cloud and entering them into the desired layer of symbols immediately (Fig. 15). After obtaining the basic data set, which, as mentioned above, consists mainly of linear and point elements, we proceed with the data export function. This action is performed using the console, as shown in Fig. 16.

After exporting the data, we import it into the Digitals environment. The result is displayed in Fig. 17. Subsequent data processing involves integrating the available mapping methods to create an effective workflow that ensures the rapid generation and processing of fieldwork materials.

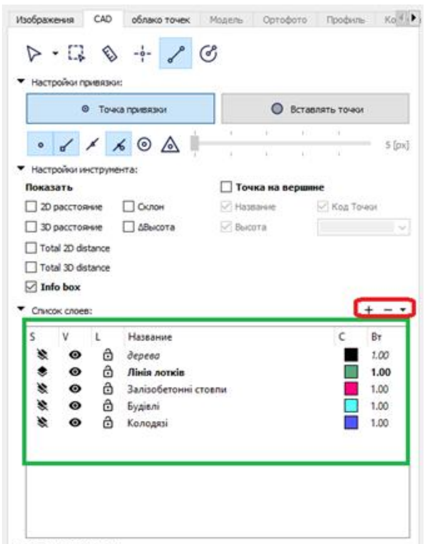

Fig. 14. Layer creation within the program's workspace

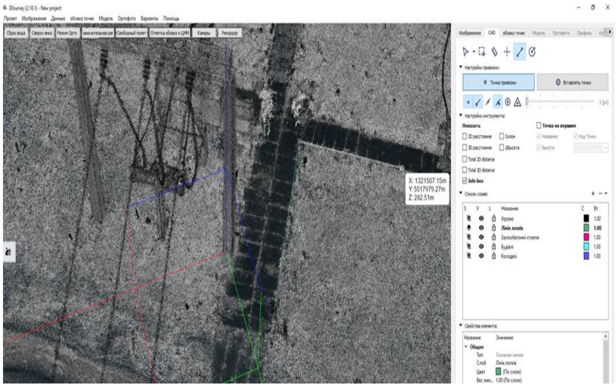

Fig. 15. Drawing of terrain features on the point cloud

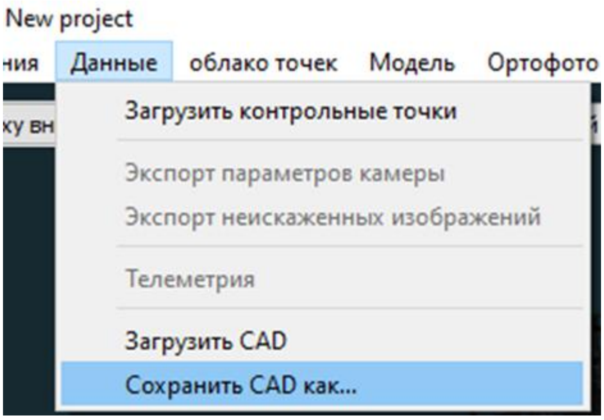

Fig. 16. Data export function

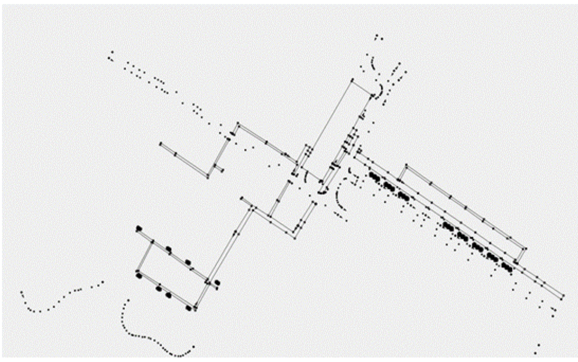

Fig. 17. Data upload into the Digitals environment

Thus, we proposed using both classical and non-classical methods – combining a linear point data frame (Fig. 17) with orthophoto terrain maps – presented as a point cloud image with varying gradient fills, point densities, point sizes, and image contrasts (Figs. 18, 19).

The combination of these methods results in a high-quality terrain image. Using a comprehensive approach to digital mapping with various software products in modern engineering, geodetic, and topographic work enables the rapid and efficient creation of a topographic plan at the desired scale. It also guarantees a reduction in labor costs, which can be decisive in the modern realities of wartime. In our reality, the speed of work in the field can also play a decisive role in the safety of employees, which is a priority in our time. After downloading the fieldwork materials and importing them into the Digitals software environment, the classic mapping process is carried out, ensuring that the requirements for topographic plans at the specified scale are met. Based on the results of this processing, we created a topographic plan of the territory of the selected object at a scale of 1:500. The choice of this scale was determined by the technical conditions and task requirements for the work after downloading the fieldwork materials and importing them into the Digitals software environment, a classic mapping process takes place, ensuring the requirements for topographic plans at the specified scale are met.

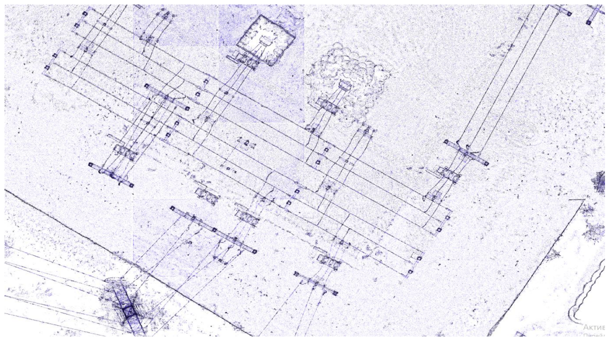

Fig. 18. View of an orthophotoplan fragment – adjusted point size and contrast

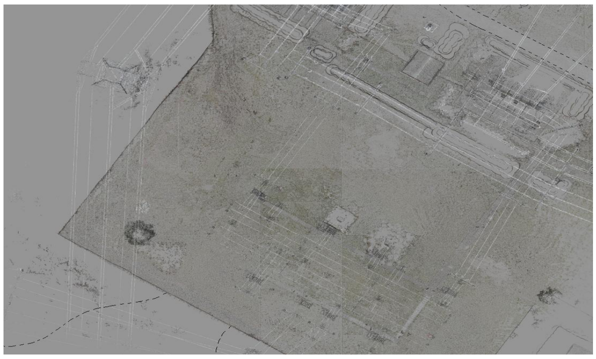

Fig. 19. View of an orthophotoplan fragment – adjusted point cloud density and display color

Based on the results of this processing, we created a topographic plan of the territory of the specified object at a scale of 1:500. The technical conditions and task requirements for the work determined the choice of this scale. A fragment of this is presented in Fig. 20.

Fig. 20. Fragment of a topographic plan of the area at a scale of 1:500

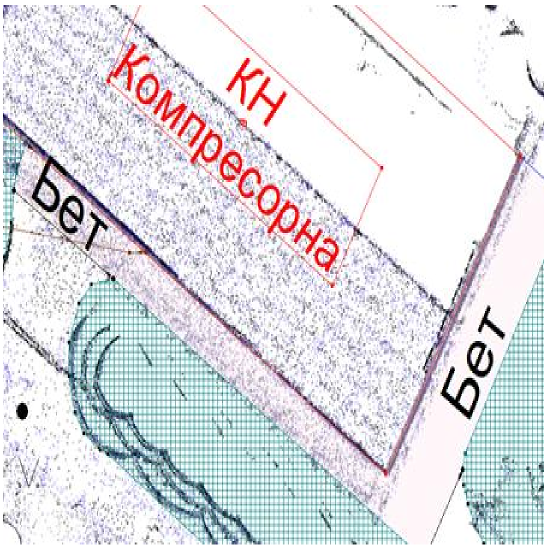

Fig. 21. Comparison of the building's planimetric position on the existing topographic plan with the building outlines on the point cloud

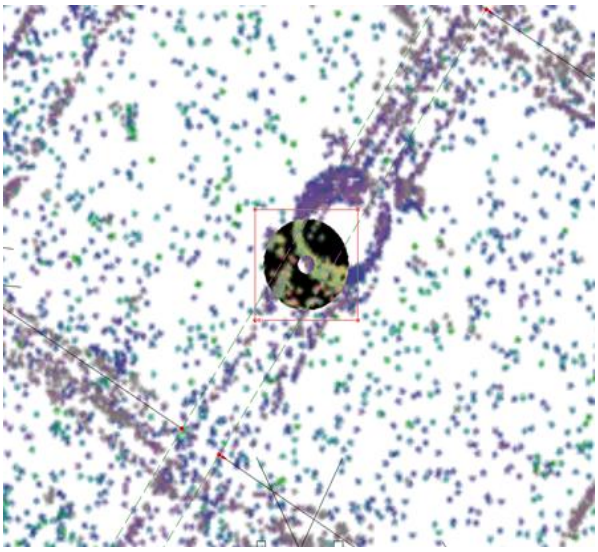

Fig. 22. Comparison of the planimetric position of the electric pole on the existing topographic plan with its position on the point cloud

After creating the topographic plan, we conducted an additional analytical study of its accuracy. This was done by comparing the position of spatial objects on the topographic plan created using SLAM technology with the topographic survey material obtained using classical equipment –

an electronic total station and a GNSS receiver. This comparative analysis is purely informative and cognitive, as the SPC of earlier measurements supports the use of SLAM technology. For the analysis, several random terrain elements were selected, and discrepancies in spatial position were measured by determining linear deviations. The results of this analysis, presented in Figs. 21–22, demonstrate that the linear deviations between objects on the topographic maps are minor, amounting to approximately 0.1 mm on the plan, which corresponds to distances of up to 5 cm on the ground according to the map scale. This is an excellent outcome, considering the experimental nature of SLAM technology and its innovative application in topographic-geodetic and cartographic work. Thus, we can confirm the effectiveness and clear feasibility of using this technology to reduce the demand for professional personnel in the geodetic services sector. Developing and integrating innovative approaches and modern equipment into classical geodetic processes is a critical task for specialists in this industry. New techniques allow for the optimization of costs and significantly increase the speed of task completion, while maintaining the quality of the final materials. Integrating modern approaches is essential for staying current, following the example of progressive, world-leading countries, and adopting their methods for optimizing and increasing process efficiency.

Scientific novelty and practical significance

This study evaluates SLAM technology in ground-based handheld laser scanners as an alternative to traditional topographic surveying methods. When used correctly, this type of equipment fully meets the accuracy requirements for topographic plans at a scale of 1:500 and, in some cases, even 1:200. This, in turn, creates opportunities for the broader implementation of SLAM in topographic and geodetic practices. Applying SLAM technology and modern handheld laser scanners for topographic, geodetic, and mapping tasks can significantly reduce costs, resource consumption, and labor efforts while requiring fewer personnel and pieces of equipment. The study evaluates the possibilities of using SLAM technology and its accuracy. The article proves that using SLAM technology and handheld 3D scanners is an accurate and reliable tool for performing work in modern realities.

Conclusions

Key findings were obtained from a study on SLAM technology for digital mapping of areas using handheld laser scanners, highlighting the accuracy and efficiency of the method. The fieldwork conducted with the Stonex X120GO scanner demonstrated high accuracy in the collected data, meeting the regulatory and legal requirements for producing topographic plans at a scale of 1:500, and in some cases, even 1:200, which is an exceptionally high indicator. Additionally, the UPC (Unit of Precision Coordinates) analysis of measurements taken during the fieldwork confirmed that the obtained values are within permissible limits. This further demonstrates the high potential of SLAM mapping technology as a viable alternative to traditional geodetic methods and underscores the importance of its rapid integration into geodetic processes to increase efficiency and reduce costs for high-expense fieldwork in digital mapping of territories.

This study plays a pivotal role, proving that using SLAM technology in modern handheld laser scanners can significantly reduce the time required for fieldwork. The ability to quickly process large areas, while acquiring high-quality data and creating detailed and accurate three-dimensional terrain models, makes it ideal for mapping territories. However, certain aspects of using modern approaches in cartographic work must also be noted. While SLAM technology offers significant advantages, such as speed and resource savings, it also has limitations, particularly the potential effects of external factors on scanning accuracy. Weather conditions (e. g., snow or rain) can introduce additional noise and interference, and varying surface types or other technical elements can affect the effectiveness of this technology. These factors must be carefully considered to ensure maximum accuracy and reliability of the results.

Nevertheless, the findings from the study provide reliable evidence that SLAM technology, when combined with laser scanners, is highly promising. This represents a new direction in developing geodetic and cartographic work in modern conditions. Innovations such as these enhance the efficiency of work processes and significantly expand the possibilities in environments with limited resources or challenging natural conditions. Considering these factors, it is clear that integrating SLAM technology into modern mapping practices can shortly play a decisive role in optimizing the processes of producing digital maps and terrain models. Thus, using SLAM technology for territory mapping is a reliable and highly effective method that fully meets the requirements of modern geodesy and cartography. It holds significant potential for further development and implementation in various geodetic, engineering, and construction projects.

References

Alsadik, B., & Karam, S. (2021). The simultaneous localization and mapping (SLAM): An overview. *Surveying and geospatial engineering journal, 1*(2), 1–12. https://doi.org/10.38094/sgej1027

Chen, M., Yang, S., Yi, X., & Wu, D. (2017, July). Real-time 3D mapping using a 2D laser scanner and IMU-aided visual SLAM. In *2017 IEEE International Conference on Real-time Computing and Robotics (RCAR)* (pp. 297–302). IEEE. https://doi.org/10.1109/RCAR.2017.8311877

Chong, T. J., Tang, X. J., Leng, C. H., Yogeswaran, M., Ng, O. E., & Chong, Y. Z. (2015). Sensor technologies and simultaneous localization and mapping (SLAM). *Procedia Computer Science, 76*, 174–179. https://doi.org/10.1016/j.procs.2015.12.336

Droeschel, D., & Behnke, S. (2018, May). Efficient continuous-time SLAM for 3D lidar-based online mapping. In *2018 IEEE International Conference on Robotics and Automation (ICRA)* (pp. 5000–5007). IEEE. https://doi.org/10.1109/ICRA.2018.8461000

Huang, L. (2021, November). Review on LiDAR-based SLAM techniques. In 2*021 International conference on signal processing and machine learning (CONF-SPML)* (pp. 163–168). IEEE. https://doi.org/10.1109/CONF-SPML54095.2021.00040

Jia, S., Liu, C., Wu, H., Zeng, D., & Ai, M. (2021). A cross-correction LiDAR SLAM method for high-accuracy 2D mapping of problematic scenario. ISPRS *Journal of Photogrammetry and Remote Sensing, 171*, 367–384. https://doi.org/10.1016/j.isprsjprs.2020.11.004

Kazerouni, I. A., Fitzgerald, L., Dooly, G., & Toal, D. (2022). A survey of state-of-the-art on visual SLAM. *Expert Systems with Applications*, *205*, 117734. https://doi.org/10.1016/j.eswa.2022.117734

Khairuddin, A. R., Talib, M. S., & Haron, H. (2015, November). Review on simultaneous localization and mapping (SLAM). In *2015 IEEE international conference on control system, computing and engineering (ICCSCE)* (pp. 85–90). IEEE. https://doi.org/10.1109/ICCSCE.2015.7482163

Kim, P., Chen, J., & Cho, Y. K. (2018). SLAM-driven robotic mapping and registration of 3D point clouds. *Automation in Construction, 89*, 38–48. https://doi.org/10.1016/j.autcon.2018.01.009

Palomer, A., Ridao, P., & Ribas, D. (2019). Inspection of an underwater structure using point-cloud SLAM with an AUV and a laser scanner. *Journal of field robotics, 36*(8), 1333–1344. https://doi.org/10.1002/rob.21907

Pierzchała, M., Giguère, P., & Astrup, R. (2018). Mapping forests using an unmanned ground vehicle with 3D LiDAR and graph-SLAM. *Computers and Electronics in Agriculture, 145*, 217–225.

Shan, J., & Toth, C. K. (2018). Topographic Laser Ranging and Scanning: Principles and Processing (2nd ed.). Taylor & Francis Group. https://doi.org/10.1016/j.compag.2017.12.034

Taheri, H., & Xia, Z. C. (2021). SLAM; definition and evolution. Engineering *Applications of Artificial Intelligence, 97*, 104032. https://doi.org/10.1016/j.engappai.2020.104032

Yue, X., Zhang, Y., Chen, J., Chen, J., Zhou, X., & He, M. (2024). LiDAR-based SLAM for robotic mapping: state of the art and new frontiers. *Industrial Robot: the international journal of robotics research and application, 51*(2), 196–205. https://doi.org/10.1108/IR-09-2023-0225

Zhang, S., Zheng, L., & Tao, W. (2021). Survey and evaluation of RGB-D SLAM. IEEE Access, 9, 21367–21387. Zhang, S., Zheng, L., & Tao, W. (2021). Survey and evaluation of RGB-D SLAM. IEEE Access, 9, 21367-21387.

Zhang, Y., Shi, P., & Li, J. (2024). 3d lidar slam: A survey. *The Photogrammetric Record, 39*(186), 457–517. https://doi.org/10.1111/phor.12497

МАКСІМ БІЛЯВСЬКИЙ[1*], НАЗАРІЙ ДАНИЛІВ[2*]

[1] Кафедра інженерної геодезії, Національний університет “Львівська політехніка”, вул. С. Бандери, 12, Львів, 79013, Україна, e-mail: maksim.o.biliavskyi@lpnu.ua, https://orcid.org/0009-0008-9270-5142
[2] Кафедра вищої геодезії, Національний університет “Львівська політехніка”, вул. С. Бандери, 12, Львів, 79013, Україна, e-mail: nazarii.v.danyliv@lpnu.ua

ЦИФРОВЕ КАРТОГРАФУВАННЯ ТЕРИТОРІЙ ЗА ДОПОМОГОЮ ТЕХНОЛОГІЇ SLAM. АНАЛІЗ ТОЧНОСТІ ОТРИМАНИХ РЕЗУЛЬТАТІВ

У статті розглянуто питання цифрового картографування територій із застосуванням сучасного обладнання та інноваційних методів виконання топографо-геодезичних робіт. *Мета.* Дослідження сучасних методів картографування територій, а також обґрунтування підходів до виконання робіт із картографування за допомогою технології SLAM. *Методика та основні результати.* У дослідженні використано методику картографування територій за допомогою ручних лазерних сканерів із технологією SLAM. Здійснено рекогностування місцевості, закладено контрольні геодезичні пункти, виконано польові роботи сканером Stonex X120GO. Отримані хмари точок зіставлено із результатами тахеометричного знімання. Аналіз середніх квадратичних похибок підтвердив відповідність точності нормативним вимогам. *Наукова новизна та практична значущість.* Дослідження дає змогу оцінити ефективність застосування технології SLAM у наземних ручних лазерних сканерах як альтернативи традиційним видам топографічного знімання. Похибки під час застосування такого типу обладнання за умови правильного використання повною мірою задовольняють вимоги до точності виготовлення топографічних планів у масштабі 1:500, а в окремих випадках навіть 1:200, що забезпечує можливості для ширшого впровадження SLAM у практику топографо-геодезичних робіт. Застосування технології SLAM та сучасних ручних лазерних сканерів для виконання топографо-геодезичних та картографічних завдань може істотно знизити витрати коштів, ресурсів та сил із задіянням меншої кількості працівників та одиниць обладнання. У дослідженні оцінено можливості застосування технології SLAM та її точність. У статті доведено, що технологія SLAM та ручні 3D-сканери є точним та надійним інструментом виконання робіт у сучасних реаліях.

Ключові слова: SLAM (Simultaneous Localization and Mapping), ПЗ Digitals, картографування територій, лазерне сканування, програмний продукт, лідар (LIDAR), топографічний план, інтегрування сучасних підходів, GNSS-приймач, хмара точок, ручний сканер, топографо-геодезичні роботи.

Received 29.03.2025