UDC 528.9

MOBILE LiDAR, GEOINFORMATION TECHNOLOGIES AND CROWDSOURCING FOR THE DOCUMENTATION AND PRESERVATION OF CULTURAL HERITAGE OBJECTS IN TERRITORIAL COMMUNITIES

Koshel A., *Doctor of Economics*

National University of Life and Environmental Sciences of Ukraine

e-mail:koshelao@gmail.com

Kolhanova I., *PhD in Economics*

National University of Life and Environmental Sciences of Ukraine

e-mail: kolganova_i@ nubip.edu.ua

Poltavets A., *Doctor of Economics*

National University of Life and Environmental Sciences of Ukraine

E-mail: anatoliy.poltavets@nubip.edu.ua

Yukhymiuk V., *Master of land management,*

National University of Life and Environmental Sciences of Ukraine E-mail:

vladislavuhimuk@gmail.com

Abstract. The article substantiates the integrated use of LiDAR technologies, geographic information systems (GIS) and crowdsourcing approaches for identifying, recording and monitoring historical and cultural heritage sites within local communities. It is emphasised that in the context of military action, urbanisation pressure and territorial transformations, cultural heritage is considered an important resource for sustainable development in accordance with UNESCO approaches and the World Heritage Sustainable Development Policy (2015).

It is shown that modern LiDAR systems, including sensors built into smartphones, provide dense point clouds and three-dimensional models of objects with sufficient accuracy to solve a significant part of the tasks of documentation and operational monitoring, although they are inferior to high-precision ground and airborne laser scanners. Particular attention is paid to the hypothesis regarding the possibility of creating 3D models of cultural heritage objects using common smartphone models with built-in LiDAR sensors and assessing the accuracy of measurements of such models.

To test the approach, a field scan of the local hydrological natural monument "Natural Spring" within the Shpanivska territorial community of the Rivne region was performed using a smartphone with a LiDAR module. Processing point clouds in Polycam, AutoCAD, PIX4D, 3ds Max, and Blender software made it possible to build a 3D model of the structure and estimate the relative error in measuring linear dimensions. For a reference section 210 cm long, the relative measurement error was 2.04%, which is consistent with the results of international studies on the accuracy of mobile LiDAR sensors, which demonstrate millimetre-centimetre accuracy for small objects and centimetre-decimetre errors in complex environments.

The technical limitations of mobile LiDAR (limited scanning range, reduction in density and accuracy with distance, sensitivity to surface properties, influence of the operator's scanning trajectory, need for control measurements) were analysed and the prospects for their application for mass crowdsourced data collection on heritage objects were demonstrated. Based on an analysis of geocrowdsourcing experience, it is argued that the combination of the prevalence of smartphones, mobile LiDAR sensors and web GIS creates the conditions for the formation of distributed information systems for recording, monitoring and preliminary assessment of the condition of monuments at the level of local communities, provided that data standardisation and quality control procedures are implemented.

Keywords: geoinformation technologies, Lidar, amalgamated territorial community, historical and cultural heritage, sustainable development.

Actuality. Cultural heritage is seen as a system of tangible, intangible and natural elements that connect the past with the present and shape the identity of communities. In contemporary international approaches, heritage is directly integrated into sustainable development policies, as enshrined, in particular, in the policy of integrating the sustainable development perspective into the processes of the World Heritage Convention (2015) and in UNESCO's global report "Culture: Urban Future".

For local communities in Ukraine that are affected by military action, intensive urbanisation and land use transformations, the task of promptly identifying, recording and monitoring historical and cultural heritage sites is of critical importance. Traditional field survey methods and classical geodetic surveying are often labour-intensive, require significant financial resources and do not provide sufficient data update frequency.

The development of geoinformation technologies, remote sensing and 3D documentation has created qualitatively new opportunities for modelling and analysing heritage objects. LiDAR technologies (ground-based, mobile, airborne laser scanning) allow us to obtain highly detailed digital models of terrain and objects, detect hidden archaeological structures and record deformations with high metric accuracy.

For a long time, the use of LiDAR for cultural heritage tasks was limited by the high cost and complexity of the equipment. However, the emergence of solid-state LiDAR sensors in mass-market mobile devices (tablets and smartphones) has significantly lowered the threshold for entry into the technology. Studies show that LiDAR sensors built into smartphones are capable of providing millimetre-centimetre accuracy in laboratory and controlled conditions and centimetre-decimetre errors in complex natural scenes.

At the same time, crowdsourcing and citizen science approaches are developing, based on the voluntary collection of spatial data by users using mobile devices. For cultural heritage, the effectiveness of geocrowdsourcing for collecting photographs and metadata on historical objects using web maps and voluntary geographic information (VGI) has already been demonstrated. This creates the conditions for the mass involvement of citizens in recording the condition of monuments using smartphones as sensor platforms.

In this context, it is particularly important to test the hypothesis that widely available smartphone models with built-in LiDAR sensors can be used to create point clouds and 3D models of cultural heritage objects with sufficient accuracy for initial inventory and monitoring at the local community level.

Analysis of the latest scientific research and publications. Analysing recent scientific research on the creation of digital models of historical and cultural heritage objects, it is worth noting Chetverikov, who concluded that the systematisation of tasks and methods of spatial identification and monitoring of the territory of historical and cultural heritage objects using geoinformation technologies allows the creation of a conceptual model that includes the stages of data collection, analysis and interpretation [1]. In turn, Biryova O. notes in her scientific work that "today, one of the popular areas of work for museums in the digital space is the creation of virtual museums. The creation of a 3-D museum is possible with the use of photogrammetry. This technology is also relevant when creating electronic museum catalogues and digitising three-dimensional exhibits (tableware, sculptures, weapons, etc.). One type of modern technology in museums is augmented reality, which does not change but rather complements the exhibition. To convey information, all you need is a gadget and the appropriate application or marker [2].

GIS mapping of historical and cultural heritage is particularly important for creating a database of natural and cultural monuments with the aim of organising their registration and taking measures for their preservation. GIS makes it possible to map environmental objects and then analyse them according to a huge number of parameters, visualise them and, based on this data, predict a wide variety of events and phenomena.

However, issues directly related to the integrated use of Lidar and geoinformation technologies for the identification and preservation of historical and cultural heritage objects within territorial communities require further research.

The aim of the study is the integrated use of Lidar and geoinformation technologies for the identification and preservation of historical and cultural heritage sites within territorial communities.

Materials and methods of scientific research. The research materials include spatial data necessary for a comprehensive analysis of the state of historical and cultural heritage sites within the territorial community. The main information base consists of LiDAR data obtained from mobile laser scanning materials.

The scanning was performed using an iPhone 13 Pro mobile phone and a depth sensor (Sony IMX590 TOF 3D LiDAR scanner). It emits a series of laser pulses (infrared light) and measures the time it takes for the light to return to the receiver. It is capable of capturing objects at a distance of up to 5 metres. The quality of the measurements is controlled by measuring the reference value and checking the same value in the software. Point cloud filtering was performed automatically by software.

The methodological basis of the study is based on the integrated use of geoinformation technologies and LiDAR data processing tools. Primary processing of point clouds was carried out by classification, noise filtering, and selection of ground surfaces and above-ground objects.

To identify historical and cultural heritage objects, methods of automatic and semi-automatic detection of structural anomalies were applied, using morphological filters, local topographic indicators, and advanced 3D analysis tools.

Overall, the set of methods used made it possible to determine the spatial characteristics of cultural objects and justify management decisions regarding their preservation at the local community level.

Research results and their discussion. Historical and cultural heritage sites around the world are unique, and if damaged or destroyed, they are irreplaceable. They consist of architectural structures and other constructions that are the main evidence of human historical activity and, as such, must be substantially protected [4]. The preservation and restoration of historic buildings requires a special approach in order to safeguard their unique characteristics. Therefore, each such building must be carefully researched in order to identify these unique characteristics: type of construction, construction methods, reconstruction and restoration over time, materials used and their source, types of use, etc.

To store collected heterogeneous data sets, such as multispectral images, geophysical data, or Lidar data, a hybrid approach consisting of different media, for example, one for each data type, is often used. However, several persistent problems need to be addressed: the combination of completely different types of data, the enormous amount of data generated by most of the above-mentioned technologies, and 3D digital documentation of architectural heritage [5].

The use of building information modelling (BIM) can greatly facilitate the management and planning of conservation and restoration work on historic buildings [6], as it allows for the geospatial integration of datasets obtained using different techniques and covering different fields of knowledge, such as architecture, archaeology, engineering, materials and remote sensing [7].

In September 2015, the United Nations (UN) adopted 17 Sustainable Development Goals to transform our world by 2030 (United Nations, 2015). Prior to this, in 2013, the United Nations Educational, Scientific and Cultural Organisation (UNESCO) had already stated that culture should be at the heart of sustainable development policies, and cultural heritage was included in the Sustainable Development Agenda. Subsequently, in November 2015, the 20th General Assembly of States Parties to the World Heritage Convention adopted a Policy on Integrating a Sustainable Development Perspective into the World Heritage Convention Process (UNESCO, 2015). UNESCO then launched the Culture for Sustainable Urban Development programme (UNESCO, 2016) to highlight the role of culture in sustainable development and illustrate the link between the implementation of UNESCO's conventions on culture and the achievement of sustainable development goals. Cultural heritage is therefore now considered an important factor in sustainable development and is directly and indirectly reflected in the Sustainable Development Goals.

Geoinformation technologies, including photogrammetry, laser scanning, remote sensing, web mapping, and geospatial data science, have long played an important role in documenting and preserving cultural heritage [8, 9].

Although the accuracy of the model depends on various factors (such as image network, resolution, number of images, calibration), highly accurate geometric models can be obtained [10]. The created 3D models are 3D surfaces with photorealistic textures and are therefore suitable for visualisation and animation. In addition, digital cameras are now ubiquitous, affordable, portable, and easy to use. This means that even non-experts can use this technique after minimal training [11], and therefore photogrammetry is no longer limited by the knowledge or location of users and can be easily implemented worldwide. Unmanned aerial vehicles (UAVs) have become a popular platform for medium- and large-scale 3D terrain mapping. However, as a passive sensing technology, photogrammetry has its limitations, such as dependence on lighting, lack of scale, and the need for image texture.

Laser scanning in various forms generates dense clouds of 3D points that describe the geometry of an object. Laser scanning has quickly become popular in the surveying industry due to its direct and accurate 3D measurement capabilities and ease of use. Data collection can be effective and planned regardless of lighting conditions thanks to active probing, which can be critical for underground measurements, for example. Another feature of laser scanning that allows it to penetrate vegetation is its ability to capture objects behind or under foliage. Therefore, among other active sensing technologies, laser scanning is commonly used to record, model, and monitor deformations or structures of cultural heritage objects [12].

A combination of ground-based geoinformation technologies will meet the needs for documenting and monitoring small- and medium-scale cultural heritage, but for large archaeological sites this can be a labour-intensive and time-consuming process, especially for sites that are not suitable for on-site surveys, such as conflict zones. In such circumstances, space-based or aerial remote sensing is an ideal alternative.

Geoinformation technologies have long been used to manage spatial databases of cultural heritage for improved planning and conservation. UNESCO and UNITAR (United Nations Institute for Training and Research) have joined forces to protect cultural and natural heritage sites using the latest geospatial technologies.

Thanks to the widespread use of smartphones and the Internet, crowdsourcing and citizen science are becoming increasingly popular through the combination of GIS and modern web maps and are being successfully applied to document cultural heritage.

All of these geoinformation technologies actively contribute to one or more aspects of cultural heritage preservation. Closely related technologies, such as computer-aided design (CAD) and virtual reality (VR), are also used to protect and promote cultural heritage and are based on the results of these geoinformation technologies.

Research by Ukrainian authors confirms that digital models of relief and cultural heritage objects, built on the basis of geoinformation technologies and remote sensing data, are a key element in the systematisation of information about monuments and spatial analysis of threats. Works [1; 3] propose the use of GIS to integrate archival maps, aerial photographs and modern data, which enables the identification, classification and mapping of heritage objects.

Photogrammetry, including multi-image reconstruction, has long been the basic technology for 3D documentation of monuments; numerous studies show that with proper planning and elevation referencing, it is possible to achieve high geometric accuracy of models. Its limitations include dependence on lighting, surface texture, and the difficulty of ensuring scale without control measurements.

Laser scanning (ground-based and mobile) provides direct measurement of 3D coordinates with high accuracy and density. It is successfully used to monitor building deformations, conduct detailed surveys of structures, and create high-precision digital models of monuments. At the same time, the high cost of equipment, the need for qualified operators, and the complexity of logistics limit the scale of such surveys, especially at the level of small territorial communities.

With the advent of LiDAR sensors in mass-market mobile devices (tablets, smartphones), active research into their suitability for surveying and geoinformation tasks began. Initial assessments showed that the iPhone/iPad LiDAR sensor provides very low errors at short distances (on the order of millimetres to centimetres), but accuracy decreases significantly with increasing distance, geometric complexity, and surface heterogeneity. Further work has shown that iPhone LiDAR can provide absolute accuracy of approximately ±1 cm for relatively large objects, but accuracy deteriorates in conditions of dense vegetation and complex terrain.

Studies focused on combining smartphones with RTK solutions (e.g., viDoc RTK Rover) show that such a system is capable of achieving centimetre-level accuracy in plan and elevation for a wide range of engineering and surveying tasks.

During the study, an object was selected for testing: the hydrological natural monument of local importance "Natural Spring" (Fig. 1). The site, with an area of 0.3 hectares, is located within the Shpanivska territorial community of the Rivne district of the Rivne region, on the north-eastern outskirts of the village of Khotyn [11]. The status was granted in accordance with the decision of the regional executive committee dated 22 November 1983 No. 343. It is under the jurisdiction of the Shpanivska village council [11].

Fig. 1. Created 3D model of the hydrological natural monument of local importance "Natural Spring" compared to its original.

The resulting point cloud contained sufficient readings to accurately reflect the dimensions of the hydrological monument "Natural Spring" and the main elements of its design. After filtering out noise and constructing a triangular surface, a three-dimensional model of the structure was formed, suitable for visualisation and measurement.

Visual analysis of the 3D model showed:

- correct reproduction of the main planes and edges of the structure;
- satisfactory representation of small elements (steps, ledges);

- local artefacts in areas with high lighting contrast and in places of contact with the water surface, which is consistent with the known limitations of LiDAR sensors regarding transparent and highly reflective surfaces.

The relative error δ was determined using the formula:

$$\delta = \frac{|\ L_{etal}\ - L_{LiDAR}}{L_{etal}} \cdot 100\%$$

where L_{LiDAR}– length obtained from the 3D model,

L_{etal}– length measured with a tape measure.

This approach is consistent with standard practices for assessing the accuracy of LiDAR and photogrammetric models in studies devoted to mobile and portable scanners.

The front side of the structure was chosen as the reference point, and its length was measured with a tape measure:

L_{etal} = 210 cm.

Based on a 3D model constructed using LiDAR data from a smartphone, the following was obtained:

L_{LiDAR} = 205,7 cm.

Relative error:

$$\delta = \frac{210 - 205{,}7}{210} \cdot 100\% \approx 2{,}04\ \%.$$

Therefore, the measurement error of the linear parameters of the structure created using LiDAR — a model scanner — does not exceed 2.04%, which is acceptable.

The point cloud loaded into the programme has a density sufficient to determine the reflection of the dimensions of the structure on the created 3D model with sufficient accuracy. The front side of the structure, with a length of 210 centimetres measured with a tape measure, was selected as the reference value.

The experiment with 3D modelling of a hydrological monument, combined with a literature review, allows us to identify promising areas of application for mobile LiDAR in the field of heritage:

1. Initial inventory of small objects;

2. Monitoring of deformations and damage (at a qualitative level);

3. Preparation of data for digital twins;

4. Rapid documentation of objects in risk areas;

5. Crowdsourcing and citizen science.

From the perspective of organising mass recording of heritage objects, the key advantage of mobile LiDAR sensors is their accessibility: a significant portion of the population already has smartphones of the appropriate class. This creates potential for crowdsourcing platforms where users can:

● perform local 3D scanning of objects;

● upload point clouds or 3D models to the web portal;

● supplement them with attribute information (name, status, condition, threats).

Conclusions and perspectives. The cultural heritage of local communities in conditions of military action, urbanisation pressure and territorial transformations requires prompt, spatially detailed and regular documentation, in line with UNESCO's current approaches to integrating heritage into sustainable development policies. LiDAR technologies and geographic information systems are effective tools for detecting, identifying and monitoring cultural heritage sites, and LiDAR sensors built into smartphones make it possible to use such technologies on a mass scale.

Experimental scanning of the hydrological natural monument "Natural Spring" using a smartphone with a LiDAR module showed that the relative error in measuring the control length (210 cm) using a 3D model does not exceed 2.04%. This result is consistent with international estimates of the accuracy of mobile LiDAR and is acceptable for the tasks of primary inventory and monitoring of small heritage objects.

The main limitations of mobile LiDAR are scanning range, accuracy dependence on scene complexity and surface properties, sensitivity to operator movement trajectory, and the need for additional georeferencing for integration into GIS. This requires the development of clear regulations and methodological recommendations for the use of smartphones in 3D heritage documentation tasks.

The combination of mobile LiDAR, GIS platforms, and crowdsourcing approaches creates prospects for the formation of distributed systems for accounting and monitoring the cultural heritage of local communities. Provided that data collection protocols are standardised and quality control procedures are implemented, involving citizens in 3D recording of objects can significantly improve the completeness and relevance of information resources.

References

1. Chetverikov, B., Babii, L., Kuzyk, Z., Zaiats, I., & Protsyk, M. (2022). Doslidzhennia tsyfrovykh modelei reliefu nerukhomykh obiektiv istoryko-kulturnoi spadshchyny, stvorenykh za rizni roky [Study of digital terrain models of immovable objects of historical and cultural heritage created in different years]. *Heodeziia, kartohrafiia i aerofotoznimannia*, 96, 65–76.

2. Birova, O. (2023). Istoryko-kulturna spadshchyna Ukrainy: tsyfrovi tekhnolohii zberezhennia ta populiaryzatsiia v umovakh voiennykh dii [Historical and cultural heritage of Ukraine: digital technologies for preservation and popularization under wartime conditions]. *Naukovo-teoretychnyi almanakh Hrani*, 26(5), 90–94. https://doi.org/10.15421/1723106

3. Kalynych, I. V., Chetverikov, B., & Khintsitskyi, O. (2021). Metodyka kartohrafuvannia obiektiv istoryko-kulturnoi spadshchyny zasobamy HIS-tekhnolohii iz vykorystanniam arkhivnykh kartohrafichnykh ta aeromaterialiv [Methodology of mapping historical and cultural heritage objects using GIS technologies with archival cartographic and aerial materials]. *Suchasni dosiahnennia heodezychnoi nauky ta vyrobnytstva*, I(41), 97–103.

4. Vecco, M. (2010). A definition of cultural heritage: From the tangible to the intangible. *Journal of Cultural Heritage*, 11, 321–324.

5. Slla, M., Gonçalves, L. M. S., Gonçalves, G., Francisco, C., Puente, I., Providência, P., Gaspar, F., & Rodrigues, H. (2020). A Building Information Modeling Approach to Integrate Geomatic Data for the Documentation and Preservation of Cultural Heritage. *Remote Sensing*, 12(24), 4028. https://doi.org/10.3390/rs12244028

6. Bruno, N., & Roncella, R. (2019). HBIM for Conservation: A New Proposal for Information Modeling. *Remote Sensing*, 11, 1751.

7. López, F. J., Lerones, P. M., Llamas, J., Gómez-García-Bermejo, J., & Zalama, E. (2018). A Review of Heritage Building Information Modeling (H-BIM). *Multimodal Technologies and Interaction*, 2, 21.

8. Remondino, F., & Rizzi, A. (2010). Reality-based 3D documentation of natural and cultural heritage sites—techniques, problems, and examples. *Applied Geomatics*, 2(3), 85–100.

9. Dhonju, H. K., Xiao, W., Shakya, B., Mills, J. P., & Sarhosis, V. (2017, April). Documentation of heritage structures through geo-crowdsourcing and web-mapping. In *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* (Vol. 42, pp. 17–21). Copernicus Publications.

10. Koutsoudis, A., Vidmar, B., Ioannakis, G., Arnaoutoglou, F., Pavlidis, G., & Chamzas, C. (2014). Multi-image 3D reconstruction data evaluation. *Journal of Cultural Heritage*, 15(1), 73–79.

11. Boochs, F., Heinz, G., Huxhagen, U., & Müller, H. (2007, October). Low-cost image based system for nontechnical experts in cultural heritage documentation and analysis. In *XXI International CIPA Symposium, AntiCIPAting the future of the cultural past*. 01–06.

12. Jaafar, H. A., Meng, X., Sowter, A., & Bryan, P. (2017). New approach for monitoring historic and heritage buildings: Using terrestrial laser scanning and generalised analysis. *Structural Control and Health Monitoring*, 24(11), e1987.

Кошель А., Колганова І., Полтавець А., Юхимюк В.

МОБІЛЬНИЙ LIDAR, ГЕОІНФОРМАЦІЙНІ ТЕХНОЛОГІЇ ТА КРАУДСОРСИНГ У ФІКСАЦІЇ Й ЗБЕРЕЖЕННІ ОБ’ЄКТІВ ІСТОРИКО-КУЛЬТУРНОЇ СПАДЩИНИ ТЕРИТОРІАЛЬНИХ ГРОМАД

Анотація. *У статті обґрунтовано інтегроване використання LiDAR-технологій, геоінформаційних систем (ГІС) та краудсорсингових підходів для виявлення, фіксації й моніторингу об’єктів історико-культурної спадщини в межах територіальних громад. Наголошено, що в умовах воєнних дій, урбанізаційного тиску та територіальних трансформацій культурна спадщина*

розглядається як важливий ресурс сталого розвитку згідно з підходами ЮНЕСКО та Політики сталого розвитку Всесвітньої спадщини (2015 р.).

Показано, що сучасні LiDAR-системи, включно з вбудованими у смартфони сенсорами, забезпечують отримання щільних хмар точок і тривимірних моделей об'єктів з точністю, достатньою для вирішення значної частини завдань документування та оперативного моніторингу, хоча й поступаються високоточним наземним й аеролазерним сканерам. Особлива увага приділена гіпотезі щодо можливості створення 3D-моделей об'єктів культурної спадщини за допомогою поширених моделей смартфонів із вбудованим LiDAR-сенсором та оцінки точності вимірювань таких моделей.

Для апробації підходу виконано польове сканування гідрологічної пам'ятки природи місцевого значення «Природне джерело» в межах Шпанівської територіальної громади Рівненської області за допомогою смартфона з LiDAR-модулем. Оброблення хмар точок у програмному забезпеченні Polycam, AutoCAD, PIX4D, 3ds Max і Blender дало змогу побудувати 3D-модель споруди й оцінити відносну похибку вимірювання лінійних розмірів. Для еталонної ділянки довжиною 210 см відносна похибка вимірювання становила 2,04 %, що узгоджується з результатами міжнародних досліджень точності мобільних LiDAR-сенсорів, які демонструють міліметрово-сантиметрову точність для малих об'єктів та сантиметрово-дециметрові похибки у складному середовищі.

Проаналізовано технічні обмеження мобільного LiDAR (обмежена дальність сканування, зниження щільності та точності з відстанню, чутливість до властивостей поверхні, вплив траєкторії сканування оператора, необхідність контрольних вимірювань) та показано перспективи їхнього застосування для масового краудсорсингового збору даних про об'єкти спадщини. На основі аналізу досвіду геокраудсорсингу обґрунтовано, що поєднання поширеності смартфонів, мобільних LiDAR-сенсорів і веб-ГІС створює передумови для формування розподілених інформаційних систем обліку, моніторингу та попереднього оцінювання стану пам'яток на рівні *територіальних громад за умови впровадження процедур стандартизації й контролю якості даних.*

Ключові слова: *геоінформаційні технології, Lidar, об'єднана територіальна громада, історико-культурна спадщина, сталий розвиток.*