The cross-disciplinary influence of aerial measurement techniques: Exploring archaeological studies through photogrammetry and LiDAR

Maria FILIP-GHERMAN*, Simion BRUMA, Cătălin SABOU, Mircea NAP, Elemer-Emanuel SUBA, Tudor SĂLĂGEAN

University of Agricultural Sciences and Veterinary Medicine, Faculty of Forestry and Cadastre, 3-5 Mănăştur Street, 400372, Cluj-Napoca, Romania; filipghermanmaria@gmail.com (corresponding author); brumasimion@gmail.com; sabou_cata@yahoo.com; mircea.nap@usamvcluj.ro; elemer-emanuel.suba@usamvcluj.ro; tudor.salagean@usamvcluj.ro

Abstract

This research aimed to evaluate the efficacy of contemporary digitization methods for archaeological sites, specifically focusing on aerial approaches. The study is concentrated on the examination of two primary methods: LiDAR sensor and photogrammetry. The chosen case study revolves around the Camp of the V Macedonica Legion, a pivotal feature of the former Roman city now known as Turda, a city in Cluj County, Transylvania, Romania. Through analysis and comparison, the paper revealed that each of these aerial 3D scanning techniques possesses unique strengths, which, when combined, offer a comprehensive approach to archaeological digitization. These complementary attributes must be carefully considered and integrated considering the specific requirements and objectives of the archaeological project at hand when selecting the appropriate method. Furthermore, the research underscores the pivotal role of presenting archaeology in 3D, emphasizing its significant impact on both public and academic audiences. Achieving this presentation necessitates the utilization of specialized software for modelling, rendering, and animating objects of interest, thus enhancing the accessibility and engagement of archaeological findings. The comprehensive findings of this study demonstrate the vast potential offered by aerial 3D scans in the field of archaeology. Moreover, it serves as a potential call for the meticulous selection of the analysis method, recognizing its crucial role as a valuable tool for researchers and archaeologists. By leveraging 3D technologies in their activities, professionals in the field can significantly enhance the accuracy, depth, and accessibility of their archaeological investigations, thereby enriching our understanding of the past.

Keywords: aerial measurement techniques; archaeology; LiDAR; photogrammetry

Introduction

Unmanned aerial vehicles (UAVs), commonly known as drones, have gained significant use in various environmental and civil applications due to their ability to acquire detailed digital surface models (DEMs) and orthoimages (Ghamari et al., 2022; Mohsan et al., 2022, 2023; Puchalski and Giernacki, 2022). The precision of the derived datasets resulting from drone missions is based on the used techniques for collecting the data.
This encompasses options such as using active LiDAR sensors or relying on passive remote sensing sensors like cameras (Gupta and Shukla, 2018; Chandran et al., 2023; Telli et al., 2023).

LiDAR, an acronym for Light Detection and Ranging, stands as a prominent remote sensing technique employed to permit the examination of the Earth’s surface and its features. This method is based on the use of pulsed laser beams to precisely determine varying distances between the sensor and objects on the ground, thus enabling accurate topographic and spatial measurements (Lefsky et al., 2002; Reutebuch et al., 2005; Lillesand et al., 2015). By emitting short bursts of laser light towards the surface and subsequently measuring the time it takes for the light to return after reflecting off objects, LiDAR provides valuable information about terrain elevation, vegetation density, building structures, and other physical characteristics of the landscape (Vierling et al., 2008; Ghamari et al., 2022). This technology finds wide-ranging applications in fields such as archaeology, contributing significantly to our understanding of the Earth’s intricate features and dynamic changes over time. These laser pulses, combined with other data collected by the airborne system, can generate high-quality three-dimensional representations of the scanned area (Di Stefano et al., 2021; Ghamari et al., 2022; Li et al., 2023).

LiDAR represents a highly precise and efficient technology with the capacity to generate intricate 3D maps, offering a detailed representation of the terrain surface (Asvadi et al., 2016). On the other hand, photogrammetry uses overlapping photographs taken from different angles to reconstruct 3D models of objects and terrains. This approach is highly versatile and can be implemented using a variety of devices, including drones, satellites, and ground-based cameras. Photogrammetry’s strength lies in its accessibility and cost-effectiveness. It doesn’t require specialized equipment and can be used by a wider range of users, including researchers, archaeologists, and even hobbyists (Iheaturu et al., 2020; Rajarjun Reddy et al., 2022). Additionally, the high-resolution imagery captured through photogrammetry can yield intricate textures and details, which is particularly useful in cultural heritage preservation, archaeological site documentation, and creating visually appealing models for architectural visualization (Jiménez-Jiménez et al., 2021; Lozić and Štular, 2021; Marín-Buzón et al., 2021).

Focusing more on the topic considered for this study, the continuous development of 3D measurement techniques brings archaeologists a more efficient and precise alternative. In the last decades, archaeology has undergone a significant revolution, which can be seen from the increase in research works carried out in favour of all the specialized fields that include it as a scientific component (Opgenhaffen, 2021). These evolutionary steps, therefore, transform it into a subject that refers to the experimental sciences and helps to integrate techniques found in disciplines such as engineering. Within this last aspect, it is important to remember the great progress that 3D measurement technologies have brought to archaeology (Lambers and Remondino, 2008). Through the application of 3D measurement methods, data is directly captured in digital form, effectively eliminating the potential for human errors. Moreover, these digitally recorded data can be effortlessly transferred and accessed within virtual environments, enabling archaeologists to interpret, analyze, and visualize them with efficiency and precision. This significantly enhances the depth of understanding regarding archaeological sites and facilitates a more comprehensive documentation (Arias et al., 2022). Archaeology has adopted a diverse range of digital tools to capture, manage, analyze, and visualize archaeological data over the last 50 years, and archaeological investigation now takes place inside a digital world, involving primarily screen work and digital apps (Opgenhaffen, 2021). The ongoing advancement of modern techniques has yielded notable enhancements, using increasingly sophisticated sensors and systems for data visualization. This highlights their pivotal role in the realm of terrestrial measurements, particularly in their archaeological applications. Thoroughly documenting cultural heritage items is indispensable, encompassing detailed aspects such as structural morphology, color profiles, geometric attributes, as well as historical and constructional facets. The ceaseless progress of scientific exploration now presents fresh prospects and technologies, necessitating a responsible and conscious approach, grounded in an ethos of experimentation and innovation (Cardaci et al., 2013).

Within the context of the considered topic, the focus stays on evaluating modern digitization approaches, particularly aerial such as LiDAR sensor and photogrammetry, for the documentation of
archaeological sites. Through the implementation of LiDAR and photogrammetry technologies, the objective is to assess their effectiveness in enhancing the documentation, analysis, and visualization of archaeological sites. Looking forward, it is essential to embrace a stance of responsible innovation to fully harness the potential of these tools in preserving and comprehending our shared human history.

**Materials and Methods**

**Description of the Area**

The archaeological site of Potaissa, located on Dealul Cetății near the city of Turda, Romania (Figure 1), situated at a northern latitude of 46°34′15″ and an eastern longitude of 23°46′45″, has become a captivating focal point for the application of cutting-edge technologies in the field of archaeology. The convergence of LiDAR scanning and photogrammetric measurements has unveiled a new way of understanding and preserving this historical treasure.

![Figure 1](image.jpg)

*Figure 1. Representative area for the case study location*
The fortress of the Fifth Macedonian Legion stands as an exceptionally valuable historical and archaeological monument, graced with a strategically favourable geographical location within the Transylvania region. Also known as the Roman Fortress Turda, as per information provided by the Ministry of Culture and National Identity, Potaissa holds the mantle of a vital archaeological hub, sheltering the ruins of both, a formidable fortress, and an ancient Roman settlement. These discoveries offer a captivating glimpse into the daily life and military activities of the Roman era.

To safeguard and promote this landmark, the employment of modern 3D measurement techniques becomes imperative, promising manifold benefits for its study and documentation. It stands as one of the most impressive and expansive legionary fortresses in Dacia, boasting an enduring existence and significant historical relevance within the region’s history. Its impressive dimensions underscore the immense nature of this military stronghold. With its long sides spanning 573 meters and its short sides measuring 408 meters, the fortress forms an enormous rectangle covering an area of 23.37 hectares.

The plateau upon which the Potaissa fortress is situated commands attention with its dominant position overlooking the ancient city and its surrounding territories. Positioned at an absolute altitude of 375 meters, the elevated plateau, rising about 40 meters, provides a panoramic perspective and excellent visibility from within the fortress, extending over remarkable distances.

**LiDAR or photogrammetry?**

*Field Work Flights*

To effectively collect data, utilizing a DJI M210 v2 drone, equipped with the LiDAR 100 Lite system and the Zenmuse X4S camera, has emerged as a game-changing approach for archaeological site assessments, exemplified by its application at sites like Potaissa. However, the successful implementation of such technology demands a careful flight planning and execution to ensure the fidelity and reliability of collected data, subsequently facilitating insightful analysis. At the heart of this process lies the intricate synergy between drone capabilities and LiDAR technology. The TOPODRONE LiDAR 100 lite incorporates an advanced GNSS-based inertial navigation system, offering a full 360° field of view, and achieving an impressive accuracy of up to 3 cm in the x, y, and z dimensions. To harness this potential, the planning phase commences with the study of the site’s characteristics, including its topography, vegetation cover, and potential obstructions.

Simultaneously, the Zenmuse X4S camera comes into the discussion, capturing high-resolution aerial imagery. This visual component supplements the LiDAR data, providing context and detail that enriches the subsequent analysis. The camera’s role extends beyond; it contributes to the creation of orthomosaics and high-resolution digital elevation models (DEMs), consolidating the dataset generated during the survey.

However, the journey from airborne data collection to insightful analysis is not without challenges. The sheer volume of data acquired demands advanced processing techniques to refine and align the point clouds with imagery. This involves the use of specialized software to fuse LiDAR and imagery datasets seamlessly, ensuring that the resultant models accurately reflect the surveyed site. Advanced algorithms aid in noise reduction, data filtering, and feature extraction, producing a refined dataset.

**Data Processing**

Before detailed processing can begin, some initial preprocessing steps are performed to clean and prepare the data for analysis. Post-processing and image geotagging play pivotal roles in deriving accurate and meaningful insights from aerial measurements, particularly when utilizing both cameras and LiDAR sensors. Upon completion of the flight mission, it is needed to transfer the UBX file from the GNSS receiver’s SD card to a designated folder on the computer and convert the base station file into RINEX format, which will be included in the process. These intricate processes are integral to transforming raw data into actionable information for various applications, ranging from cartography to environmental monitoring (Figure 2).
RINEX observations from the GNSS receivers on the aerial platform can be used to reconstruct the trajectory of the platform during data collection. This trajectory information is crucial for accurately georeferencing the captured data points, especially in LiDAR data processing. RINEX observations are often used in differential GNSS processing, which involves comparing observations from a stationary reference station (known as a base station) to those from a moving receiver (such as an aerial platform). This differential approach allows for the removal of common errors, such as atmospheric effects and satellite clock errors, further enhancing the accuracy of the positioning solution.

In summary, RINEX observations are an integral part of the post-processing and geotagging process for aerial measurements, alongside camera and LiDAR data. They contribute to achieving high-precision positioning and accurate georeferencing, especially when integrated with other data sources and processing techniques.

Results

Upon completion of the data processing, a graphical interface will emerge, presenting a window that provides comprehensive insights. Within this window, there will be an opportunity to visualize the trajectory followed by the rover, along with essential metrics. These metrics encompass the count of captured photos, timestamps, and alignment instances. These marks are differentiated by a vivid green hue for those attained through a fixed solution and a distinct yellow shade for those obtained via a float solution. This visual distinction facilitates easy identification and assessment of the accuracy associated with the various marks generated during the process (TOPODRONE Post Processing Manual).

The processing data obtained in current investigation are presented in Figures 3-13.

LiDAR Cloud Generation

Generating a LiDAR point cloud using the TOPODRONE Post Processing software involves a systematic procedure. It commenced by initializing the software interface, followed by navigating to the “LiDAR Cloud Generation” tab. This specialized tab encompasses the requisite tools and parameters essential for the generation of a precise LiDAR point cloud derived from the provided data.
Delineating the pathway to the dataset’s LiDAR information, encapsulated in the ".pcap" format, this establishes the foundational dataset for subsequent processing. Furthermore, inclusion of the corresponding trajectory file, formatted as "track_.pos", within the designated “Track file” field, serves as the guiding trajectory for the ensuing point cloud generation procedure. During this stage, the software undertakes the task of generating the point cloud, which is subsequently saved in the .LAS/.LAZ file format (TOPODRONE Post Processing Manual).
Data Processing in Pix4Dmapper

Pix4Dmapper is a software application for photogrammetry and 3D mapping developed by Pix4D, which provides users with the ability to transform aerial or ground images into accurate three-dimensional models and detailed digital maps. By using advanced image processing algorithms, the software delivers high-quality results efficiently and quickly.

Figure 5. The process of cloud generation using TOPODRONE Post Processing software

Figure 6. The uploading high-precision coordinates of the images
The photogrammetric procedure begins with "Structure from Motion" (SfM), a method that uses overlapping two-dimensional photographs to reconstruct three-dimensional models. This stage involves analysing the dataset and detecting geometric patterns to reconstruct the virtual positions of the cameras and align the images, thereby generating a point cloud (Rowell, 2023). In contrast to traditional photogrammetry, the camera positions obtained through Structure from Motion (SfM) do not include the scaling and orientation provided by ground control coordinates. As a result, the three-dimensional point cloud generated in SfM is expressed in a relative coordinate system in “image space”, and to align them to an absolute coordinate system in “object space”, a transformation is necessary. This transformation is typically achieved by using a three-dimensional similarity transformation based on several Ground Control Points (GCPs) with known coordinates in the site’s space.

In the end, the resulted point cloud can be used for a detailed analysis of the archaeological site at Potaissa, potentially providing valuable information about the structures, topography, and other features of the site, thereby facilitating archaeological research and interpretation.

Furthermore, in addition to the point cloud obtained after data processing, an orthophotoplan of the archaeological site can also be generated. An orthophotoplan represents a 2D image of the archaeological site in which perspective distortions are corrected, thus providing a flat and true-to-scale representation of the terrain and objects in perspective (https://www.usgs.gov/). To generate the orthophotoplan, Pix4D utilizes positioning and orientation information from the point cloud, as well as camera calibration data used in the photogrammetric flight. This information is employed to project the points from the point cloud onto a horizontal plane, resulting in an orthogonal image of the site.

**The Interest of Digital Elevation Models**

Another aspect that captures the interest of specialists in the field of archaeology is the generation of Digital Elevation Models (DEMs), which are an essential component in terrain mapping and analysis, fundamental in fieldwork. Photogrammetry, an interdisciplinary field that combines principles of photography and geometry, has proven to be one of the most efficient methods for obtaining these accurate and detailed models, facilitating virtual exploration and in-depth study of the terrain. Additionally, these models can be used to reconstruct aspects of the site that have been destroyed or deteriorated over time, as well as undiscovered structures still buried underground.
By employing various algorithms in the process of point cloud classification and classification verification, along with other processes, a Digital Elevation Model (DEM) was generated within the Global Mapper software. Digital elevation models are available in several file formats, such as GeoTIFF, IMG, Gridfloat (.flt), and ArcGRID. However, the GeoTIFF file format is the most used within the global geospatial community due to its interoperability across computing systems and many commercial software products for spatial data analysis. A significant advantage of the GeoTIFF format is its ability to retain essential geographic information, such as coordinate systems and projections, making it a recognized industry standard.
The current model was exported as a file in GeoTIFF format, with centimeter-scale resolution. Essentially, the GeoTIFF format is a raster file format that contains georeferencing information, such as elevations, coordinate systems, ellipsoids, datums, and projections. This format employs a specific set of TIFF tags to convey this information, which is embedded within the raster file (https://equatorstudios.com/).

**Figure 10.** DEM - an overview of the studied area

**Figure 11.** DEM – an overview for the main buildings
Pix4Dsurvey

Moving further in geospatial data processing, this synergy of data acquisition techniques has paved the way for the digitization of information that was once the domain of manual interpretation, ushering in a new era of efficiency and accuracy.

At the heart of this transformation lies Pix4Dsurvey, a cutting-edge software solution that harnesses the power of LiDAR and photogrammetry integration. As we delve into the realm of post-processing, the intricate mix between lasers and photographs allows us to traverse beyond the limitations of traditional surveying methods. The result? A digital twin of reality, meticulously reconstructed from raw point clouds and high-resolution imagery. This digital approach provides a multidimensional perspective of the site, allowing researchers to observe and analyse important features of the targeted object. Moreover, the use of Pix4D Survey software enables archaeologists to create realistic virtual reconstructions of the sites, aiding in the visualization and communication of results in a more accessible manner for the public. These reconstructions can be used for educational purposes, presentations, and exhibitions, contributing to the promotion, and understanding of archaeological heritage.

Integrating the outputs of photogrammetry and LiDAR within Pix4Dsurvey heralds an advancement in the realm of geospatial data digitization. By fusing these two distinct data acquisition methods, a wealth of advantages emerges, reshaping the way we perceive, analyse, and interact with the chosen area of interest.

Photogrammetry, with its high-resolution imagery, captures intricate surface details with remarkable precision. LiDAR, on the other hand, excels in penetrating foliage and providing accurate elevation data, even in complex terrains. When combined, these techniques complement each other’s strengths, creating a synergy that transcends the limitations of either method used in isolation. The resulting amalgamation is a comprehensive dataset that showcases the terrain’s surface morphology, structures, and topography with unparalleled fidelity. Furthermore, the integration of photogrammetric imagery and LiDAR point clouds affords enhanced data validation. Divergent datasets can be cross-referenced and cross-verified, lending a higher degree of confidence to the final results.

Figure 12. Reconstructing the buildings within the Fortress of the Legio V Macedonica - Pix4D Survey
Discussion

The Utility of Aerial Technologies in Archaeological Research

The integration of the two technologies in archaeological research represents a significant advancement in the field. These methods offer precise and detailed data acquisition capabilities, allowing the exploration and interpretation of the archaeological sites with unprecedented accuracy and efficiency. By combining the strengths of LiDAR’s penetrating capabilities with the accessibility and non-invasiveness of photogrammetry, researchers can gain deeper insights into the hidden features of the landscapes while preserving cultural heritage.

Laser scanning, photogrammetry, and survey using UAV-based surveys were successfully used for the analysis of excavated sites from the Roman period. 3D surveys using both laser scanning instruments and drone-mounted photo cameras ensure precise measurements of the archaeological sites and their peculiarities of interest (Fabbri et al., 2021; Pérez et al., 2023). The new technological borders provide us with increasingly precise and advanced measuring mechanisms for conducting inventories of surfaces or monumental structures located on them. These devices allow for relatively easy recording of the geometric and spatial parameters of any architectural or archaeological context which is about to be investigated (Waagen, 2019). It is important to mention that for qualitatively obtaining results, there is not strictly a separate method for processing information, nor is there a universal device. Each measurement is based on a complex combination of techniques, which are applied depending on the project’s purpose.

The introduction of aerial technologies into the archaeological field research leads us toward a revolution in terms of the utility of these new advances for specialists. While satellite images allow us to visualize...
the Earth’s surface from above, a closer technology can provide us with details impossible to obtain previously. The ongoing evolution of equipment and 3D modelling techniques based on the use of aerial devices and advanced data visualization systems highlights the value of using these methods in the field of archaeology. In particular, the contributory role that these technologies play in the interpretative phase, for archiving and preserving visualization data in digital format, becomes evident. All these aspects play an important role in enhancing information related to the discussed subject, even implying an increase in the value of research conducted in favour of this subject (Russo et al., 2011).

The use of laser techniques, such as the LiDAR sensor, allows us to obtain detailed maps of the terrain with high accuracy. Through laser scanning of the terrain, relief forms, buried or hardly visible archaeological structures, as well as subtle details of the landscape, can be identified and highlighted. This information assists in identifying and delineating potential archaeological sites, facilitating the planning and direction of the archaeological excavations. The classes of sensors addressed in this paper are based on the use of light waves, which opens a broader discussion related to the nature of the light used in the measurements. If the light is encoded in a way that influences the measurement process, active sensors will be included, which involve the use of laser scanners, radar, total stations, etc. On the other hand, when it comes to natural light, data recording methods are classified as passive methods, which include photogrammetric measurement techniques. Those techniques represent an important application in archaeology, whether it is terrestrial or aerial photogrammetry (Opitz and Cowley, 2013).

Technical Challenges

Navigating the technical challenges inherent in combining photogrammetric and LiDAR data is a complex process that requires a blend of expertise, ingenuity, and adaptability. The convergence of these two distinct data sources introduces a host of obstacles that necessitate innovative approaches to unlock their full potential. At the forefront is the task of effectively integrating datasets with divergent characteristics. While photogrammetry captures intricate visual details, LiDAR excels at providing precise elevation and spatial information. Ensuring a seamless alignment of these datasets demands advanced algorithms capable of harmonizing data points cohesively. This involves addressing issues of accurate registration, managing variations in spatial resolution, and rectifying potential data disparities. Handling the immense volume and complexity of data represents another significant challenge. Both photogrammetry and LiDAR generate substantial amounts of information, often requiring substantial computational resources and storage capacity. Overcoming the computational hurdles entails devising efficient data management strategies, leveraging parallel processing techniques, and considering cloud-based computing to expedite the analysis process.

Conclusions

This paper explores the synergy of combining LiDAR and photogrammetry in archaeology. It explores LiDAR’s role in site assessment and demonstrates how photogrammetry complements it. Combining photogrammetric measurement methods with LiDAR data, along with the use of associated software, paves the way for highly versatile and efficient solutions in obtaining three-dimensional data and creating remarkably precise models. This synergy of technologies has revolutionized the way we perceive and interact with the surrounding environment, providing a comprehensive approach to capturing details and complex features of objects and terrains. By combining the rich details provided by photogrammetric methods with the accuracy of LiDAR data, a comprehensive picture of the surrounding environment takes shape. This approach not only enables the acquisition of highly precise information across a wide range of fields, from cartography and monitoring to archaeology and urban planning, but also provides a solid foundation for decision-making in various industries. Moreover, the integration of data from photogrammetry and LiDAR into specialized software simplifies processing and analysis, offering users a more efficient and intuitive workflow. This
A combination of technologies opens doors to new opportunities for research, innovation, and development, providing powerful tools to gain a deeper understanding of the environment and study objects.

**Authors’ Contributions**

The authors were involved in all aspects of the research and writing process for the manuscript. They read and approved the final manuscript.

**Acknowledgements**

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

**Conflict of Interests**

The authors declare that there are no conflicts of interest related to this article.

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