Application of UAVs with GNSS, LiDAR, and Photogrammetry Technologies in Terrain Mapping

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https://doi.org/10.29227/IM-2025-02-04-005

Submission date: 01-06-2025 | Review date: 24-06-2025

Abstract

This paper offers a comprehensive summary of recent publications that explore the use of UAV technology for terrain mapping. The results obtained from these studies indicate that integrating UAVs with photogrammetry, LiDAR, and GNSS technologies is highly effective for producing detailed and accurate topographical maps. These technologies enable the precise representation of terrain features, making them invaluable for various mapping applications. The study not only highlights the practical applications of UAV technology in topographic mapping but also serves as a technical reference for advancing knowledge and understanding of these applications. By examining the methodologies and outcomes of numerous research efforts, this paper provides insights into the capabilities and benefits of using UAVs for terrain mapping. It underscores the importance of UAVs in enhancing the accuracy and efficiency of topographic surveys, particularly in challenging environments.

Keywords: *UAVs, GNSS, lidar, photogrammetry technology, terrain mapping*

1. Introduction

Terrain maps that show the characteristics of terrain, landmarks and place names according to coordinate systems, elevation systems, at a specific scale. There are many technologies used to measure for creating maps. One of the technologies that is commonly used today is unmanned aerial vehicles (UAVs). This technology has become a standard tool for generating terrain maps, widely utilized due to its efficiency and accuracy. Numerous reviews have been conducted to provide a comprehensive overview of the use of UAVs in mapping. For instance, [1] presented an in-depth analysis of damage mapping using UAVs, while [2] offered a broad overview of various UAV systems, applications, and case studies, along with the latest advancements in UAV image processing for creating 3D maps. Additionally, [3] described the use of drones for geo-mapping and discussed useful tools. Furthermore, [4] explored boundary-delineation possibilities for cadastral mapping using UAVs, and [5] evaluated fundamental modeling, simulation, and applications for mapping with multiple UAVs. On the other hand, [6] delved deeply into the use of UAVs in cadastral surveying, corridor surveying, and automated mapping, discussing both opportunities and challenges. Moreover, several studies have highlighted the utilization of UAVs to create maps for various purposes, such as the construction industry [7], civil engineering [8], and the mining industry [9]. In addition to reviews on the use of UAVs for thematic mapping, some studies have assessed the application of UAVs in terrain mapping. For example, [10] provided a comprehensive overview of the applications of UAVs in mapping and surveying within the mining industry, including mine terrain maps. Similarly, [11] presented an overview of utilizing UAVs in the survey of terrain maps. The findings indicated that presented an overview of utilizing UAVs in the survey of terrain maps. The findings indicated that UAV technology has the capability to update, modify, and enhance geospatial and geoenvironmental survey data in real-time, providing businesses and governments with the most current geographic data and ensuring information assurance for resource management, land development, and environmental improvement. In addition to offering an overview of UAVs in generating maps, [12] highlighted the precision and limitations of terrain surveying based on UAS and Structure from Motion (SfM). Furthermore, [13] classified UAV applications for terrain mapping and identified the systems and outcomes that enhance UAV use in terrain mapping. However, most studies have concentrated on reviewing the applications of UAVs for specific mapping purposes, such as construction, damage assessment, mining, cadastral mapping, and 3D maps. Although some studies address terrain maps generated from UAVs, they are typically applied to complex terrains or analyze factors affecting map accuracy or the classification of UAV-based terrain map usages. UAV technology is very effective, it provides a high-resolution, economical, and effective substitute for traditional mapping methods, especially when it is combined with other advanced technologies. This study aims to review the research related to using UAV with other modern technologies such as GNSS, photogrammetry and Lidar for terrain mapping.

2. Methodology

The study starts by identifying key works and specific concepts relevant to the topic. The search terms and syntax are established as follows: (1) The search syntax includes terms like "unmanned aerial vehicles," "UAVs," "UAV," "Global Navigation Satellite System," "GNSS," "light detection and ranging," "LiDAR," "terrain mapping," and "topographical mapping." These terms are carefully selected to ensure the search results are highly relevant to the research topic; (2) This search syntax is then used to systematically search various databases, including Google Scholar, Web of Science, Scopus and Sci-

Fig. 1. Phantom 4 RTK – integrated high precision positioning system
Rys. 1. Phantom 4 RTK – zintegrowany system precyzyjnego pozycjonowania

Fig. 2. Inspire 2 with high resolusion camera Zenmuse X5S
Rys. 2. Inspire 2 z kamerą wysokiej rozdzielczości Zenmuse X5S

enceDirect, chosen for their extensive collections of academic and scientific literature; (3) The primary language for these searches is English; (4) The systematic search results in a comprehensive collection of scientific literature covering many aspects of UAV mapping techniques. This collection provides a wealth of information and insights into the topic; (5) The types of literature collected include book chapters, conference proceedings, and original papers published in international journals following a rigorous peer review process. These types of literature are chosen for their academic rigor and relevance to the research topic.

3. Application of UAV and GNSS technology in terrain mapping

The integration of UAV and GNSS techniques has emerged as a highly effective method for generating DEMs and maps with great efficiency and accuracy [14] The use of UAV images combined with GPS technology has significantly enhanced the precision and timeliness of high-resolution digital maps. [15] illustrated the application of Pix4D GPS and GIS systems for processing images and creating terrain maps. This study utilized primary data from field surveys that incorporated both UAV-based and DGPS-based ground surveys. The GCP coordinates were obtained through a static DGPS survey using a Stonex S8 Plus. This approach has proven to be a reliable and portable solution for remote data collection, delivering results with exceptional spatial and temporal resolution, even in challenging terrains, at a low cost. According to [16], modern terrain mapping techniques employ DGPS and UAVs. UAVs operate close to the ground to capture precise and high-quality aerial photographs, using GPS for accuracy, which enables rapid and detailed image acquisition. DGPS enhances GPS accuracy from 15 meters to approximately 10 cm by transmitting the difference between observed and computed coordinates through a network of ground-based reference stations. To create a terrain map of Dhulikhel Ward No 4, UAV and DGPS technologies were used to gather primary data. This data was processed using Pix4Dmapper software, generating point cloud data, DSM, DTM, and orthophotos. The processed data was then exported to a GIS environment for terrain mapping. The contour lines on the map accurately represent elevation changes from 1472 to 1492 meters. Additionally, [17] assessed the use of UAV PHANTOM 4 for data collection to create a terrain map, DTM, and orthophoto of the region, highlighting the advantages of this new technology. The ortho-rectified imagery was compared to RTK-acquired GCPs, yielding RMSE values of 0.00603m for planimetric and 0.00290m for vertical coordinates. These accuracy metrics demonstrate the reliability of UAV technology in mapping and surveying. Furthermore, [18] suggested that GCPs in SfM photogrammetry surveys could be minimized or eliminated using UAVs equipped with RTK GNSS. They conducted a comprehensive evaluation of the impact of GCPs on terrain data generation with RTK-GNSS UAVs. This study demonstrated the effectiveness of RTK-GNSS UAVs for terrain surveying in longitudinally extended areas such as beaches and river valleys. The findings also validated the results of aerial surveys in hazardous and inaccessible terrains, like rocky coastal regions and landslides, where ground control is challenging. Moreover, [19] evaluated the use of Direct Georeferencing techniques in UAVs for accurate terrain mapping. Direct georeferencing on UAVs eliminates the need for GCPs, allowing for minimal tie-point measurement. The study used a multi-rotor UAV DJI Phantom 4 RTK/PPK with a high-accuracy GPS antenna for data collection. The horizontal precision test results showed a value of 0.040 m using a Circular Error of 90%. The findings revealed that UAVs with direct georeferencing techniques produce highly accurate maps for relatively small areas. According to [20], traditional aerial photogrammetry methods using helicopters or airplanes are costly and complex for small areas. In developing countries like Nepal, UAVs have been used to quickly and affordably acquire geographic data. The use of UAVs is rapidly increasing in Nepal due to their ability to capture im-

ages from a distance and provide high spatial and temporal resolution data at a low cost, even in difficult terrains. The study used UAVs for image acquisition and DGPS for setting CPs and GCPs. The effectiveness of UAVs for mapping and terrain surveying was examined, comparing orthophotos with and without GCPs. The results indicated that UAVs could revolutionize efficient and rapid spatial data collection at minimal cost and time in developing countries like Nepal, where geospatial data is highly sought after. Additionally, [21] presented a photogrammetric method for processing UAV images using stereo optical compilation and GCP from GPS data to create a terrain map of Borobudur Temple, Indonesia. The GPS survey aimed to establish a representative GCP network with good spatial distribution in the study area. The study focused on the geometric accuracy assessment of DEMs and orthophotos used for deriving terrain maps. The findings suggested that achieving 1:5,000 terrainal mapping accuracy requires full control or 8 GCPs per model. At this level of geometric precision, Precise Point Positioning (PPP) can save time, cost, and reliance on reference stations, meeting GCP accuracy requirements

Terrain charting of water bodies, marshlands, or land areas devoid of land cover using conventional surveying techniques is challenging and time-consuming, as noted by [22]. To address this, UAVs, GNSS, and GIS were utilized to create a terrain map of a rainforest mining area in Osino, Ghana's Eastern Region. This combination, with a terrain map precision of less than 5 cm, offers an efficient and suitably accurate method for mapping inaccessible places. Additionally, [23] employed survey-grade UAVs equipped with onboard RTK-GPS for high-precision positioning to conduct a survey at Narrabeen Beach, Australia. This allowed for detailed observations of dune and beach erosion across the entire 3.5 km long bay at a spatial scale and temporal resolution. This instrument requires only one operator to deploy securely in the field, eliminating the need for time-consuming and independent on-ground surveying of GCPs. The results indicate that UAVs provide a productive and economical survey tool for terrain mapping and measuring in coastal regions. Furthermore, to collect more accurate data, aircraft manufacturers have recently included onboard RTK functionality in their UAVs. High-accuracy GNSS technology enables the camera's 3D position to be detected within a few centimeters at the moment of each capture. The study [24] used the DJI Phantom 4 RTK to survey the topography of a coastline area of the Northern Adriatic Sea (Italy). The findings demonstrate that the UAV-RTK method significantly accelerates the accurate mapping of coastal areas, with a single GCP potentially required to estimate the focal length with any degree of accuracy.

In addition to combining UAV and GNSS to create and update maps of accessible areas, this method is also used in terrain surveys of difficult-to-access areas such as mining regions. According to [25], aerial photogrammetry produces high-quality products with an outstanding level of information in the outputs, is less expensive, and offers faster data acquisition and processing than classical topography and possibly more recent methods like laser scanning. UAVs were used to create various surfaces for a small open pit quarry in southern Brazil. For geolocation support and comparison, well-known terrain surveying techniques were employed, specifically laser scanning and RTK (real-time kinetic) GNSS. Compared to the laser-scanned surface, the UAV results were less inconsistent around the RTK sites. This indicates that photogrammetric surfaces can be a faster and easier option for mining reconciliation, with reduced uncertainty compared to traditional techniques.

Besides mapping terrain on the mainland, coasts, and difficult-to-reach areas such as forests, mountains, and mines, UAVs are also used for mapping on islands. The study [26] analyzes the fundamental technologies of the low-altitude UAV aerial photographic system in island terrain mapping. This includes the flight plan considering the island's characteristics, exposure control auto excursion angle rectification, and exposure point calculation by differential GPS. The island's morphological features should be thoroughly considered during the aerial design phase to decrease the number of photos that fall into the ocean and improve the strength of the model's connectedness. The findings demonstrate that, with a limited number of control points, UAV aerial photography technology can provide large-scale island terrain mapping, thereby addressing the gap in Chinese island mapping capabilities.

4. Application of UAV and photogrammetry technology in terrain mapping

Photogrammetry technology represents an advanced technique used to gather, examine, and process imagery obtained from Unmanned Aerial Vehicles (UAVs). This technology is essential for creating highly precise and detailed two-dimensional (2D) and three-dimensional (3D) maps, models, and measurements of various objects or landscapes. These 3D models, built upon photogrammetric processes, stand out for their remarkable precision, offering an accurate representation of the terrain's current conditions [27]. As highlighted by [28], UAVs have emerged as the most recent and widely embraced tools for terrain mapping globally. The study assessed the influence of UAV platforms on the quality and precision of the resulting images and related outputs, which include contours, digital surface models (DSM), digital terrain models (DTM), and orthomosaic images. Specifically, the research investigated whether the high-cost fixed-wing eBee drone could be effectively replaced by the more economically viable Phantom 4 Advanced UAV. The findings indicated that the Phantom 4 Advanced is highly maneuverable, even in restricted spaces, and its stable flight patterns contribute to enhanced image quality. The potential of utilizing UAVs for conducting terrain surveys with high-resolution details was thoroughly examined in [29]. According to the analysis provided in [29], although various satellite imaging methods and field-based surveying techniques are available for depicting the earth's relief features, these methods are often found to be less accurate, overly time-consuming, or prohibitively expensive. In contrast, UAVs equipped with high-resolution imaging capabilities present an efficient and cost-effective alternative for capturing highly accurate depictions of terrestrial relief. To explore this potential, researchers examined UAV applications for conducting terrain surveys in Bangladesh. Their approach involved using UAV technology to acquire high-resolution elevation imagery, extracting point elevation data from the images, and subsequently generating generalized terrain

Fig. 3. An UAV with attached lidar sensor
Rys. 3. Bezzałogowy statek powietrzny z zamontowanym czujnikiem lidar

surface models, including DSMs and DTMs, based on the collected data. The study concluded that UAV platforms offer immense possibilities for terrain surveying, particularly in providing real-time altitude data with precision. In parallel, a study detailed in [30] utilized high-resolution UAV imagery to conduct land surveys for a proposed hydroelectric power project in the Patgaon region of Maharashtra, India. From a high-resolution orthomosaic image captured by the UAV, the research team extracted essential features to assist in generating accurate terrain maps. The Indian-manufactured quadcopter employed for capturing these images demonstrated outstanding capabilities in image acquisition. Moreover, the positional accuracy achieved was notable, with a Root Mean Square Error (RMSE) of 0.00237 meters, validating that UAVs provide a reliable and economical approach for conducting geospatial analyses, creating point clouds, and performing mapping and surveying tasks.

Additionally, as stated in [31], UAVs offer a cost-efficient method to capture extremely high-resolution images compared to traditional satellite and aerial photography techniques. This innovative approach facilitates the acquisition of high-resolution digital surface models (DSMs) and multi-temporal aerial stereo images. In their research, UAV technology was employed to gather real-time survey data for terrain mapping in the Tainan region of Taiwan. To ensure exceptional accuracy, the study calibrated the high-resolution UAV-based terrain data using local ground control points (GCPs). These GCPs were measured with a total station, achieving an accuracy greater than 1/2000, thereby enhancing the reliability of the UAV-derived terrain outputs in the study area. In the study [32], researchers outlined the comprehensive steps involved in producing large-scale terrain maps through the application of UAV photogrammetry at the Siman Fars manufacturing site. The findings highlighted the creation of a 10 cm densely colored 3D point cloud using UAV imagery. This point cloud demonstrated superior accuracy for generating 20 cm contour lines compared to traditional ground mapping techniques. The high density of 3D points achieved through UAV imaging was unparalleled, exceeding the capabilities of ground surveying methods. Illustrated in Figure 1, this advancement underscores the exceptional benefits of UAV photogrammetry, which include lower costs, enhanced quality, faster processing times, and improved safety. As a result, UAV photogrammetry has emerged as an innovative and efficient solution for surveyors in the field of mapping. Focusing on large-scale mapping, [33] explored a rapid and efficient methodology for acquiring and processing terrain map data using low-altitude UAV photogrammetry technology. The study investigated the development of a swift mapping system based on an electronic plate mapping mechanism. This system introduces a transformative change to the conventional mapping paradigm by significantly enhancing mapping efficiency. The research concluded that UAV technology provides novel methods for conducting fast and large-scale surveys. The technical advantages, alongside the potential for diverse surveying applications, reinforce its importance in contemporary mapping practices.

Similarly, study [34] addressed the UAV image processing workflow using the Agisoft Photoscan software. This software's results were compared against measurements obtained from traditional ground surveying methods. The comparison revealed that terrain maps could be created both rapidly and accurately with UAV technology, showcasing its advantages over conventional approaches. The study also emphasized that UAV-based mapping proves particularly effective for large-scale terrain projects, especially in smaller areas where traditional methods may fall short. Furthermore, according to [35], UAV-generated digital photographs form a reliable foundation for creating orthophotomaps of exceptional quality. The study illustrated techniques for developing terrain maps in rural areas using orthophotomaps derived from UAV-captured imagery. To enhance efficiency in identifying the types and extents of specific terrain features, the researchers employed both supervised and unsupervised object classification techniques. The results are intended for use in generating terrain maps of the study area. The authors stressed that maintaining a high degree of accuracy and ensuring the simplicity and speed of updating mapped objects are critical factors in modern cartography.

In another innovative application, [36] utilized low-altitude UAV photography alongside optical profilometry techniques and a remotely operated aircraft controlled by a ground operator to enable optical 3D measurements. The system comprised a compact ultrasonic sensor mounted on the UAV, a camera, and a miniature projector. Additionally, a CCD camera paired with a small projector was employed to acquire highly accurate elevation data at low altitudes for smaller-scale regions. This method proved effective in capturing intricate terrain information, enabling the creation of detailed maps for small geographical areas. Similarly, [37] conducted a study using the DJI Phantom 3 drone, which was flown at a height of 120 meters to capture data. The raw images obtained were processed using Pix4D software to produce ortho-mosaic maps with remarkable precision. This approach facilitated the creation of more accurate digital surface models (DSMs). The study highlighted the scientific contributions

of UAV technology to the surveying field, emphasizing its ability to significantly reduce both time and financial investment. Beyond increasing efficiency by enabling surveyors to complete more projects within the same time frame, UAV technology also improves the quality of datasets, allowing for more comprehensive planning. Traditional surveys, by contrast, demand considerable time, money, and labor, making UAV solutions a transformative advancement in this sector.

The feasibility of conducting terrain mapping in small areas through the use of affordable commercial UAVs has been underscored in numerous studies. For instance, [38] delved into the potential of utilizing inexpensive commercial UAVs to generate digital surface models (DSMs) for small-area terrain mapping data sources. Employing a commercial quadcopter UAV, the researchers gathered aerial imagery that yielded two key outputs: a building footprint vector line and a DSM. These outputs demonstrated promising results, achieving sub-meter planimetric precision alongside vertical accuracy within 5 meters. The study concluded that inexpensive commercial UAVs exhibit significant potential for gathering detailed terrain data, which is critical for producing meticulously crafted plans.

Beaches endure significant deterioration driven by both natural forces and human activities. According to [39], the development of models that can predict the changes in these delicate ecosystems requires access to high-resolution terrain data. These models are essential for assessing the rapid transformations that occur in such environments. The study presented a detailed and practical procedure for employing low-altitude UAVs to monitor the topography and morphological changes in the shoreline of Wujiao Bay. By utilizing advanced UAV techniques, the research improved existing methods for conducting high-resolution terrain surveys and identifying geomorphic alterations in complex coastal landscapes. This breakthrough significantly expanded the scope and applications of UAV remote sensing in coastal studies. In addition, [40] highlighted the critical role of the intertidal zone, not only as an essential component of the marine environment but also as a natural barrier against disasters such as storms and coastal erosion. Mapping the topography of this region is vital for studying its functions and dynamics. However, traditional surveying techniques for intertidal zones face inherent challenges, making this task difficult. The study adopted UAV photogrammetry as an alternative, revealing its immense potential for creating accurate terrain maps of intertidal regions. This modern technique shows promise for capturing detailed terrain and measuring the spatial extent of the intertidal zone.

Drones are being employed in mining regions in seemingly limitless ways, providing real-time data collection capabilities directly from the ground. For example, [41] introduced a cost-effective approach utilizing UAV technology for 3D terrain mapping at open-pit mine sites in Vietnam. Through the use of aerial imagery transmitted to a ground monitoring station, the study successfully generated detailed and expansive 3D terrain maps. Field test results indicated that these affordable UAVs are well-suited for creating accurate 3D representations of deep and vast coal pits. The findings emphasized that the low-cost UAV offers a reliable alternative to traditional surveying methods while maintaining effectiveness in large-scale mapping endeavors. Additionally, [42] developed an efficient process for employing rotary-wing unmanned aerial vehicles (UAVs) to create comprehensive terrain maps for open-pit mines. This process was carefully designed to guarantee safety, accuracy, and efficiency in map creation while adhering to governmental standards and established theories related to terrain measurements and edits—both generally and specifically for mine environments. Experimental results revealed that this methodology is highly reasonable, accurate, simple to implement, secure, and efficient, further reinforcing the utility of UAVs in mining applications within Vietnam.

5. Application of UAV with Lidar technology in terrain mapping

Due to the limitations of cameras commonly used with UAS, such as their inability to penetrate foliage, LiDAR sensors are increasingly popular in UAS mapping. [43] examined various performance factors of UAS LiDAR point cloud production based on UAS flights using the Velodyne laser scanner and cameras. The accuracy of the final UAS LiDAR point cloud was assessed by comparing it to point clouds derived from dense image matching, based on the generated DSM. Although the precision of the UAS LiDAR point cloud is lower than that of point clouds derived from images, it is still adequate for terrain mapping applications where optical imaging is not effective. Similarly, in the study [44], a UAV with a LiDAR sensor was used to acquire data for terrain mapping in Ha Tinh province, Vietnam, due to the region's 1 km height difference between the mountain's base and peak and high coverage density. The horizontal RMS error was 10.4 cm, and the vertical RMS error was 1.3 cm, indicating sufficient reliability to produce a terrain map at a 1:2000 scale. It can be concluded that drone surveying will soon replace traditional field surveying methods, and vegetation canopy will no longer be a barrier. Additionally, [45] used a low-altitude UAV combined with LiDAR distance measurements and a Post-Processing Kinematic Global Positioning System (PPK-GNSS) to produce cropland terrain maps with centimeter-level precision quickly and affordably. The obtained Root Mean Square Error (RMSE) demonstrated that high-precision terrain information could be collected using UAV-LiDAR technology, which might provide valuable data for precise field leveling.

According to [46], UAV-based remote sensing methods have shown significant promise for tracking abrupt shoreline changes. Compared to LiDAR mapping, UAV image-based mapping produces relatively subpar results in low-textured areas. This study demonstrates how UAV LiDAR can be used to map coastal landscapes. The findings revealed that both image-based and UAV LiDAR methods produce point clouds compatible within a 5–10 cm range, offering high-resolution, high-quality terrain data. A distinct advantage of UAV LiDAR is its ability to capture points below the canopy by penetrating vegetation, providing vast and consistent ground coverage across various geomorphic situations, and increasing point density.

With its advantages, UAV and LiDAR technology is an effective method for terrain surveys in difficult-to-access areas such as mines, forests, and mountains. In the study [47], terrain surveying of a complex mountainous terrain area was conducted using UAV technology, aerial photography, and aerial LiDAR. The main goal was to create a map with a 1:1,000 scale and a 1.0 m contour interval, along with 3D

point clouds, a DEM, and an orthomosaic. The combination of aerial LiDAR and UAV photographic data creates a comprehensive and complete information repository on the surveyed terrain, proving that UAV LiDAR technology is a reliable instrument for gathering geographic data, especially in Vietnam's challenging terrain conditions.

6. Conclusion

The paper examined published research that focused on establishing terrain maps using UAV technology. The findings revealed that UAVs can be integrated with photogrammetry, LiDAR, and GNSS technologies to create these products. Additionally, the results demonstrated that these technologies not only represent the terrain of flat, accessible land areas but also facilitate the data collection process for mapping difficult areas. Moreover, the study highlighted several advantages, including high resolution and accuracy, cost-effectiveness, rapid data collection, flexibility and accessibility, enhanced safety and reduced human risk, advanced modeling, and 3D mapping capabilities.

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Zastosowanie UAV z technologiami GNSS, LiDAR i fotogrametrii w mapowaniu terenu

Ten artykuł oferuje kompleksowe podsumowanie najnowszych publikacji, które badają wykorzystanie technologii UAV do mapowania terenu. Wyniki uzyskane z tych badań wskazują, że integracja UAV z fotogrametrią, LiDAR i technologiami GNSS jest wysoce skuteczna w tworzeniu szczegółowych i dokładnych map topograficznych. Technologie te umożliwiają precyzyjne odwzorowanie cech terenu, co czyni je nieocenionymi dla różnych zastosowań mapowania. Badanie nie tylko podkreśla praktyczne zastosowania technologii UAV w mapowaniu topograficznym, ale także służy jako odniesienie techniczne do poszerzania wiedzy i zrozumienia tych zastosowań. Analizując metodyki i wyniki licznych badań, ten artykuł dostarcza wglądu w możliwości i korzyści wynikające z użycia UAV do mapowania terenu. Podkreśla znaczenie UAV w zwiększaniu dokładności i efektywności badań topograficznych, szczególnie w trudnych warunkach, gdzie tradycyjne metody mogą być mniej skuteczne.

Słowa kluczowe: *UAVs, GNSS, lidar, technologia fotogrametrii, mapowanie terenu*