Advancing Topographic Mapping with UAVs: Technologies, Challenges, and Prospects

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Abstract
UAV technology is currently routinely utilized to generate topographic maps. This paper summarizes recent publications on the use of unmanned aerial vehicle (UAV) technology for terrain mapping based on the results of research published from 2010 to January 2025. The quantitative synthesis of the literature reveals that photogrammetry remains the most prevalent method, accounting for 64% of the studies, followed by LiDAR at 26%, while other emerging technologies comprise 9.8% of the research landscape. The obtained results showed that the UAV method with photogrammetry, lidar, and GNSS technologies are useful techniques for producing topographical maps. Also included in this study are some of the technology's drawbacks and advantages. Finally, the prospects of development of methods such as RTK/PPK integration for centimeter-level accuracy, AI-driven autonomous flight planning, multi-sensor fusion (combining thermal, multispectral, and LiDAR data), swarm UAVs, the integration of UAVs with IoT, smart sensors were also presented. This study provides a technical reference for advancing knowledge and comprehension of UAV applications in creating the topographic maps.

Keywords: Terrain Map, Topographic Map, UAV

1. Introduction

One of the maps that is used the most is the topographic map. A topographic map faithfully represents the natural and man made features on the ground such as traffic routes, residential areas, elevation, rivers, lakes, etc. [1] They offer useful data for various uses, such as infrastructure construction, environmental control, and urban planning [2]. When gathering data on topographic objects, the following needs to be done: (1) identify the type and character of phenomenon or object; (2) forecast the range of occurrences; (3) give an exact location; (4) classify objects into appropriate classes and categories; (5) conduct the process of cartographic generalization [3]. Traditional surveying approaches, UAV or satellite image-based remote sensing methods, and digital mapping technologies can be used to establish these maps [2]. However, according to [3], UAVs are the measuring method that yields fast and precise topographic data. In addition, UAV technology is currently widely used in small-area topographic mapping due to its low cost and high-quality output [4]. Today, a variety of UAV types have proven their accuracy when performing topographic surveys around the world. Compared to traditional surveying and manned aerial mapping, UAV technology offers transformative advantages for topographic data collection [5] and [6]. These systems are characterized by high cost-effectiveness and operational flexibility, allowing for rapid deployment in challenging environments [4] and [7]. Furthermore, the integration of advanced sensors enables UAVs to deliver high-resolution geospatial products that meet the stringent requirements of modern mapping [8]. Beyond these technical capabilities, UAVs represent a user-friendly and time-efficient technology, granting researchers seamless access to high-accuracy data [8] and [9]. As noted by [10], this method proves more economical than conventional approaches due to its significantly reduced field time. Consequently, this tool has been widely adopted for generating topographical maps of both unobstructed flat areas [11][12] and [13] and complex, inaccessible terrains such as mining sites or rocky regions [14] and [15], etc.

Several reviews have been conducted to offer an overview of the use of UAVs in mapping. While [16] presented a thorough analysis of how damage mapping using UAVs, [17] provided an overview of various UAV systems, applications, and case studies as well as the most recent advancements in UAV image processing to make a 3D map, [18] described how to use drones for geo-mapping and talked about helpful tools. Besides, [19] analyzed boundary-delineation possibilities for cadastral mapping using UAVs, and [20] assessed fundamental modeling, simulation, and applications for mapping with multiple UAVs. On the other hand, using UAVs in cadastral surveying, corridor surveying, and automated mapping and its opportunities as well as challenges were discussed deeply in [21]. Moreover, some studies have mentioned the utilization of UAVs to create maps for various purposes such as the construction industry [22], civil engineering [23], mine industry [24]. In addition to reviews on the use of UAVs for thematic mapping, some studies have evaluated the application of UAVs in topographical mapping. In the study [15], the authors conducted a comprehensive overview of the applications of UAVs in mapping and surveying in the mining industry including mine topographical maps. Besides, [25] presented an overview of utilizing UAVs in the survey of topographic maps. The findings indicated that UAV technology has the ability to update, alter, and improve geospatial and geoenvironmental survey data in real-time, give businesses and the government access to the most recent geographic data, and provide information assurance for resource management, land development, and environmental improvement. In addition to providing an overview of UAVs in generating maps, [26] indicated the precision and limitations of topographic surveying based on UAS and Structure from motion (SfM). Additionally, classifying UAV applications for terrain mapping, as well as pinpointing the system and outcomes that enhance UAV use in terrain mapping was presented in [27]. However, most studies have focused on reviewing the applications of UAVs for mapping for specific purposes such as construction, damage, mining, cadastral, 3D maps, etc. Furthermore, although some studies deal with terrain maps generated from UAVs, they are only applied to complex terrains or analyze factors affecting map accuracy or classification of usages of UAV-based topographic maps. On the other hand, A systematic review along with analysis of the technologies used in conjunction with UAVs has also not been performed in the existing studies [25].

While previous reviews have provided valuable insights into domain-specific UAV applications such as cadastral surveys [21], construction management [22], or mining [24], they often overlook the holistic technical integration and the comparative performance of hybrid sensor systems (GNSS, LiDAR, and Photogrammetry) specifically for general topographic mapping standards [24][25][26] and [27]. Furthermore, there is a notable lack of research addressing how different topographic conditions influence the effectiveness of UAV applications. This review fills these gaps by providing a cross-disciplinary synthesis and evaluating the collective impact of these technologies on the precision and scalability of topographic data across diverse and complex terrains. To enhance the methodological rigor, this study formulates the following research questions:
RQ1: What are the predominant trends and the statistical distribution of UAV-based technologies utilized for topographic mapping from 2010 to 2025?

RQ2: How do the technical advantages and drawbacks of UAV-Photogrammetry compare with UAV-LiDAR across various complex terrains?

RQ3: What are the emerging technological prospects and integration pathways (e.g., AI, multi-sensor fusion, RTK/PPK) that will shape the future of UAV topography?

2. Methodology

In order to find, assess, and analyze all relevant research on the use of UAV technology in establishing topographic maps, this study employed a systematic literature review (SLR) approach. To ensure methodological rigor and transparency, the review process was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. After defining the research objectives, they were broken down into specific concepts along with corresponding keywords. Numerous publications were retrieved from online databases such as Web of Science, Google Scholar, Science Direct, and others. The following search terms were used to query these platforms: "drone" OR "unmanned aircraft system/UAS" OR "unmanned aerial vehicle/UAV" combined with "topographic map" OR "topographic mapping" OR "terrain map" OR "terrain mapping". The selection process involved three rigorous stages of screening (as illustrated in the PRISMA Flow Diagram - Figure 1):

Identification: A total of 786 records were initially identified. After removing duplicates, 520 records remained for screening.

Screening: Titles and abstracts were examined to determine alignment with the scope. 380 records were excluded as they focused on non-topographic UAV applications (e.g., military, agriculture, or simple aerial photography).

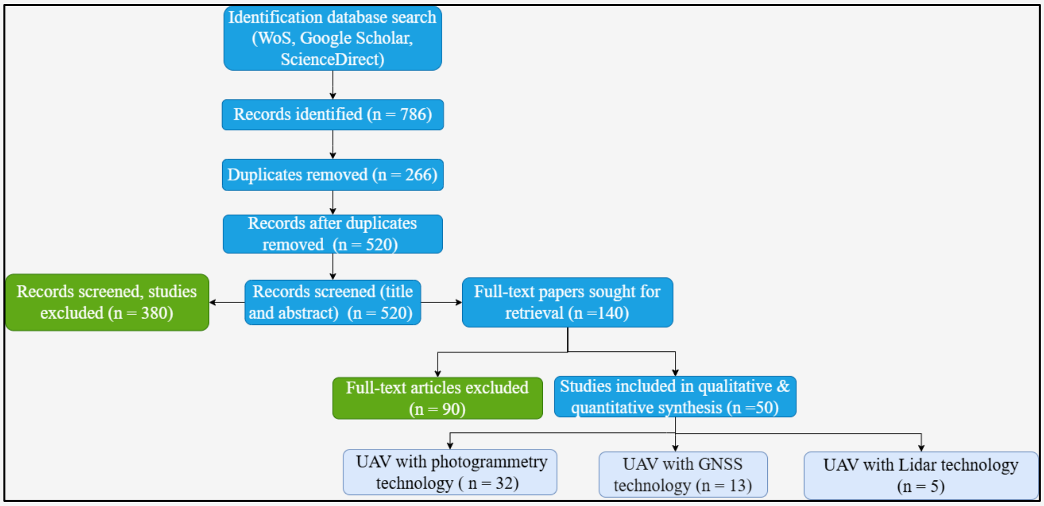

Figure 1: PRISMA flow diagram of the systematic literature review process

Eligibility: 140 full-text articles were evaluated for suitability. To ensure consistency, only English-language journal articles, conference papers, and book chapters published between 2010 and January 2025 were considered. Studies that lacked clear reporting of technical sensors or accuracy metrics (e.g., RMSE) were excluded.

Ultimately, 50 studies formed the core body of literature for this systematic analysis. To provide a structured synthesis, the studies were categorized into a classification framework based on technology types (Photogrammetry, GNSS, LiDAR) and application outcomes. This structured approach allows for a comprehensive evaluation of how different technologies perform across diverse topographic environments.

3. Applications of UAVs in Topographical Mapping

In general, precise topographic surveys that depend on traditional field-based techniques (such as the Global Positioning System and Total Station) are expensive, time-consuming, and demanding, particularly when mapping vast or isolated regions where access may be problematic [28]. Therefore, for recent years, topographic maps have been created and updated using aerial photos taken by UAVs as an alternative for conventional field-based topographic techniques. A variety of cutting-edge technologies are used by UAVs to accomplish high-precision topographical mapping including photogrammetry, Lidar (Light Detection and Ranging), multispectral and hyperspectral sensors. These technologies improve mapping capabilities, processing efficiency, and data accuracy.

3.1 Application UAV with Photogrammetry Technology in Topographical Mapping

Photogrammetry technology is a method of gathering, analyzing, and processing UAV imagery to create high-precision 2D and 3D maps, models, and measurements of objects or terrain. These 3D models based on photogrammetry exhibit excellent accuracy and accurately depict the terrain's current condition [29]. According to [30], UAVs are the newest and most popular surveying tools for topographic mapping worldwide. This study evaluated the impact of the UAV platform on the quality of images and its products, such as contours, DSM, DTM, and orthomosaics. This study examined if the expensive Fixed Wing eBee drone could be used in place of the less expensive DJI Phantom 4 advanced UAV. Findings showed that DJI Phantom 4 advanced is easy to maneuver in confined spaces, and its steady flying geometry improves image quality. Possibility of employing UAVs for high-resolution topographic surveys was presented in [31]. According to [31], even though there are several satellite imaging and field-based techniques for representing the earth's relief, they are both less accurate and either expensive or time-consuming. With less expense and effort, high-resolution UAVs could be able to depict highly exact Earth's relief features. Therefore, they investigated the possibilities of using UAVs for high-resolution topographic surveys in Bangladesh. In order to accomplish this goal, they used UAV to gather high-resolution elevation detailed photographs, extracted the point elevations to create the collected images, and generated a generalized topographical surface model such as DSM, DTM, etc. utilizing the information retrieved. The research showed that UAVs have enormous potential for topographic surveying with real-time altitude. Similarly, utilizing high-resolution photos, [32] conducted a land survey for a proposed hydroelectric power plant in the Patgaon region of Maharashtra, India, and extracted features from a high-resolution orthomosaic image to assist in the creation of topographic maps. The Indian-made quadcopter, which demonstrated excellent image acquisition capabilities, was used to capture the images. An RMSE (Root Mean Square Error) of 0.002 m for positional accuracy showed that it is an affordable way to get dependable results that may be applied to a variety of tasks, including point cloud production, mapping, geospatial analysis, and surveys. In addition, according to [6], compared to satellite and aerial photography, the UAV could take very high-resolution photography affordably. This method offers a viable method for obtaining high-resolution digital surface models (DSM) and multi-temporal aerial stereo images. Thus, they used this equipment to collect the living survey data for generating a topographic map in Tainan, Taiwan. The local coordinate of GCPs utilizing the total station with an accuracy of less than 1/2000 is used to calibrate the high-accuracy UAV-based topography in the study region.

In the study [33], the authors described the steps involved in creating a large-scale topographic map production from UAV photogrammetry of the Siman Fars manufacturing site. The results showed that the 10 cm densely colored 3D point cloud created by UAV images demonstrated that the accuracy of the 20 cm contour lines is superior to direct ground mapping because of the high density of created 3D points based on UAVs that ground surveying could not achieve (Figure 1). With its unique benefits of cheaper cost, higher quality, less time, and more safety, UAV photogrammetry is a novel solution for surveyors in mapping. Also related to large-scale mapping by UAV, [34] investigated a rapid approach for acquiring and processing topographic map data that uses the UAV low-altitude aerial photogrammetry technology. The development of a quick mapping system based on an electronic plate mapping system, which alters the conventional mapping mode and significantly increases mapping efficiency, is another important technology of UAV photograph mapping that is explored in this study. The results revealed that the UAV offers new methods for quick, large-scale surveying, and it has clear technical advantages and promising surveying applications. For the same purpose as study [12] and [34] briefly described the UAV image processing process using Agisoft Photoscan software. The findings of these software programs were compared with measurements from ground surveys. The topographic map of the study area may be created quickly and accurately in comparison to traditional methods.

Additionally, compared to traditional aerial photogrammetry, this approach is highly appropriate for large scale topographic mapping, particularly for small areas. Moreover, generation and evaluation of a topographic map at a scale of 1:2000 was presented in [9]. The authors detailed the usage of a UAV, namely the PHANTOM 4 pro, to collect remote sensing data and produce digital topographic maps in the Thanh Son area of Phu Tho province. The importance of employing UAVs to construct topographic maps is confirmed by their ease of control and the timely and high-quality data they provide to control locations. The generated digital topographic map meets the documentation standards of governmental entities. The greatest height error is 4.7 cm, while the east and north coordinate errors are 1.4 and 1.8 cm, respectively. The results show that the map's accuracy falls within a reasonable range of less than 2 cm, making it appropriate for a 1:2000 scale map. According to [3], UAV digital photographs are the basis for creating a good-quality orthophotomap. In this study, they presented the technique for creating topographic maps of rural regions using orthophoto maps created from the photos obtained during the UAV flight. To improve the efficiency of identifying the types and occurrence range of individual topographic objects, supervised and unsupervised object classification techniques were utilized. The results will be utilized to create a topographic map of the area under study. The authors noted that, in the process of creating cartography, it is essential to maintain the proper degree of accuracy and the speed and simplicity of updating objects.

With the same view as the above studies, [28] believed that accurate topographic surveys that depend on conventional field-based techniques are expensive, time-consuming, and difficult, particularly when mapping vast or isolated regions where access may be problematic. Thus, they employed an inexpensive and easy-to-use low-altitude UAV as a substitute for conventional field-based topographic techniques. The study clearly shows that low-elevation UAV images, with the help of ground control points (GCPs), are appropriate for creating and updating large-scale maps up to 1:200 with 0.1-meter contour intervals. Also used a low-altitude UAV photo, [13] combined the optical profilometry methods and a ground operator-controlled remote-controlled aircraft to provide optical 3D measurements. In essence, the system consists of a lightweight ultrasonic sensor mounted on a UAV, a camera, and a tiny projector. Besides, a CCD camera, a small projector, and a UAV were utilized in this study to gather precise elevation data from low heights in small-scale locations. This technique can obtain the topographic information with great detail to generate topographical maps of small areas. In another study, [35] used the DJI Phantom 3 drone which was flown at a height of 120 meters to the DJI Phantom 3 drone, which was flown at a height of 120 meters. Pix4D software was used to post-process the raw photos into ortho-mosaic maps. This made it possible to produce more accurate DSM. This project's scientific contributions focused on demonstrating the effectiveness of UAV technology in the surveying industry. Time and financial investment could be significantly decreased with UAV solutions. In addition to increasing productivity by completing more projects in the same amount of time, surveyors can work with a more qualitative dataset, allowing for better, more thorough planning than with traditional surveys, which require a significant investment of time, money, and labor. On the other hand, according to [36], the precision of the ground sample distance decreases with height, which results in a loss of data accuracy. Threfore, they analyzed the impact of UAVs on topography mapping at “Fakulti Kejuruteraan Awam dan Alam Bina”. They used Phantom 4 Pro to take ortho images at elevations of 80, 100, and 120 meters above sea level. Pix4D software and their GSD calculator tool were utilized to investigate the relationship with four elevations through an autonomous flight plan. Findings showed that calculating several checkpoints (CPs) on the track in addition to ground control stations is a reasonable idea to improve accuracy of topography mapping.

In addition, the viability of topographical mapping in small areas using inexpensive commercial UAV was demonstrated in a lot of studies. In the study [37], the viability of generating DSM for small-area topographic mapping data sources utilizing inexpensive commercial UAVs was discussed. A commercial quadcopter UAV was utilized to collect aerial image data. The study's results included a building footprint vector line and a DSM. The results demonstrate a sub-meter planimetric precision and a 5-meter vertical accuracy. In conclusion, there is a lot of promise in using inexpensive commercial UAVs to collect topographic data for the creation of detailed plans. Similarly, [38] found that topographic surveying is becoming increasingly popular because of numerous low-cost UAVs with light weights. Thus, it can provide mapping products with centimeter-level accuracy (in XY and Z), which was previously only possible with costly field surveying techniques.

In another study, [39] demonstrated the possibilities of employing UAVs to create and update maps. To extract features with sub-decimeter accuracy, an orthophoto with a spatial resolution of 3.3 cm and a coverage of 0.095 km2 was created from 954 images acquired with a DJI Phantom 2 Vision Plus quadcopter. The findings show that UAVs provide good prospects for producing very accurate and high-resolution orthophotos, which will make the process of creating and updating maps easier topographic map 1:1000 scale. Also for the purpose of updating the map, [40] used WorldView-3 satellite imagery, UAV) data, and DEM from Synthetic Aperture Radar (SAR) to update the 1:10000 topographic map in Putrajaya, Malaysia. The planimetric coordinate variations between WorldView3 and CP, UAV and CP, and traditional aerial photogrammetry and CP had corresponding RMSE values of ±1.112 m, 0.892 m, and 1.160 m. When comparing costs and time, UAVs demonstrated cost-effectiveness in both data collection and processing. The results indicated that UAVs are the most cost-effective technique for updating a small area.

Beaches suffer from considerable degradation due to the dual influences of natural and human-induced factors. According to [41], building models that can forecast the evolution of these natural ecosystems and assess the rapid changes sometimes requires higher resolution topographic data. Thus, a thorough, workable procedure was provided in this study for deploying the low-altitude UAV to monitor the topography and the changes in the beach of Wujiao Bay. This study improved the current techniques for high-resolution topographic surveys and geomorphic change identification in the complex shoreline and significantly increased the application of UAV remote sensing. Besides, in study [42], the authors developed a technique for beach topography surveillance using UAV technology and in situ direct measurement methodologies. The study utilized aerial photogrammetry and aerial triangulation techniques to match the image feature points and determine the corresponding topography points in the sand. The findings of direct measurements and image-matching point clouds were compared. The results showed that UAV imaging technology can minimize measurement mistakes and field measurement expenses by increasing the effectiveness of traditional manual sampling and lowering the cost of indirect observations. For the same purpose of the coastal topography survey, [43] evaluated the mapping and monitoring of beaches and sand dunes along the northwest coast of Portugal using UAV. Detailed DSM of the study area was acquired with grid spacing of 10 cm and vertical accuracy (RMS) varying between 3.5 and 5.0 cm. Because the relative simplicity of these tools and the potential for generating high-resolution DSMs, existing mapping techniques and databases of coastal migration and change may be able to be expanded. According to [44], in addition to being a crucial marine environment, the intertidal zone protects the interior land from the effects of natural disasters like storms and coastal erosion. Thus, the topographic map of this zone is critical for studying the intertidal zone.

However, using traditional surveying techniques to create topographic maps of the intertidal zone is extremely challenging. This study employed the UAV approach in intertidal topographic mapping. The research findings revealed that UAV photogrammetry is a promising technique for mapping the terrain and size of the intertidal zone. The use of unmanned aerial systems, or drones, to measure coastal topography has grown recently. [45] evaluated the current state of the art in photogrammetry and drones for beach surveys, along with the corresponding measurement quality attained. Also, they demonstrated how drones can achieve the high precision and speed needed for beach surveys with a minimal setup and low cost. The results showed that a final DEM accuracy of around 5 cm can be obtained using a minimal, low-cost drone configuration. The survey efficiency and the increased detail in comparison to topographic transects, that is, the ability to fully rebuild the beach topography are the main benefits of the UAS-photogrammetry technology.

In addition, the application of UAV SfM technology in topographical mapping has been shown in many studies. [46] demonstrated the potential of structure-from-motion and small unmanned aircraft systems for topographic surveys. In this research, innovative topographic survey techniques that combine small UAVs and structure-from-motion (SfM) photogrammetry are a quickly developing research method. Thus, they investigated the precision, accuracy, and possible uses of this method in this study. This method provides orthorectified aerial photos and DSMs at sub-decimeter resolutions, which can be used to quickly obtain high-precision topographic data. Although this aerial survey method is recommended for usage in various geomorphological contexts, caution must be used to guarantee that sufficient ground control is used to provide a high level of accuracy. Also, the study [47] evaluates the viability of performing photogrammetric topography surveys with a low-cost UAV and SfM. The DJI Phantom and two tiny digital cameras, the GoPro Hero 3 and the Canon SX230 HS, were used to gather data. It analyzed each camera's advantages and disadvantages. By comparing the accuracy and consistency of DSMs generated from camera imagery, this study will evaluate two SfM and MVS software systems: Agisoft Photoscan and Photosynth. Lastly, the DJI Phantom's suitability as a surveying UAV platform will be assessed, and suggestions for future enhancements will be made. According to [48], three-dimensional models of forestry are helpful for estimating tree height in forestry, which is necessary for some remote sensing applications. This model was created using a 2D image acquired by UAVs through the SfM and Multi-View Stereo (SfM-MVS) system. Additionally, topographic maps and high-resolution orthomosaic photography of the study area can be easily generated using UAV-based SfM measurements. The results showed the prospects of UAV remote sensing in topographic and vegetation surveys. In the study [49], a point cloud and derived DSM depicting a beach dune system with good topographic quality and vertical accuracy were produced by the SfM technique when applied to photos taken by a low-altitude UAV system. These results were comparable to GNSS survey data. A dense point cloud and then high-resolution DSM of a beach dune system at Marina di Ravenna (Italy) were created using UAV data and the SfM image-based technique. The UAV-SfM's elevation dataset's quality was first assessed by contrasting it with a point cloud created by a Terrestrial Laser Scanning (TLS) survey. It was shown that the UAV-based method was simple, and the vertical dataset's accuracy was on par with the outcomes of TLS technology.

In addition to mapping studies, several studies have evaluated the accuracy of these products. In parallel with analyzing the feasibility of using low-cost UAVs as mobile mapping tools for geodetic photogrammetric surveys, [50] illustrates how various UAV flight parameters and settings affect the precision of mapping products. A statistical analysis was provided to demonstrate how variations in flight altitude can affect the precision of the provided 3D data. It was discovered that increasing flying height could result in a sharp decline in accuracy; yet, caution should be used to maintain other parameters constant. Besides, [51] evaluated the accuracy of digital elevation models (DEM) produced from a variety of dense point clouds acquired by inexpensive UAV photogrammetry. The findings demonstrate that a correlation between the precision of a terrain model and the quantity of points utilized to build it can be found. Moreover, the obtained results from a study [52] showed that one alternative method to streamline the data collection process is the use of UAVs, which are easy to use and have cheap operations and manufacturing costs. They carried out a study to assess the accuracy of topographic mapping based on UAV images. This investigation indicated that the UAV image accuracy is ± 0.460 m. In conclusion, UAV imagery may be utilized to update and generate topographic maps.

Not only presenting the method and process of mapping using UAV technology, some studies have also mentioned the selection of suitable UAV types. [53] was conducted to compare the results of topographic surveys with a fixed-wing and a common rotary-wing UAV at a construction site in Yangsan-si, Gyeongsangnam-do, Korea. When the X, Y, and Z coordinates of seven ground control locations were compared between those obtained using eBee and Phantom2 Vision+ and those obtained using a differential global positioning system, the root mean squared errors of the X, Y, and Z coordinates were around 10 cm, respectively.

Drones are used in mine regions in apparently endless ways since they can help collect data in real-time on the ground. The study [14] introduces a low-cost solution based on UAV technology for 3D topographic mapping at Vietnamese open-pit mine sites. The images sent to the ground monitoring station were used to successfully build large-scale 3D topography maps. The study's field test results demonstrate the suitability of the inexpensive UAV for relatively accurate 3D mapping of deep and expansive coal pits. Also utilized UAVs for surveying topographics in a surface mine, [54] used a well-known rotary-wing UAV to conduct a topographic survey of a small-scale open-pit limestone mine in Korea. The root mean squared errors of the X, Y, and Z coordinates of five GCPs were approximately 10 cm when the coordinates obtained by UAV photogrammetry and the differential global positioning system were compared. It is anticipated that the widely used rotary-wing UAV photogrammetry will be able to replace or enhance current topographic surveying equipment in small-scale open-pit mines. Additionally, [55] created a process for employing rotary-wing unmanned aerial aircraft to create extensive topographic maps of open-pit mines. The study develops a process that guarantees efficiency, safety, and accuracy for the creation of topographic maps. It applies the government norms and theories for measuring and editing topographic maps in general and mines in particular, as well as the use of drones in Vietnam. According to experimental findings, the process is reasonable, accurate, simple, secure, and efficient.

According to [56], the quantitative analysis of active faults is based on topography with high precision and high resolution. The authors used photos taken with a cheap digital camera mounted on a UAV over the Haiyuan fault to reconstruct the fault zone's topography. The SfM-derived topography's accuracy and resolution were thoroughly assessed using the airborne lidar data that was already available as a reference. The precision of the SfM point cloud is similar to that of the lidar point cloud when taking into account the inaccuracies in the lidar data itself. The findings showed that for the topography mapping of the fault zone, the UAV-based SfM photogrammetry approach can offer a flexible, affordable, and efficient substitute for airborne lidar.

Despite the extensive application of SfM photogrammetry in UAV-based topographic mapping, several fundamental sources of error require critical consideration. Error propagation in SfM workflows originates from camera calibration uncertainty, image geometry, and ground control configuration, and can significantly affect both horizontal and vertical accuracy. Inadequate camera self-calibration, particularly when using consumer-grade sensors, may introduce systematic distortions that propagate through bundle adjustment and amplify elevation errors. Moreover, ground control strategies play a decisive role: poorly distributed GCPs can lead to local warping and vertical bias, even when the total number of GCPs is high. Studies have shown that accurate SfM-derived terrain models depend not only on GCP density but also on their spatial distribution and elevation range, especially in complex or steep terrain. These factors highlight that SfM accuracy is governed by an interconnected error chain rather than isolated parameters, underscoring the need for integrated consideration of camera calibration, control geometry, and processing strategy in high-precision topographic mapping.

3.2 Application UAV with Global Navigation Satellite System (GNSS) Technology in Topographical Mapping

The combination of UAV and GNSS techniques has become a promising method for efficiently and accurately generating DEMs and maps [57]. Digital maps with high resolution are now more precise and current than ever thanks to the usage of UAV images and GPS technology. [58] demonstrated how to use Pix4D GPS, and GIS systems for image processing and topographic map creation. The study was based on primary data gathered from field surveys that used both UAV-based and DGPS-based ground surveys. The coordinates of the GCPs were determined by a static DGPS survey with a Stonex S8 Plus. This result has demonstrated that this method is a dependable and portable device for remote data collection that can yield results with a very high spatial and temporal resolution even in inaccessible terrain at a very low cost. According to [59], the Differential Global Positioning System (DGPS) and UAVs are used in contemporary topographic mapping techniques. UAVs fly near the ground to provide accurate and high-quality aerial photography. They employ GPS for precision, which helps them take detailed photos quickly. By communicating the difference between observed and computed coordinates via a network of ground-based reference stations, DGPS increases GPS accuracy from 15 meters to about 10 cm. To prepare a topographical map of Dhulikhel Ward No 4 area, they used UAV and DGPS technology to collect primary data. All data were processed by Pix4Dmapper software. This processing creates the point cloud data, DSM, DTM, and orthorimage.

Following this procedure, the data exported to a GIS environment so that topographical mapping can be prepared. The contour lines on the topographical map precisely depict the elevation shift from 1472 to 1492 meters. Additionally, in order to create a topographic map, DTM, and orthophoto of the region, as well as to investigate the benefits of the new technology, [60] evaluated the usage of UAV PHANTOM 4 as its data gathering system to obtain digital aerial spatial information of the region. When the ortho-rectified imagery was compared to the matching RTK-acquired GCPs, the RMSE for the planimetric and vertical coordinates was 0.00603m and 0.00290m, respectively. The planimetric and vertical accuracies of the error differences between the ortho-rectified imagery and the corresponding GCPs demonstrate the dependability of the use of UAV technology in mapping and surveying. Besides, [61] indicated that GCPs in SfM photogrammetry surveys may be reduced or eliminated with the use of UAVs equipped with the Real Time Kinematic (RTK) GNSS. Thus, they have conducted a thorough evaluation of the effects of employing GCPs when generating topographic data with RTK-GNSS UAVs. This study illustrates how an RTK-GNSS UAV can be used for topographic surveying in areas with longitudinally extended corridors, including beaches and river valleys. The findings also provide credibility to the results of aerial surveys carried out over hazardous and unreachable terrain, such as rocky coastal regions and landslides, where ground control is difficult to implement.

Besides, in order to create an accurate topographic map, [62] assessed the use of Direct Georeferencing techniques in UAVs. Aerial triangulation using direct georeferencing on UAVs eliminates the need for GCPs. This method eliminates the necessity for a control point and allows for the smallest possible tie-point measurement. The study used a multi-rotor UAV DJI Phantom 4 RTK/PPK equipped with a high-accuracy GPS antenna to collect data. The test findings of horizontal precision showed the value of 0.040 m using a Circular Error of 90%. The results revealed that UAVs using direct georeferencing techniques provide maps with a high degree of precision for comparatively small mapping areas. According to [63], for small locations, the traditional aerial photogrammetry techniques involving helicopters or airplanes are expensive and difficult. Thus, in a developing country like Nepal, UAV was used to quickly and affordably acquire geographical data. UAV use is growing quickly in Nepal because of its capacity to take pictures from a distance and its potential to deliver data with a very high spatial and temporal resolution—even in inaccessible terrain at a comparatively low cost.

In the study, UAVs are used to acquire images, and DGPS is used to set CPs and GCPs. The effectiveness of UAVs for mapping and topographical surveying has been studied, as has the comparison of orthophotos taken with and without GCPs. The results showed that UAVs can be revolutionary for efficient and quick spatial data collecting at minimal cost and time in developing nations like Nepal, where geospatial data is widely desired. Also, [64] provides a photogrammetric method for processing UAV photos utilizing stereo optical compilation and GCP from GPS data to creates a topographic map in the Borobudur Temple, Indonesia. The goal of the GPS survey is to give the study area a representative GCP network with a good spatial distribution. The primary focus of this study will be the geometric accuracy assessment of DEMs and orthophotos which are used to derive topographic maps. The findings indicated that to achieve 1:5,000 topographical mapping accuracy, full control, or 8 GCPs/model, must be implemented. At this geometric precision level, Precise Point Positioning (PPP) can save time, cost, and reliance on reference stations because it meets GCP accuracy criteria.

Furthermore, according to [10], topographical charting of water bodies, marshlands, or land areas devoid of land cover using conventional surveying techniques is difficult and time-consuming.

Therefore, they used UAVs, GNSS, and GIS to make a topographic map of a rainforest mining area in Osino, Ghana's Eastern Region. With a topographic map precision of less than 5 cm, the combination of UAVs with RTK technology and GIS offers an efficient and suitably accurate way to map inaccessible places. Also used this technology for coastal surveying, [65] employed survey-grade UAVs equipped with onboard RTK-GPS for high-precision positioning to conduct a surey in a

Narrabeen Beach, Australia to obtain detailed observations of dune and beach erosion throughout the whole 3.5 km long bay at spatial scale and temporal resolution. This instrument only needs one operator to deploy securely in the field, eliminates the requirement for time-consuming and independent on-ground surveying of GCP. The results shows that UAVs offer a productive and economical survey tool for topographic mapping and measuring in the coastal region. Additionally, to collect more accurate data, manufacturers of aircraft have recently included on-board RTK functionality to their UAVs. In this sense, the 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 [5] used the DJI Phantom 4 RTK to survey 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 and that a single GCP might be required to estimate the focal length with any degree of accuracy.

Besides combining UAV and GNSS to create and update maps of accessible areas, this method is also used in topographic surveys of difficult-to-access areas such as mining areas. According to [66], aerial photogrammetry produces a number of 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. Therefore, UAVs were used to create various surfaces for a small open pit quarry in southern Brazil. For geolocation support and comparison, well-known topographic surveying techniques were employed, specifically laser scanning and the RTK (real-time kinetic) GNSS. In contrast 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.

In addition to mapping terrain on the mainland, coasts, and difficult-to-reach areas such as forests, mountains, mines, etc., UAVs are also used for mapping on islands. The study [67] analyzes the fundamental technologies of the low-altitude UAV aerial photographic system in island topographic mapping, such as the flight plan taking into account the island's characteristics, exposure control auto excursion angle rectification, exposure point calculation by differential GPS, and so on. The island's morphological features should be completely considered during the aerial design phase in order 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 topographic mapping, thereby addressing the gap in Chinese island.

Furthermore, in UAV-based topographic mapping, GNSS positioning techniques can be broadly classified into RTK, PPK, and PPP, each offering distinct operational characteristics and accuracy levels. RTK provides real-time centimeter-level positioning but requires a continuous radio link to a reference station, which may limit its applicability in remote or obstructed environments. PPK achieves comparable or slightly higher accuracy by correcting positioning errors during post-processing, offering greater robustness against signal interruptions and making it well suited for complex terrains. In contrast, PPP relies on precise satellite orbit and clock products without local base stations, but typically yields decimeter-level accuracy and is less suitable for high-precision topographic applications. Furthermore, GNSS-based mapping workflows can be divided into direct georeferencing, where image or LiDAR data are positioned solely using onboard GNSS/IMU measurements, and indirect georeferencing, which incorporates Ground Control Points (GCPs) to refine spatial accuracy. While direct georeferencing improves operational efficiency and reduces fieldwork, multiple studies indicate that the inclusion of well-distributed GCPs remains critical for achieving high vertical accuracy and mitigating systematic biases, particularly in SfM photogrammetry. Consequently, the choice between RTK, PPK, or PPP and the use of direct or indirect georeferencing should be guided by required accuracy, terrain complexity, and operational constraints.

3.3 Application UAV with Lidar Technology in Topographical Mapping

This technology offers accurate elevation information, particularly helpful in difficult or vegetated terrain. Due to the limitations of the cameras commonly employed with UAS, such as their inability to penetrate foliage, LiDAR sensors are becoming more and more popular in UAS mapping. Based on UAS flights using the Velodyne laser scanner and cameras, [4] examined a number of UAS LiDAR point cloud production performance factors. Based on the generated DSM, the final UAS LiDAR point cloud's accuracy was assessed by comparing it to point clouds derived using dense image matching. Even while the UAS LiDAR point cloud's precision is less than that of point clouds derived from images, it might still be adequate for topographic mapping applications in which optical imaging is not useful. Similarly, in the study [11], because the study region has a height difference of 1 km between the mountain's base and peak and high coverage density, the UAV with LiDAR sensor is utilized to acquire data for topographic mapping in Ha Tinh province, Vietnam. The horizontal RMS error is 10.4 cm, and the vertical RMS error is 1.3 cm, indicating sufficient dependability to produce a topographic map at 1:2000 scale. It can be concluded that drone surveying will soon replace field surveying methods, and vegetation canopy will no longer be a barrier. In addition, in order to produce cropland topographic maps with centimeter-level precision quickly and affordably, [68] used a low-altitude UAV combined with LiDAR distance measurements and a Post-Processing Kinematic Global Positioning System (PPK-GNSS). The obtained Root Mean Square Error (RMSE) showed that topographic information with high precision could be collected using the UAV-LiDAR technology, which might offer useful data for precise field leveling.

According to [69], remote sensing methods based on UAVs have shown a lot of promise for tracking abrupt shoreline changes. Compared to LiDAR mapping, UAV image-based mapping produces comparatively subpar results in low-textured areas, therefore this study shows how UAV LiDAR may be used to map coastal landscapes. Obtanied findings revealed that both image-based and UAV LiDAR methods produce point clouds that are compatible within a 5-10 cm range and offer high-resolution, high-quality topographic data. A definite advantage of UAV LiDAR is its capacity to capture points below the canopy by penetrating vegetation, its vast and consistent ground coverage across various geomorphic situations, and its increased point density.

With its advantages, UAV and LiDAR technology is an effective method used in topographic surveys in difficult-to-access areas such as mines, forests, mountains, etc. In the study [70], topographic surveying of the complex mountainous terrain area was conducted using UAV technology, aerial photography, and aerial LiDAR. The main goal was to create a map with a scale of 1: 1,000 with a contour interval of 1.0 m, 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 difficult terrain conditions. To provide a holistic view of the current technical landscape, Table 1 synthesizes the key performance indicators from the reviewed literature, contrasting different UAV configurations, sensor types, and their achieved accuracies across various terrains.

Based on the comparative summary presented in Table 1, it is evident that the accuracy and applicability of UAV-based topographic mapping approaches strongly depend on sensor type, flight configuration, and terrain characteristics. Photogrammetry and SfM methods generally achieve high planimetric accuracy in open and moderately complex terrains but show increased vertical errors in densely vegetated or rugged areas. In contrast, UAV-LiDAR systems demonstrate more stable elevation accuracy across complex terrains, particularly under forest canopies, albeit at higher operational cost and with increased sensitivity to scan geometry and filtering strategies. GNSS-assisted direct georeferencing techniques reduce dependence on dense ground control networks and improve operational efficiency; however, their accuracy remains highly contingent on positioning mode (RTK/PPK) and platform stability. These comparisons highlight that no single approach is universally optimal, and method selection should be tailored to terrain conditions, required accuracy, and logistical constraints.

In addition to the comparative summary presented in Table 1, several technical factors critically influence the positional accuracy of UAV-based topographic mapping and should be considered in an integrated manner. Platform type plays a key role, as multi-rotor UAVs generally provide higher positional accuracy due to superior flight stability and hovering capability, whereas fixed-wing platforms offer greater area coverage at the expense of reduced vertical accuracy. Ground control points (GCPs) also exert a significant influence; however, accuracy improvements depend more on their spatial distribution than on sheer quantity, with well-distributed GCPs across the survey area yielding more reliable georeferencing results. Flight altitude and image overlap further affect accuracy by controlling ground sampling distance (GSD) and tie-point geometry, where lower altitudes and higher overlaps typically enhance vertical precision but increase data volume and processing demands. For UAV-LiDAR systems, additional limitations arise from scan pattern geometry, multi-path effects in complex terrain or vegetated areas, and filtering uncertainties during digital terrain model extraction. These factors collectively explain the variability in reported accuracies across different studies and highlight the need for carefully balanced survey design rather than reliance on a single technical parameter.

Table 1: Overview of UAV technology, sensors, flight configurations, terrain types. achieved positional accuracy, and key limitations in topographic mapping studies

Technology	Sensor Type	Typical Altitude (m)	Terrain Type	Accuracy (RMSE)	Key Limitation
Photogrammetry	RGB / Prosumer Cam	80 - 120	Flat, Coastal, Urban	5 - 10 cm	Shadow and Occlusion
UAV-LiDAR	Laser Scanner	50 - 100	Dense Forest, Mining	2 - 5 cm	High cost, Multipath
SfM-MVS	Low-cost/ Action Cam	< 50	Complex Shorelines	10 - 20 cm	Error propagation
Hybrid (RTK/PPK)	GNSS Integrated	100 - 150	Large scale areas	< 3 cm	Signal obstruction

Table 2: The number of studies using UAV technology for topographic mapping

Application	Terrain features	References	Total
Application UAV with photogrammetry technology [32 articles]	Accessible, flat, on land	[3][6][9][12][13][28] [30][31][32][33][34] [35][36][37][38][39][40][46][47] [50][51][52] and [53]	23
	Beaches, coastal, intertidal zone	[41][42][43][44] and[45]	5
	Forest, mining area	[14][48][54] and [55]	4
Application UAV with GNSS technology [13 articles]	Accessible, flat, on land	[58][59][60][61][62] and [63]	6
	Beach, Coastal	[5][49] and [65]	3
	Forest, Mining area	[10] and [66]	2
	Fault zone	[56]	1
	Island area	[67]	1
Application UAV with Lidar technology [5 articles]	Accessible, flat, on land	[4][11] and [68]	3
	Mountainous terrain area	[70]	1
	Beach	[69]	1
Sum			**50**

4. Results and Discussion

The obtained results show that UAVs can be integrated with different technologies, including photogrammetry, LiDAR, and GNSS, to generate topographic maps. Table 2 summarizes the 50 selected studies, detailing the applied UAV-based technologies and the types of terrain investigated, such as accessible flat areas, beaches, coastal and intertidal zones, forests, mountainous regions, mining areas, islands, and fault zones. Based on the systematic classification presented in Table 1, each study was assigned to a primary technology category according to its dominant role in terrain modeling and accuracy assessment. In cases where multiple technologies were combined, the classification followed a mutual-exclusivity rule to avoid double counting. This process forms the basis for the statistical synthesis presented in this section. The literature review indicates that photogrammetry-based UAV studies account for the largest proportion (64%), followed by GNSS-assisted approaches (26%), while LiDAR-based UAV applications represent a smaller share (approximately 9.8%). Figure 2 illustrates the distribution of publications by UAV technology used for topographic mapping. Regarding terrain suitability, Table 1 and Figure 2 show that most UAV applications have been conducted in accessible and relatively flat onshore areas, where flight planning, ground control deployment, and data acquisition are more straightforward. Nevertheless, UAV-based methods have also demonstrated potential in more challenging environments, such as beaches, coastal and intertidal zones, and mining areas. Although studies addressing mountainous terrain, islands, and fault zones remain limited, Figure 3 indicates a growing research interest in applying UAV technologies to these complex landscapes. Beyond terrain suitability, a quantitative cross-study comparison reveals clear performance trends relevant to topographic mapping guidelines.

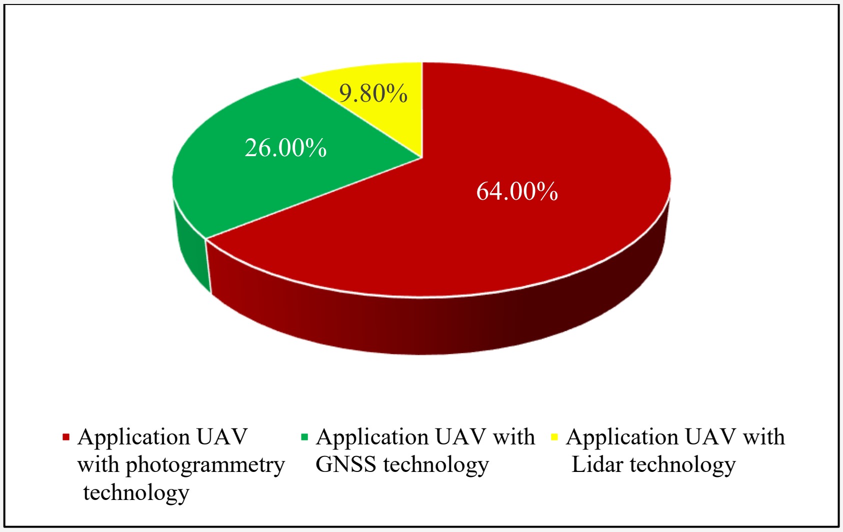

Figure 2: Distribution of reviewed studies by UAV-based technology used for topographic mapping (Photogrammetry, GNSS-assisted, and LiDAR-based approaches)

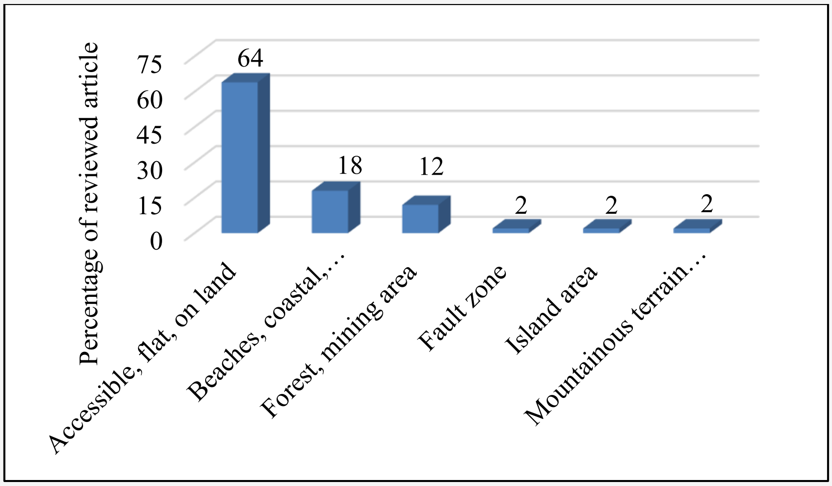

Figure 3: Distribution of reviewed UAV-based topographic mapping studies across different terrain types (flat terrain, coastal and intertidal zones, forests, mountainous areas, mining sites, islands, and fault zones)

Photogrammetry-based UAV surveys conducted at flight altitudes of 80-120 m typically achieve DSM/DEM RMSE values in the range of 5-10 cm over flat and coastal terrains, supporting map scales up to 1:1000-1:2000. In contrast, UAV-LiDAR systems consistently report vertical accuracies of 2-5 cm, particularly in vegetated or mining environments, enabling reliable terrain representation where image-based methods degrade. GNSS-assisted workflows (RTK/PPK) further enhance positional accuracy, often achieving sub-3 cm RMSE while reducing dependence on dense ground control networks. Flight altitude emerges as a critical factor across studies, with increased altitude improving coverage but degrading vertical accuracy due to coarser GSD. These quantitative comparisons indicate that sensor choice, flight configuration, and positioning strategy jointly determine achievable accuracy and feasible map scale, providing practical guidance for selecting UAV-based methods in operational topographic mapping.

5. Advantages, Disadvantages of Using UAV in Topographic Mapping and Actionable in the Future

5.1 Advantages of Using UAV in Topographic Mapping

The literature showed that UAV technology provides a high-resolution, economical, and effective substitute for traditional mapping methods. The benefits of utilizing this method in generating a topographic map are indicated below.

High Accuracy and Resolution: With a Ground Sampling Distance (GSD) of a few centimeters, UAVs are capable of capturing high-resolution imagery that exceeds the capabilities of most commercial satellites [12] and [17]. By utilizing LiDAR sensors and sophisticated photogrammetric algorithms such as Structure from Motion (SfM), UAVs can generate dense point clouds and high-precision elevation models with sub-decimeter accuracy [6] and [26].

Cost-Effectiveness: UAVs drastically lower operational expenses compared to traditional aerial surveys using manned aircraft or high-resolution satellite constellations. They eliminate the need for expensive flight crews and fuel, providing a budget-friendly solution for small to medium-scale mapping projects [10] and [37]. Studies have shown that for areas under 100 hectares, UAV mapping is significantly more economical than traditional terrestrial surveying or manned aerial photography [21] and [66].

Rapid Data Acquisition and Deployment: UAVs are ideal for projects with tight timelines due to their rapid deployment capabilities. They can cover large areas in a single day and, with advancements in edge computing, allow for near real-time data processing, which is crucial for emergency response and prompt decision-making [32] and [44].

Flexibility and Accessibility: Unlike traditional methods, UAVs can operate at low altitudes and in hard-to-reach or high-risk locations such as disaster-stricken sites, dense forests, active mining areas, and steep terrain [66] and [70]. Their ability to fly under cloud cover allows for data collection in weather conditions that would ground traditional optical satellite sensors [15] and [33].

Security and Decreased Human Danger: People can lessen their exposure to hazardous weather conditions and fieldwork mishaps by using UAVs. Also, surveyors no longer have to operate in dangerous areas (such as cliffs, mines, or building sites) thanks to UAV-based mapping [53].

Advanced Modeling and 3D Mapping: UAV data can be utilized for 3D terrain modeling, DSM, DEM, DTM of the study regions [59]. Additionally, they easily integrate with Geographic Information Systems (GIS) to provide sophisticated geographical analysis [10].

Enhanced Safety and Risk Mitigation: The use of UAVs minimizes human exposure to hazardous environments and fieldwork accidents. Surveyors are no longer required to physically traverse dangerous terrains like unstable cliffs, active construction sites, or contaminated areas, as high-accuracy results can be obtained remotely [8] and [53]

Advanced Modeling and Multi-Sensor Integration: Beyond 2D maps, UAV data provides a robust foundation for 3D terrain modeling, including Digital Surface Models (DSM), Digital Elevation Models (DEM), and Digital Terrain Models (DTM) [51] and [59]. Furthermore, modern UAVs facilitate the integration of various sensors (LiDAR, multispectral, and thermal), which easily feed into Geographic Information Systems (GIS) for sophisticated spatial analysis and environmental monitoring [10] and [69]. However, despite their benefits, UAV-based mapping has drawbacks that need to be taken into account. The following highlights the difficulties of mapping topography with UAVs.

Weather Dependency: UAVs are extremely vulnerable to weather-related factors such as severe winds, precipitation, and hot temperatures, thus restricting their hours of operation. Besides, bad weather can cause data inconsistencies that need to be corrected by repeated flights [50].

Battery Life and *Range Limitations:* The majority of UAVs have a short battery life, usually between 20 and 60 minutes, which limits the region they can fly over in a single flight. Thus. for Large-scale mapping projects, it is necessary to require multiple flights and battery replacements, leading to increasing operational time [23].

Regulatory Restrictions: UAV activities are governed by stringent laws pertaining to license requirements, airspace limits, and flight height. Moreover, the complexity of operations is increased by the fact that many nations want certifications or permissions for commercial UAV operations [21].

Data Processing Complexity: It takes a lot of processing power to handle the vast amount of high-resolution imagery. Additionally, to create accurate maps, sophisticated software and knowledge of photogrammetry and GIS are required [26] and [64].

Limited Payload Capacity: Due to their limitations in carrying bulky or several sensors, small UAVs may not be able to capture as much data. Although LiDAR-equipped UAVs are more effective, they are more costly and need specific knowledge [68].

Potential for Errors: Hardware failures, GPS errors caused by multi-path interference, and loss of signal connection are persistent risks. Especially in dense forest or urban environments, signal blockage of GNSS can lead to severe positioning errors or even the loss of the equipment [29] and [62].

Security and *Privacy Concerns*: Unauthorized access to aerial imagery or data breaches represent potential risks associated with UAV missions. Furthermore, privacy concerns arise when UAVs operate over sensitive areas or densely populated residential zones [21] and [71].

Radiometric Inconsistency: Variations in solar intensity, sun sensors' angles, and camera settings during flight can lead to non-uniform pixel values across captured images. This poses significant challenges in generating orthomosaics with consistent color quality and negatively impacts the accuracy of surface classification algorithms [50]**.**

Shadowing and Occlusion in Steep Terrain: In areas characterized by abrupt elevation changes or steep cliffs, shadowing and object occlusion occur frequently. These phenomena lead to data gaps or 'blind spots' in 3D models, necessitating the design of complex flight plans with high overlap and multiple camera tilt angles [33] and [56].

GNSS Signal Issues in Challenging Environments: In dense forests or urban canyons, satellite signals are frequently obstructed (signal blockage) or affected by multi-path interference. These phenomena significantly degrade the positioning accuracy of RTK/PPK systems and can even cause data link loss, leading to severe errors in the direct georeferencing process [29] and [62].

LiDAR Waveform Limitations: The effectiveness of LiDAR depends heavily on its pulse return capability. Low-cost LiDAR sensors often only support single-return waveforms, which face significant difficulties in penetrating dense canopy to accurately derive Digital Terrain Models (DTM). In contrast, multi-return systems, while more effective at discriminating between vegetation and the ground surface, are considerably more expensive and require complex processing workflows [70] and [72].

System Calibration and Boresight Alignment: A frequently overlooked challenge is the systematic error arising from the misalignment between the sensor (Camera/LiDAR) and the positioning/navigation unit (GNSS/IMU). Without rigorous boresight alignment and calibration, accumulated errors will compromise the accuracy of large-scale topographic mapping [62] and [68]. Despite certain obstacles, UAVs have supported topographic mapping by offering quick, high-resolution, and affordable data collecting techniques.

5.2 Possible Future Research Areas of UAV Topographic Mapping

The rapid evolution of automation and sensor technology is set to transform UAV-based topographic mapping from a manual-intensive process into a fully autonomous, intelligent system. Future research should prioritize the following technical advancements:

5.2.1 AI-Driven autonomous workflows

Future UAV mapping will transition from simple automation to complex intelligence by integrating Deep Learning and Computer Vision directly into the photogrammetry pipeline:

- Automated GCP Detection: Research will focus on the automated identification and sub-pixel centering of Ground Control Points or coded targets, significantly reducing manual labor in post-processing while maintaining high geodetic rigor [73].

- Deep Learning-based Feature Extraction: Beyond basic landform classification, DL models (e.g., CNNs) will enable the automated extraction of complex topographic features, such as breaklines and drainage networks, with higher fidelity than traditional thresholding methods [74] and [75].

- Real-time Photogrammetry Pipelines: Future systems will aim for "on-the-fly" reconstruction using onboard SLAM (Simultaneous Localization and Mapping) and rapid SfM algorithms, allowing for immediate quality assessment and gap detection during the flight [75] and [76].
- Onboard Obstacle Avoidance: Integration of advanced collision avoidance systems (LiDAR-based or binocular vision) is crucial not only for safety but also for maintaining mapping accuracy by ensuring stable flight paths and consistent image overlap in complex environments [29].

5.2.2 Technical depth in swarm UAV mapping

Utilizing a swarm of UAVs for large-scale mapping requires solving several high-level technical challenges:
- Coordination and Path Planning Algorithms: Developing decentralized algorithms to optimize area coverage and minimize redundant data

acquisition while preventing mid-air collisions among dozens of units [71].

- Synchronization of GNSS Time Tags: A critical technical requirement for swarm mapping is the microsecond-level synchronization of GNSS time tags across all platforms. This ensures that data from multiple sensors can be accurately fused into a single, coherent spatial model [62].

- Inter-UAV Communication Latency: Future research must address the impact of communication latency on swarm stability and data consistency. Low-latency protocols (e.g., 5G/6G integration) will be essential for real-time sensor fusion and collaborative navigation [77].

5.2.3 Advanced positioning and multi-sensor fusion

- GNSS Advancements: Beyond RTK and PPK, the adoption of Precise Point Positioning will enable centimeter-level accuracy in remote areas without the logistical burden of local base stations [73] and [78].

- Holistic Multi-sensor Integration: The future lies in the simultaneous operation of LiDAR, multispectral, and thermal sensors. Compact, high-performance LiDAR with multi-return capabilities will allow for superior vegetation penetration and more accurate Digital Terrain Model generation in dense forests [70] and [72].

5.2.4 UAV- Internet of Things (IoT) ecosystems

The integration of UAVs as mobile nodes within an Internet of Things framework will facilitate continuous, real-time environmental monitoring [79]. This "connected sensor" approach allows for autonomous triggering of mapping missions based on sensor data (e.g., soil moisture or seismic activity), providing a dynamic and predictive mapping capability [77].

In sum, in the future, the studies on topographic mapping using UAVs will be focused on automation, AI-based analytics, and multi-sensor integration.

6. Conclusion

This review has synthesized the rapid evolution of UAV technology in topographic mapping from 2010 to early 2025. While UAVs have democratized high-resolution spatial data acquisition, several critical gaps remain in the current literature. Most existing studies focus on ideal environmental conditions, leaving a significant lack of robust methodologies for "challenging environments" such as dense tropical forests, urban canyons with high multi-path interference, and extremely steep terrains where occlusion is prevalent. Among the evaluated technologies, UAV-LiDAR and Direct Georeferencing (RTK/PPK) emerge as the most promising for professional geomatics applications. LiDAR's multi-return capability is the primary solution for overcoming the limitations of photogrammetry in vegetated areas, while RTK/PPK integration significantly reduces the logistical burden of GCPs without compromising centimeter-level precision. To overcome current technical bottlenecks, future research must shift toward AI-driven workflows and multi-sensor fusion. The integration of deep learning for automated feature extraction and real-time photogrammetry pipelines will address the current lag in data processing. Furthermore, technical challenges in Swarm UAV mapping specifically microsecond-level GNSS time synchronization and low-latency communication must be resolved to enable large-scale, high-efficiency topographic surveys.

Finally, to ensure scientific consistency and comparability across global studies, this paper strongly recommends the adoption of standardized accuracy reporting. Future research should move beyond generic error descriptions and consistently report results using recognized statistical metrics, including RMSE, Circular Error at 90% confidence (CE90), and Linear Error at 90% confidence (LE90). These standards will facilitate a more rigorous evaluation of UAV systems against traditional aerial and terrestrial surveying benchmarks, ultimately bridging the gap between experimental research and professional surveying requirements.

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