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Thematic review of light detection and ranging and photogrammetric technologies in unmanned aerial vehicles: comparison, advantages, and disadvantages

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ABSTRACT

The development of unmanned aerial vehicles (UAVs) has positively influenced various remote sensing techniques, making them more accessible to different types of users. Among these, photogrammetry and light detection and ranging (LiDAR) stand out for their versatility and possibilities in terrain modeling. This study evaluates the advantages of each one in various fields of knowledge and industry, comparing their possibilities in terms of positional accuracy, completeness, and efficiency in terrain modeling. It is evident that the use of these techniques in different areas generates an opportunity to implement algorithms or processes in mapping and cartography. Regarding their use, the advantage of the LiDAR sensor is identified in inhospitable and inaccessible areas covered by vegetation and with problems in the geodetic network. On the other hand, the versatility of photogrammetry is shown in small areas with exposed soil. The advantage of point cloud fusion or the combination of techniques in the construction industry and in archaeological and architectural surveys is also noted. Finally, emphasis is placed on variables to consider, such as georeferencing techniques, the ground control point (GCP) network, algorithms and software, and flight plan reviews, in order to improve their accuracy.

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1. INTRODUCTION

Positional accuracy is defined as the difference between the measured value and the expected value. It is also considered a fundamental characteristic in the different solutions aimed at understanding the environment, due to the continuous need to model the geographic space, whether to carry out designs that allow human development or to mitigate problems generated by threats. Positional accuracy can include measurement uncertainties ranging from meters to high precisions involving millimeter measurements [1]. Historically, work requiring high precision has been carried out with conventional surveying and geodetic methods that include global navigation satellite systems (GNSS). However, with the evolution of unmanned aerial vehicles (UAVs), measurement through indirect methods such as photogrammetry and direct methods such as light detection and ranging (LiDAR) has increased its positional accuracy. The great advantage of these vehicles is related to cost, since it considerably reduces the value in surveys of large areas; in addition, they allow capturing information in hard-to-reach areas.

Currently, the most popular UAVs are those equipped with global navigation satellite systems/inertial navigation system (GNSS/INS) receivers and sensors with high spatial and/or radiometric resolutions, as they have applications in earth, natural, and environmental sciences, engineering, as well as uses in various fields of the economy and industry, including agriculture, construction, and infrastructure [2]. UAVs have approximately 150 years of history; their development includes everything from kites to modern equipment, including balloons and paragliders, among others. Today, with the industry highly developed, there is no standardized classification of these aircraft. However, categorizations can be used that take into account the level of risk by use, those based on their size or weight, as well as those involving their flight autonomy or those that indicate whether they have wings or rotors. A more detailed classification proposes categorizing according to the use of the UAV, for example, for cartography and topography, environmental and agricultural activities, heritage and archaeology, natural hazards, and other applications [3]. This article includes those experiments with UAVs that generate cartographic and topographic information. To generate such information, it is necessary to model the captured data, taking into account the geometric characteristics, including height variations, generating digital elevation models (DEMs), which can be classified into digital terrain models (DTMs) and digital surface models (DSMs), which include, in addition to the terrain, vegetation and man-made structures [4]. Model generation can be done from different sources, such as LiDAR and digital photogrammetry. Next, the operation of these is briefly explained:

LiDAR is composed of a light transmitter system, which emits stored energy; it also contains a receiver system and a processing system. Due to this configuration, it is an active sensor that is responsible for measurement and detection using laser. LiDAR is the acronym for “light detection and ranging”. It works by transmitting pulses of light that are reflected off any object, in order to obtain the positions of these elements and their geometric characteristics, through the travel time of the pulses [5]. In order to guarantee the required positional accuracy, its proper calibration, the temporal synchronization between its components, the scanning angle, the range of the light beam, and, when on UAVs, characteristics such as the X, Y, Z position and the angles of the different rotations of the aircraft must be considered [6]. The literature indicates that, to process the point cloud, it is essential to classify these points and perform the necessary filtering according to the requirement.

Digital photogrammetry in UAVs collects images in the visible part of the electromagnetic spectrum. It requires ground control points (GCP), which must be previously georeferenced with a technique capable of achieving positional accuracy in the order of millimeters or centimeters. In addition, it requires the definition of longitudinal and lateral overlap, ground sample distance (GSD), and flight parameters, among others [7]. With the use of drones, the structure from motion (SfM) technique has been developed, where photographs of the same object are often used with different angles and distances, in order to generate three-dimensional images. Despite this, the basis for resolving the 3D structure has the same starting point as stereoscopic photogrammetry: from the superposition of images with different viewpoints, by identifying homologous pixels, the position of the point and the orientation and position of the camera can be obtained. The SfM technique is complemented with algorithms such as random sample consensus (RANSAC), which allows cleaning the models or making them geometrically more precise; the scale-invariant feature transform (SIFT), which allows object recognition; and the multi-view stereo (MVS) technique, which serves to improve the accuracy of 3D models and provide more detail to the scene [8].

The article is divided into the methodology chapter, followed by the results and analysis chapter, which is divided into three sections that include: the evaluation of trends in the digital photogrammetric sector; LiDAR in UAVs and the expectations in their combination; and finally, LiDAR vs photogrammetry. Together, separate, which is better? In these sections, the evaluation of the positional accuracy of different products is reviewed, to have a general overview and recommend the sensor according to the purpose of the survey.

2. METHODOLOGY

In the article, systematic procedures were developed that allowed the comparison of the techniques, guaranteeing the quality of the results. The search for information, its classification, organization, and analysis were included, concluding with the writing. Figure 1 illustrates the methodology used. The first activity consisted of an exhaustive bibliographic review on digital elevation models, LiDAR techniques, photogrammetry in UAVs, and GNSS satellite receiving equipment. With this, the most used techniques, their advantages and limitations, as well as the most common applications were identified. It should be noted that this review also included current scientific trends and procedures related to the topics mentioned. The search, in addition to including the algorithm with the keywords, was not limited to a specific time, since it is understood that the sensing technology and the transport platform addressed are recent, having appeared at the end of the first decade of 2000. In Figure 2, the interest per year is observed, where information is recorded from 2007; the high number of articles since 2017 is highlighted, with a maximum peak in 2021 that had 75 articles.

The spatial distribution of interest in these topics is global. However, the countries that contribute the most to their research are the United States, China, and Italy, each with more than 45 articles written. If analyzed by continent, Europe takes the lead with more than 265, followed by the American continent with more than 130, and Asia with more than 120. It is worth noting that, when analyzing the research centers where the most is written on the subject, China has 5 institutes among the top ten, Italy has 2 (including the Politecnico di Torino with the highest number of publications, 17), and the United States has 1. If analyzed by thematic areas, Earth sciences, with 25% of the total articles analyzed, take the lead, followed by computer sciences, social sciences, engineering, and environmental sciences, with 18%, 13%, 11%, and 8%, respectively. Figure 3 shows the geographical and thematic distribution of the articles. After reviewing the articles described, more than 50 have been selected that align with the interests of this review, as they include relevant topics such as new procedures, comparisons, algorithm development, case studies, and technique integration, all framed within positional accuracy or the development of terrain modeling.

Figure 1. Methodology used for the comparison of techniques

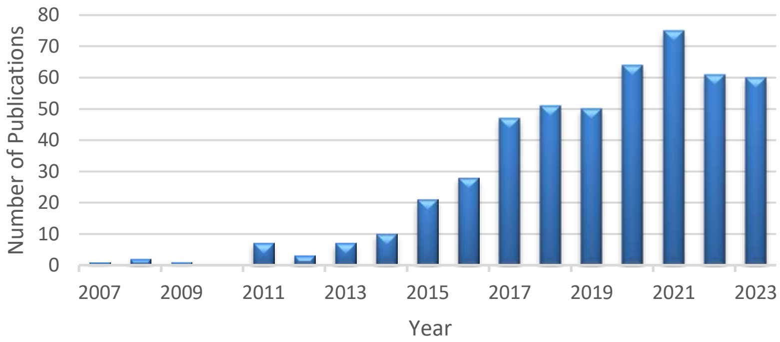

Figure 2. Annual publications related to keywords. own source

Figure 3. Publications geospatial distribution

3. RESULTS AND DISCUSSION

According to preliminary research, it has been decided to divide this paper into three main topics. The first section will delve into the photogrammetric sector, exploring its significant advances and current trends in detail. Subsequently, the second topic will provide a comprehensive review of LiDAR technology specifically integrated into UAVs, highlighting its capabilities and applications. Finally, the third section will focus on the practical uses of both technologies, combining and comparing them to identify the most effective and optimal options for various applications.

3.1. Digital photogrammetry sector evaluations and trends

Digital photogrammetry techniques are based on algorithms that have allowed fieldwork to reduce its cost and be carried out in UAVs [9]. There are several ways to evaluate the accuracy of the products; one of them is done through the review of the DEMs created with these techniques. When analyzing them, it is evident that the technology equipping the UAVs, the georeferencing techniques, and the flight parameters imply variations in terms of quality. Errors in DEMs increase with the distance to the GCPs, the increase in flight altitude, the decrease in sensor resolution, and the lower density distribution of the GCPs [10].

In Mexico, the use of DTMs generated from UAVs has been compared with the technique called 'erosion bridges' to identify the topographic change produced by erosion in cross-sections, with satisfactory results that include a root mean square error (RMSE) between 2.9 and 3.2 cm and great similarities with direct techniques. It is worth noting that 15 ha were verified, divided into 6 plots of 50×50 m each, with 72 GCPs, of which 9 were used for control and the rest for checking. The author highlights that, for large areas, there are limitations in terms of the densification of the terrestrial geodetic network or the placement of GCPs; these problems could be solved with the implementation of aircraft with post-processed kinematic (PPK) or real-time kinematic (RTK) technologies [11]. López and Munjy [12] present a study in California including these positioning techniques, with dual-frequency satellite receivers, a sensor in the visible spectrum (RGB) with GSD between 1.91 and 2.45 cm, and flights at altitudes between 84 and 115 m above the ground. In their work, they included 80 control points distributed in 5 GCPs and 75 control points. The study area was 320×320 m. The information was processed with two commercial software programs, obtaining errors with PIX4D of 4 cm, while in Metashape they were 6.5 cm for the horizontal component, while for the vertical they were 8.5 and 5.3 cm, respectively. However, when comparing the GCPs, the RMSE in heights was better in PIX4D (2.0 cm), while in Metashape it was 2.6 cm, very close to that generated by helicopter-borne LiDAR, which served as a reference and was 1.5 cm [12].

In order to carry out the survey and modeling of a plot of approximately 81 ha in the central part of Nigeria, 20 GCPs, RTK techniques, and flight heights of 120 m were used. There, positional accuracies of 12 and 92 cm were obtained in horizontal and vertical, respectively [13]. It is evident that the flight height and the number of GCPs in the study area are directly related to the reported positional accuracy. In other studies, it is observed that the sensor, the UAV, the software, and even the algorithms or methods used are related to the positional quality parameters. The quality of DEMs is also tested in different ground covers, conducting experiments in forested terrain, wasteland, and plots without vegetation cover in northeastern China. The results show that the model in the forested area presents large differences when compared to a DEM generated from airborne LiDAR: 95% of the errors are below 3.65 m, while in the other covers it was 0.67 and 0.64 m, respectively [14].

Another way to evaluate photogrammetric products is by comparing sensors available on the market through practical experiments, such as the detection of power lines, mapping of forests and urban areas, where different photogrammetric solutions are investigated to carry out cartography using UAVs. A study aimed at determining the best sensor for a given accuracy used two different types of cameras (Sony RX1 and Sony QX1); the first is characterized by using a full-frame sensor, generating better radiometric performance, more accurate tie point matching, and a sharper 3D reconstruction. For information processing, 3 different software programs were used: MicMac, Agisoft Metashape, and Pix4D Mapper, in order to establish the best performance in terms of point cloud generation, positional accuracy, and representation in different types of areas, such as forests, asphalt, and gravel. The results showed MicMac's inability to effectively handle forest areas and the inefficiency of Pix4D Mapper's 3D model, which generates noise in homogeneous areas. LiDAR data was used as a baseline for modeling, observing that for some purposes, success can be achieved with photogrammetric data alone. However, LiDAR allows for accurate mapping of the ground, even under dense vegetation cover, demonstrating its usefulness for obtaining accurate information about the tree canopy and improving the accuracy of canopy estimation [15]. It is worth noting that the flight parameters of the photogrammetric sensors used were similar, while the LiDAR flight had a higher altitude and a lower GSD.

On the other hand, studies can be conducted to identify the advantages offered by various UAV systems for photogrammetric production, evaluating DEMs, DTMs, and orthophotos. In Malaysia, a study was developed with these topics, in which it was demonstrated that a drone equipped with an RTK positioning system achieves a positional accuracy between 9 and 30 cm when evaluating its produced orthophotos. Now, when evaluating the DTMs, the system that included LiDAR with 15 GCPs in 60 ha of the study has the best results. It should be noted that these points were positioned with rapid static methods which, according to the literature, have a maximum range of horizontal positional accuracies of 2 cm [16]. However, other studies propose a new way to evaluate information through the interpretation of the point cloud, extracting geometric characteristics of the detected objects through principal component analysis (PCA), covariance matrix values, and statistical information, generating differentiation between vertical planes, horizontal planes, roughness, and others. Thus, establishing a new methodology that aims to understand the structure of a 3D scene by defining the classification and segmentation of the associated points. In addition, it uses the RANSAC algorithm to extract geometric shapes; with them, it segregates to define anthropic and natural components [7].

Digital photogrammetric technology in UAVs has been so useful that efforts have been made to take it to other types of ultralight aircraft, thus achieving low-cost cartography of large areas. A clear example is the one achieved in a wooded area in southeastern Belgium, with an area of approximately 1200 ha, where drone sensors and controllers were taken on an ultralight aircraft platform to acquire multispectral images with spatial resolutions from 5.2 to 48.1 cm [17]. In the construction and infrastructure industry, this technology also stands out. In this section, the application of SfM in historical photographs was used for the restoration and control of works, also to monitor coastal dunes, and managed to obtain DSMs with an error of approximately 1 m from historical photographs [18].

Regarding SfM techniques, some authors have worked on possible solutions for the improvement of topographic surveys through photogrammetry in UAS. While it is true that this technique is not exclusive to these aircraft, its development has indeed gone hand in hand, due to its easy application. One possible improvement lies in the method for performing the geometric pre-calibration of its sensors in the visible spectrum, using a 3D structure *in situ*; finding its best results at a constant flight height of 30 m, although its importance in geomorphological studies is indicated [19]. In the city of Manizales (Colombia), a positional accuracy is reported that satisfies cartography at a scale of 1:500 through the use of drones and digital photogrammetric procedures. However, it is noted that their study is not conclusive, since it was carried out with a specific drone and in a small area [20]. Figure 4 shows the characteristics for evaluating photogrammetric products and the parameters to be taken into account for this purpose. In conclusion, and as shown in the figure, the positional accuracy depends on the quantity and distribution of the GCPs, the techniques for their georeferencing, the capture sensors, the inertial sensors, the UAV to be used and its flight height, without forgetting the algorithms for processing the photographs and producing the results, and, of course, the natural conditions of the area to be modeled (relief, vegetation cover, winds, and atmospheric weather).

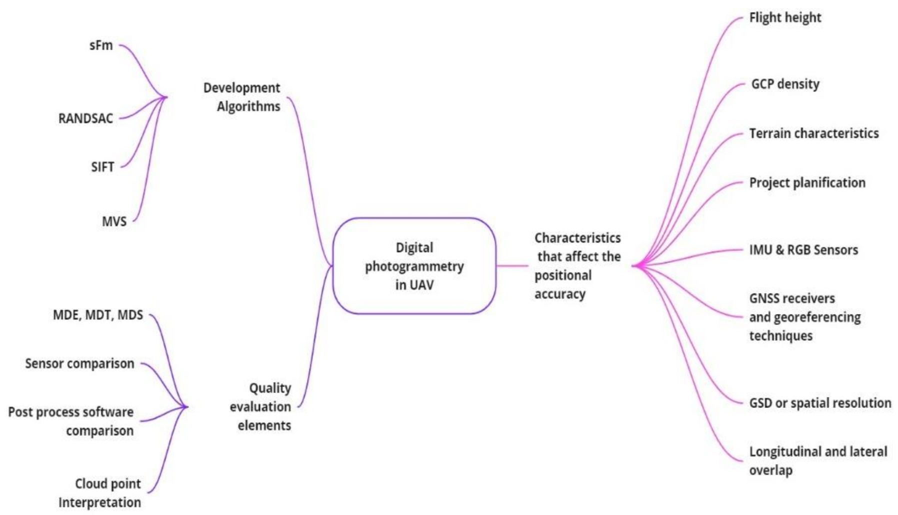

Figure 4. Digital photogrammetry aspects

3.2. LiDAR and UAV: combination expectations

LiDAR sensors have been used in the cartographic industry and in earth sciences for various purposes. However, their appearance in UAVs dates back only to the past three decades, so it is worth reviewing the positional accuracy reports of these sensors. In addition, both the flight height and speed must be controlled in order to achieve high-resolution positional accuracy. Their study presents a UAV-LiDAR system for high-resolution geomorphological mapping in forest areas, which helps in the prediction and mitigation of landslides. The methodology involved acquiring RGB images for landslide detection through the generation of 3D point clouds; with this, topographic changes and sediment transport can be calculated [21]. It should be noted that, prior to the exercises of their case study, tests were carried out with a rectangular object with known dimensions and controlled positioning, finding that their technique achieved positional accuracy relative to the object of between 5 and 10 mm in the three axes. The author recommends flying less than 70 m above the ground and at speeds less than 11 m/s, taking into account the performance of the UAV batteries.

In other studies, the vertical positional accuracy for topographic data obtained with LiDAR techniques and equipment shows variations depending on the type of terrain and the density of the point cloud. In undulating to mountainous slopes, it is set around 0.200 m, and for flat terrain, it can reach 0.150 m, as long as there is a point cloud with a density of 1 point per square meter [22]. It should be noted that in the experiment, the conventional topographic method with a millimeter-precision total station was used as a reference for positional accuracy, and it is concluded that, for large areas, LiDAR techniques should be preferred over conventional topography, since the positional accuracy is practically the same, costs are reduced, and performance is improved.

On the other hand, positional accuracy can be assessed by reviewing theoretical concepts and mathematical models and contrasting them with specific cases. In this sense, Pilarska *et al*. [6] show how quality can be evaluated through a function that considers variables such as position error, orientation error, scanner error, and the offset between the laser sensor, the GNSS antenna, and the inertial measurement unit (IMU), among others. The article concludes that the most important component in the errors is produced by the IMU units. It also indicates that GNSS units should be integrated and RTK and precise point positioning (PPP) methods should be used, and that, when using them and comparing them with the mathematical model, their positional accuracy can reach 3.5:2 cm in the horizontal component and 2.5 cm in the vertical [6]. Evaluations of solid-state LiDAR sensors have also been carried out; for example, the DJI Zenmuse L1 on a Matrice 300 RTK UAV, in order to produce DEMs in river environments with vegetation. There, the multi-scale curvature classification algorithm was applied for soil topography, and for the comparison of UAV LiDAR and terrestrial laser scanner point clouds, the multiscale model to model cloud comparison (M3C2) method was used [23]. The results of the study showed problems with dense vegetation and thick grass. Although it was demonstrated that the algorithm used is effective for river areas with vegetation, generating DEMs with accuracies of 0.015 m in bare soil and errors in areas with vegetation of variable density, ranging from 0.007 to 0.883 m, emphasizing the importance of terrain classification for accurate modeling. It should be noted that flight heights were between 60 and 80 m and speeds less than 10 m/s were used. They also conclude that wind speed can cause problems in positioning.

LiDAR technology offers advantages in terms of accessibility to inhospitable areas, and its ability to model large surfaces in less time compared to conventional technologies is evident. Furthermore, when comparing airborne LiDAR with UAV-borne LiDAR, the latter achieves a higher point density, resulting in more accurate forest measurements [24]. Regarding coverage, the canopy, branches, and terrain are all represented in their entirety. Here, it is vitally important to have multiple returns, especially the last one, since, in dense vegetation, only 11% of the first return provides ground information [25]. The efficiency of LiDAR-UAV surveys has also been demonstrated in other covers; for example, in salt marshes, where its usefulness in describing vegetation and topographic characteristics was proven, using an algorithm that manages to reduce errors in undulating terrain [26]. According to the collected information, it can be concluded that the quality of the collected information, in terms of its positional accuracy, depends, as expected, on both the transport platform and the sensor itself, taking into account variables such as flight height, its speed, inertial and georeferencing systems, as well as atmospheric phenomena, the filtering and classification of the point cloud, its density, and the number of sensor returns, see Figure 5.

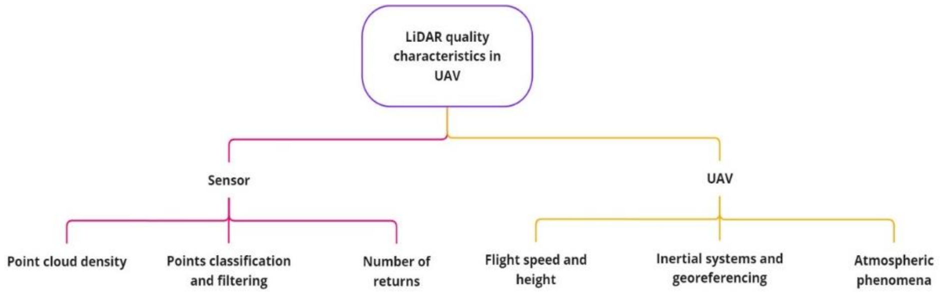

Figure 5. Lidar sensors quality aspects on UAVs

3.3. LiDAR vs photogrammetry: combined or separated, which one is better?

The previous sections show the evolution produced with the arrival of UAVs in the field of remote sensing, as well as the constant improvement in sensors in terms of their capacity and the reduction in their physical dimensions. A constant interest in various research has also been demonstrated, to improve terrain modeling based on these techniques. However, it is still not clear which technology could be applied in each case. The following paragraphs aim to guide the reader in their decision-making.

The capture of forested areas has been addressed with digital photogrammetric and LiDAR techniques, supported by the use of UAVs. The results in determining canopy areas have been practically the same when addressed separately. However, when trying to penetrate it, digital photogrammetry presents a loss of information and, therefore, lower efficiency. Regarding the use of LiDAR in UAVs, it can be identified that, with the correct parameters, the point density increases, which has a positive impact on forest measurement. With photogrammetric techniques, the poor results in areas other than the canopy, and especially in the production of DEMs, seem to be associated with variables such as image overlap less than 80%, different forest conditions, different average tree heights in the forest, stems with higher density, and even causes such as the shadow produced by the drone [24]. It should be noted that these results focus on broadleaf species with ellipsoidal crowns and conifers with conical crowns. In Australia, an experiment was conducted to model canopy cover and obtain tree heights in a eucalyptus forest using a LiDAR point cloud. A comparison of the product with the photogrammetric technique was also made, using only a sensor with the near-infrared (NIR) band. The models, in both cases, failed to fully capture the canopy cover. However, the LiDAR product was more representative; they also failed to predict tree heights with greater accuracy. The most likely explanation for the less accurate results with NIR may be due to areas without data, since, as described in previous paragraphs, the canopy prevents the penetration of photogrammetric sensors. It may also be due to the type of forest, as the studied species is usually very clustered. Photogrammetric reconstructions improve when the GSD is greater than 5 cm, and the overlap or superposition is greater than 84%. On the contrary, when the spatial resolution is 3.7 cm, matches between photographs are ignored, generating a worse reconstruction; this occurs near the canopy, because the distance to the sensor decreases [27]. According to the aforementioned research, it can be inferred that, in forest studies, the results can be divided according to interest. For canopy cover cases, both techniques seem to be efficient, with the variables controlled. However, for conducting studies of tree heights and DTMs, the LiDAR sensor has better performance.

In the field of geomorphology, the emergence of UAVs and terrestrial laser scanning (TLS) has generated a cartographic revolution in data acquisition processes, with precisions reaching centimeters, depending on the flight height, spatial resolution, and georeferencing method [28]. A workflow with UAVs and SfM photogrammetry equals airborne LiDAR methods and reduces costs. This is also identified in coastal studies in which, taking as a basis three different UASs with the same number of sensors, including one LiDAR, it is observed that the difference between the data obtained with these platforms and traditional airborne LiDAR is less than a decimeter [29]. Regarding terrestrial LiDAR and SfM, it is said that the methods are complementary and can be applied to different scenarios, where the choice of one or the other or the combination of these will depend on the nature of the geological outcrop and the operating conditions of the equipment [30].

On the other hand, in risk analysis, studies have been conducted aimed at identifying errors in digital elevation models produced with photogrammetry and LiDAR techniques in UAVs, for areas with difficult access, mountainous areas, with high vegetation density, and that also have ground movement. Errors were found that do not exceed two decimeters with LiDAR techniques, while with photogrammetry, they were below 40 cm. It is also indicated that, for small areas, due to its low costs, the most appropriate technique is photogrammetry, and that, to obtain better results and replace problems regarding the lack of GCPs, both techniques should be combined [31]. However, in studies of in-channel debris flows, which constitute massive sediment transport phenomena in mountain streams with steep slopes and where topographic surface modeling is the most important factor for predicting flow, it is concluded that the SfM technology of digital photogrammetry is not suitable, since it does not achieve statistical performance comparable to LiDAR and GNSS. This result is presented after performing a combination of surface shape analysis, vertical quality assessment, spatially distributed vertical uncertainty modeling, and probabilistic differentiation of the DEM, using full-waveform LiDAR, GNSS, and digital photogrammetry (SfM) methods, to subsequently analyze the influence of the topographic data source on a GIS model to simulate debris flows with intermediate to high magnitudes [32].

In the construction industry, airborne laser scanning and photogrammetric techniques are also used to measure construction progress, as well as for their control, terrain and surface modeling, among others. In this sense, some works present a guide to choose the appropriate technique depending on the visibility on the site, concluding that, if used separately, data collection with photogrammetric techniques is faster, but its post-processing would be more time-consuming. In addition, in the case of using only terrestrial laser scanning, the roof of the building in the case study would lack 100% of the data [33]. On the other hand, the usefulness of data coming from point clouds generated with photogrammetry is limited, since it generally introduces errors related to the environment of the constructions, and this is accentuated by the need for high positional accuracies in some works [34].

To solve these problems, proposals have been generated around the combination of UAV photogrammetry and terrestrial LiDAR data. The objective has also been to generate 3D models in areas of earth movement where the shape of the terrain changes continuously and in short periods of time (days or weeks) [35]. It is interesting to highlight that, with the combination, the two technologies complement each other perfectly, eliminating the shortcomings in data capture. It should be noted that, with the appropriate characteristics, the error between data is less than 10 cm in 86% of the data, while for the rest, the error was higher due to a blind spot in the LiDAR capture [33]. Reconstructions and heritage studies are also inherent to these fields, so much so that, in studies and monitoring of pagodas, the combination of data has been successful, generating models with maximum errors of 0.006 m, in addition to being more complete than when using a single technique [34]. In the same sense, it was demonstrated that the use of the combination of point clouds can reach a reproducibility of dam-type structures with an efficiency of 98%. It was also shown that the error in the z-axis, when combining the point clouds, improved by 12 mm compared to the error of the cloud generated by UAV photogrammetry [35].

Another use of the possible combination of techniques includes the determination of local geoid models, which are necessary in different engineering projects. While it is true that the models from the consulted articles used airborne LiDAR, they were achieved through different comparisons between the DTM produced with this technique and the one produced with UAV photogrammetry, finding an accuracy equivalent to that of high-resolution regional geoid models. However, they do not exceed 10 cm, which means that, for detailed engineering projects, they are not sufficient. Although, possibly, with UAV LiDAR and more studies, the necessary accuracies for these purposes can be achieved [36].

On the other hand, with integrated photogrammetric and LiDAR techniques, the reconstruction of historical heritage is possible. It is necessary to include, of course, GCPs with sufficient precision for their georeferencing, flight height, and sensors that allow a GSD to be compatible with this precision. Here it is relevant to indicate that their use reduces the time and cost of topographic work, compared to traditional techniques performed with optical equipment or satellite navigation, such as GNSS receivers. When checking the obtained errors, these are calculated with figures less than three times the GSD [37]. In the archaeological field, integrations of this type have also been used, although with airborne LiDAR data and open access, so that the non-specialized public can carry out reconstructions of sites of interest. However, due to the very nature of their data, positional accuracy is not relevant in these cases [38].

There are other applications arising from the combination of these techniques; for example, autonomous vehicles and their need for robust localization and mapping (SLAM), which is now based on cameras and LiDAR [39]. It should be clarified that, although both are terrestrial, they can improve the conditions for other uses and enhance the technologies of those transported in UAVs. Finally, it can be indicated that different aircraft equipped with both photogrammetric and LiDAR sensors have been compared, finding that, as described so far, the GCP network is necessary, as well as the clear advantage of the active sensor when surveying terrain with dense vegetation cover [40]. Regarding small areas with covers such as bare soil, short grass, or roads, the advantage of photogrammetry lies solely in the lower cost of the sensor, since its positional accuracy is comparable to LiDAR. In Table 1, the types of studies where a certain technique presents advantages can be observed, either due to its better positional accuracy or its cost reduction. It is also observed where their combination would be the best solution.

Finally, it can be identified that the regulation for the use of UAVs constitutes the greatest challenge faced by digital photogrammetry and LiDAR, due to the risk and civil liability for damages to third parties that involve both the manipulation of aircraft, and the capture of sensitive information that can be achieved with them. These are problems inherent to remote sensing, which must be addressed from professional ethics, ensuring responsible use of these technological tools. On the other hand, the technologies of the energy sources that use these tools are constantly growing and mutating, which will allow a massification in daily and professional activities, managing to reduce their costs and the appearance of new applications, along with this, positioning technologies that will include new solutions and densification of geodetic networks. Will improve the positional accuracy of the information collected, as well as greater spatial resolution due to the better quality of sensors and their accessibility. By combining these technologies with so-called artificial intelligence, it will be possible to automate processes in the various fields of knowledge. It is also planned to adapt these tools to augmented reality and vice versa, which will allow innovative developments and improve knowledge in various fields.

Table 1. Recommendations for the selection of the technique to be used

Recommended technique		
LiDAR	Photogrammetry	Combined
DTM in forested or densely vegetated areas	Broadleaf canopy	Canopy coverage
Canopy coverage of large areas	Bare terrains	Roads or highways
Tree heights	Coastal studies in small areas	Risk analysis
Geomorphological studies	Risk analysis in small areas	Inaccessible areas, complements GCP
Coastal studies		Architectural heritage studies
Intrachannel flows		Archaeological studies
Large area studies		Restoration studies
		Construction and infrastructure
		Regional geoid models

4. CONCLUSION

The positional accuracy in LiDAR and digital photogrammetric technologies transported in UAVs depends on atmospheric conditions, the flight plan and its parameters, the quality of the sensors, the georeferencing technique, the quantity and distribution of GCPs, the type of UAV and its inertial sensors, the processing software, its algorithms and techniques, and the coverage conditions and type of terrain to be surveyed. This is without considering the specific conditions of the technologies, which are extensively studied in other documents. Specifically, for LiDAR technology, it is essential to have multiple returns, as well as the classification of the point cloud, to guarantee optimal modeling. While, for photogrammetry, it is essential to have overlaps of more than 80% and that the GSD is in accordance with the required scale. The use of techniques and algorithms such as RANSAC, SfM, SIFT, and MVS is also essential.

It can be stated that, for areas with dense vegetation cover, such as forests and tall grasses, as well as in areas with steep slopes or high-velocity flows and even areas with difficulty in densifying geodetic networks, the positional accuracy of products made with UAV LiDAR is higher. On the other hand, for small areas that include bare soil cover, coastal studies, roads without visual obstacles, digital photogrammetric solutions are more desirable, since their positional accuracy is equivalent to that of other methods, but their costs are lower. In inhospitable and very difficult to access areas, the combination of both techniques will improve positional accuracy and avoid risks to people and equipment. In heritage, archaeological reconstruction, and infrastructure or construction studies, the fusion of point clouds produced by both techniques considerably improves modeling, optimizes resources, and reduces costs.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
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O : Writing - **O**riginal Draft
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Vi : **Vi**sualization
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CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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