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The Value of Integrating Laser Scanning and Photogrammetry to Overcome Standalone Techniques Limitations - A Review Study

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Abstract

Laser scanning and photogrammetry are two revolutionary technologies garnering an increasing interest in various engineering and construction fields. These technologies offer outstanding benefits, including non-contact remote sensing activities and highly automated and effective large-scale sampling capability that attracts more attention. New developments in remote sensing standalone methods, including range-based and image-based modeling (e.g., Terrestrial Laser Scanning and Structure from Motion- Multi-View Stereo photogrammetry), produce 3D geometrically and physical data that is more exhaustive, precise, and accurate than ever. However, neither standalone technique can offer higher-quality results than the other due to sensor limitations and shortcomings in certain conditions. On the contrary, integrating multiple techniques can help overcome the single sensor's limitation and allow complete 3D realism data outcomes that better facilitate post-processing, such as object classification and segmentation. Combining multiple RS datasets has recently obtained much attention in the Geomatics research community that has been widespread lately. To highlight the available integration and combination of laser scanning and photogrammetry approaches, this study reviews the various up-to-date approaches currently in use towards 3D realism products, both in geometric and physical aspects. This work aims to give a systematic review that depends on qualitative and scientometric analysis to describe the progress and current state-of-the-art topic. The review also brings out future research endeavors to pave the road for different studies in diverse applications. Efforts also highlight the issues arising from individual and integrated image- and range-based modeling utilization. This includes discussing the most effective methods for gathering high-resolution 3D spatial information from combination approaches.

Keywords: Remote Sensing, Standalone Approaches, Fusion Approaches, Photogrammetry, Structure-from-Motion, LiDAR, Terrestrial Laser Scanning.

قيمة دمج المسح بالليزر والمسح التصويري للتغلب على قيود التقنيات الفردية – دراسة مراجعة

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الخلاصة

يعد المسح بالليزر والمسح التصويري من التقنيات الثورية التي تحظى باهتمام متزايد في مختلف مجالات الهندسة والبناء. تقدم هذه التقنيات فوائد رائعة، بما في ذلك؛ أنشطة الاستشعار عن بعد غير المتصلة والقدرة على أخذ العينات على نطاق واسع ومؤتمتة للغاية وفعالة والتي تجذب المزيد من الاهتمام. التطورات الجديدة في أساليب الاستشعار عن بعد المستقلة، بما في ذلك النمذجة المستندة إلى النطاق والنمذجة المستندة إلى الصورة (على سبيل المثال، Terrestrial Laser Scanning and Structure from Motion- Multi-View Stereo photogrammetry)، تنتج بيانات هندسية ومادية ثلاثية الأبعاد أكثر شمولاً ودقة ودقة من أي وقت مضى. ومع ذلك، لا يمكن لأي من التقنيتين المستقلتين تقديم نتائج ذات جودة أعلى من الأخرى بسبب قيود المستشعر وأوجه القصور في ظروف معينة. على العكس من ذلك، يمكن أن يساعد دمج تقنيات متعددة في التغلب على قيود المستشعر الفردي ويسمح بنتائج بيانات واقعية ثلاثية الأبعاد كاملة تسهل بشكل أفضل المعالجة اللاحقة مثل تصنيف الكائنات وتقسيمها. لقد حظي الجمع بين مجموعات بيانات RS المتعددة مؤخرًا باهتمام كبير في مجتمع أبحاث الجيوماتكس الذي انتشر على نطاق واسع مؤخرًا. لتسليط الضوء على التكامل والجمع بين أساليب المسح بالليزر والمسح التصويري، تستعرض هذه الدراسة مختلف الأساليب المتاحة الحديثة المستخدمة حاليًا تجاه منتجات الواقعية ثلاثية الأبعاد في الجوانب الهندسية والمادية. يهدف هذا العمل إلى تقديم مراجعة منهجية تعتمد على التحليل النوعي والعلمي لوصف التقدم الذي تم إحرازه والحالة الراهنة للموضوع الفني. وتبرز المراجعة أيضًا المساعي البحثية المستقبلية لتمهيد الطريق لإجراء دراسات مختلفة في تطبيقات متنوعة. بالإضافة إلى ذلك، يتم أيضًا عرض الجهود لتسليط الضوء على المشكلات الناشئة عن الاستخدام الفردي والمتكامل للنمذجة القائمة على الصور والنطاق. يتضمن ذلك مناقشة الطرق الأكثر فعالية لجمع معلومات مكانية ثلاثية الأبعاد عالية الدقة من خلال الأساليب المركبة.

1. Introduction

Nowadays, co-registering multiple datasets from different sensors is becoming a crucial topic in various applications. Reality-based 3D modeling techniques have acquired considerable attention in recent years due to their essential role in documentation, preservation, restoration, and visualization [1]. With recent advancements, reality capture using RS approaches, including image-based and range-based modeling (e.g., SfM photogrammetry and TLS), has become a superior approach that provides accurate, fast, and reliable information [2], [3]. With the continuously growing need for three-dimensional (3D) digital models, the generation of high-quality 3D models has increased for several applications, the most prominent of which is the recording of 3D content: these criteria concern geometric accuracy, the 3D model's completeness, and image-realistic appearance.

The RS approaches, including SfM photogrammetry and Laser Scanning (LS), have specialized and enhanced in almost every process phase, from data acquisition to the generation of 3D metric products, up to the surface modeling and finally to the representation and dissemination [4]. Three approaches have commonly been used to capture and recover 3D data in terrestrial close-range applications. These standalone approaches include image-based, range-based, and fusion approaches [5]. The fusion of image-based and range-based techniques demands adopting a suitable co-registration strategy to solve the feature extraction problem between 3D point clouds and 2D digital images [6]. Based on [7]–[10] studies, Figure 1 shows various approaches for acquiring, processing, and visualizing three-dimensional information.

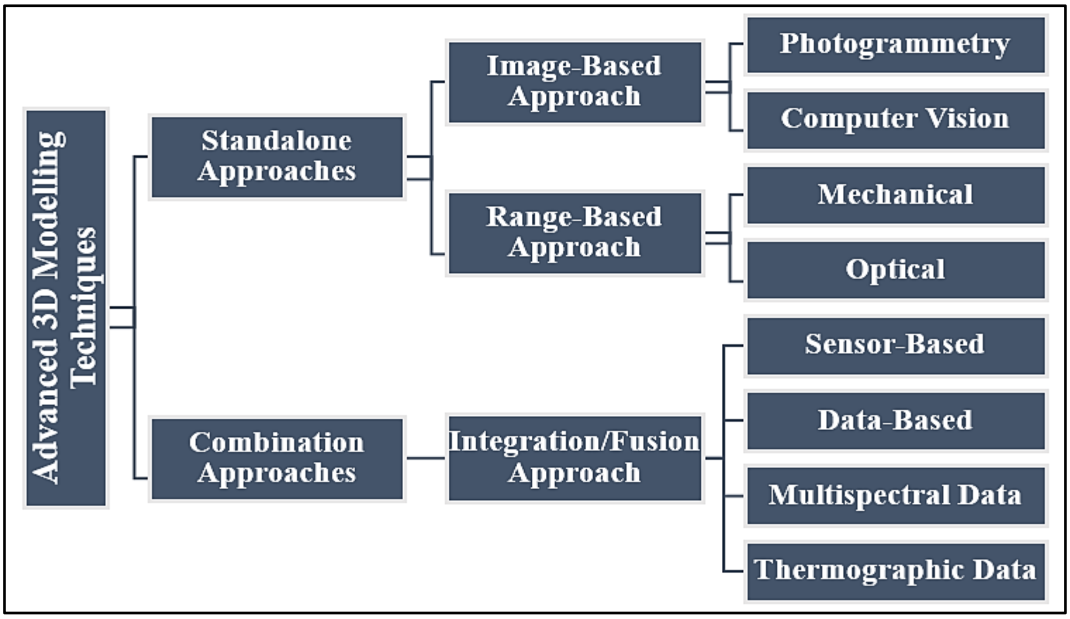

Figure 1: Taxonomy of advanced 3D modeling techniques.

3D standalone approaches, including (SfM) Photogrammetry and TLS, have been used widely in various sectors (including architectural, archaeological, structural, and many others) to reproduce the geometric properties of real-world objects. These techniques have been used for documentation, preservation, restoration, structural analysis, and maintenance [11]–[13]. The available range-based approaches directly produce 3D point clouds, which can be either sparse or dense, depending on the desired level of details (LOD) enhancement [14]. However, SfM Photogrammetry combines traditional Photogrammetry with computer vision to construct 3D point clouds from overlapping 2D images following an extensive processing pipeline [15]. Recent advances in laser scanning (LS) techniques have made it feasible to gather various 3D spatial data directly and practically, which would not be achievable in the past. With the help of these active sensors, it is possible to capture the object's geometry correctly. A novel method for gathering exceptionally complete data about the building environment has been made possible through the terrestrial laser scanner (TLS), which provides specific information that can be used for further investigation. TLS opens up new avenues of possibility for a wide variety of applications, including Building Information Modeling (BIM), the documentation of cultural assets, infrastructural inspection, and additive manufacturing in the construction industry [16], [17].

On the contrary, 3D data fusion approaches combine data from several RS sensors to obtain a more accurate 3D realistic model of an object than from data collected from a single sensor [18]. Various data-collecting strategies, such as terrestrial laser scanners (TLS), unmanned aerial systems (UAS), and digital cameras, have been utilized for data fusion scenarios towards 3D object modeling. The object's geometrical qualities, the necessary accuracy, and the cost observed are all considered when choosing the appropriate data-gathering techniques. A point cloud of the measured item can be generated with a high level of resolution using TLS, which has seen extensive use in applications requiring precise geodetic measurements, such as [19]–[23]. However, there are some applications in which TLS has delivered apparent limitations.

For instance, in applications involving 3D architectural models, the territory the TLS can scan is constrained by the sensor's line of sight [18]. Similar limitations can be observed in standalone SfM Photogrammetry approaches such as extracting BIMs [24], detecting archaeological features [25], 3D city modeling [26], etc. Therefore, the extraction of 3D models for the structural examination, CH reservation, industrial site checking and monitoring, and others have been analyzed by several studies using SfM photogrammetric techniques and (TLS), individually or in combination. However, these studies have not provided a critical review of the limitations of these approaches in individual applications and highlight how to overcome these shortcomings through the data fusion approaches. Therefore, this paper is providing a consolidated review study by showing the potential of the available up-to-date data-fusion approaches through highlighting limitations of standalone approaches in most potential applications (i.e. in engineering, construction, architecture, industrial). This work aims to describe the progress that has been made in the previous years and highlight the current state of the art in photogrammetry and LS data-fusion domain.

2. Standalone Approaches

Standalone techniques such as photogrammetry and laser scanning are essential to extract the realistic characteristics of real-world objects from 3D models. Every approach and technique has advantages and disadvantages [27]. In a 3D context, point cloud technology is a dynamic notion, photorealistic, scalable, and mostly georeferenced, where the obtained 3D data is incredibly beneficial for various applications. Many studies have used the RS standalone approaches, such as TLS, LiDAR, and photogrammetry [28]–[37]. The primary reasons for implementing such strategies are to evaluate the quality (accuracy and precision) of the data that has been supplied, to develop three-dimensional models, and to find concealed regions or characteristics.

2.1. Image-based Modeling Approach

The image-based 3D modeling is becoming increasingly popular as it is ideally suited for exact measurements and is increasingly being embraced for industrial applications and the protection of cultural heritage. The use of images, specifically photogrammetry, and computer vision, is the primary method for accomplishing the primary goal of this methodology, which is to generate accurate measurements and three-dimensional geometric models following the appropriate mathematical models to extract depth information from 2D images [38]. Image-based modeling (IBM) has seen significant improvements thanks to recent developments in dense image matching [39] and advances in camera sensor manufacturing [40]. These developments have enabled the generation of dense point clouds, high-resolution ortho-mosaics, and textured models from enormous datasets. IBM's cutting-edge approaches are based on several different computer vision photogrammetric algorithms.

Fully automated 3D reconstruction techniques based on (SfM) algorithms have received much attention in computer vision. Structure-from-motion (SfM) algorithms are the single process of concurrently establishing the 3D geometry of a scene and the multiple camera postures (i.e., Motion) from a sequence of image correspondences [41]. These techniques allow for the simultaneous estimation of camera orientations and sparse 3D point clouds derived from image correspondences. For more information, see [42]–[44]. The SfM-MVS workflow is illustrated at its most basic level in Figure 2. The technique of image-based 3D reconstruction has been applied in various fields of science and engineering. These applications can be classified as follows: civil engineering, construction monitoring, architecture, heritage preservation, industrial applications, medical applications, geoscience applications, and smart city construction [45]–[55].

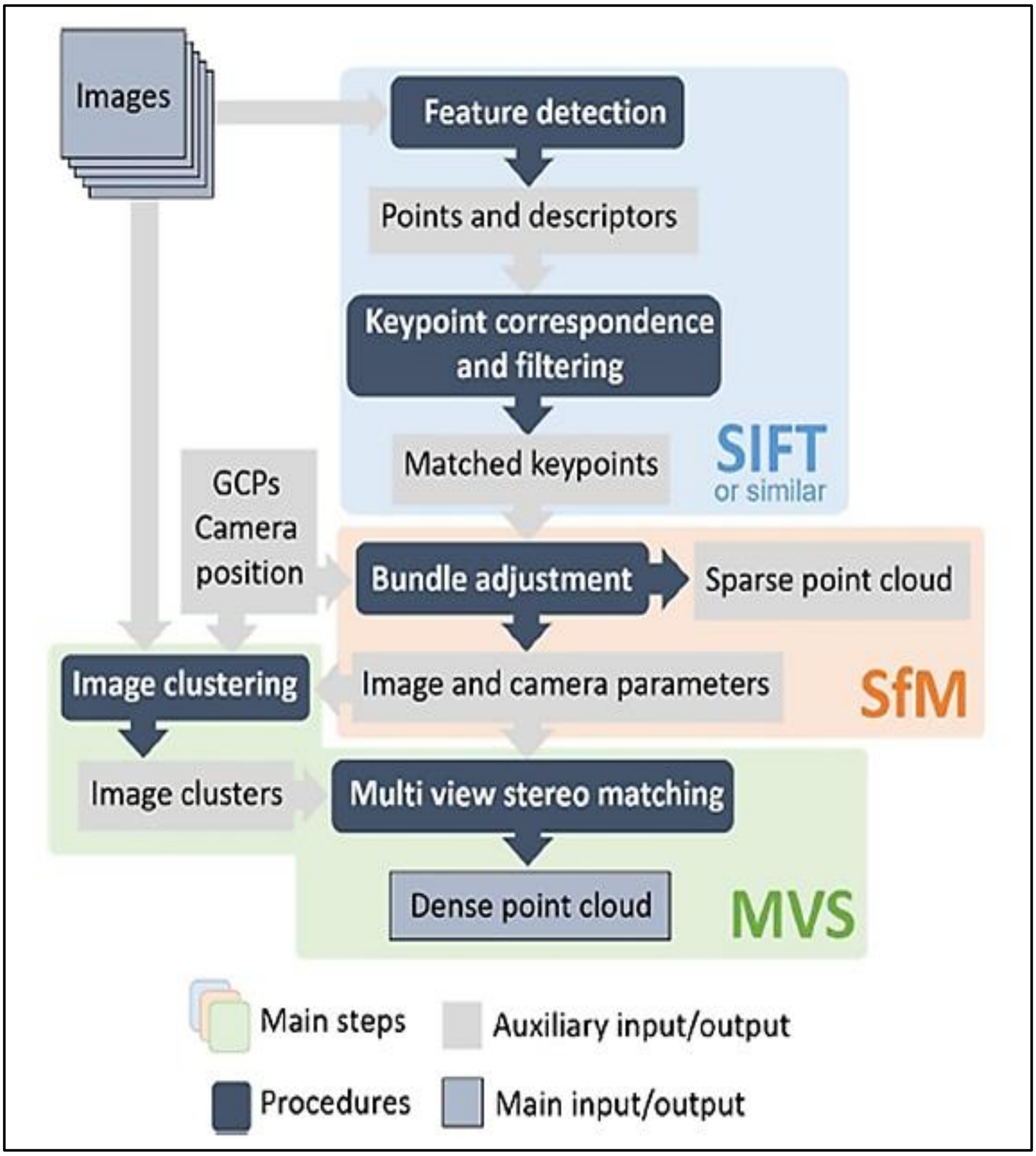

Figure 2: A schematic representation of the SfM-MVS process workflow generates a dense point cloud from image sets [15].

De Reu et al. [56] have investigated the potential uses and restrictions of image-based 3D modeling in recording a complete excavation, how this technique affects the excavation process workflow, and the following post-excavation processing. The findings indicate that image-based 3D modeling can be an effective and appropriate technique for recording, visualizing, and documenting the archaeological heritage that has been unearthed. However, the high resolution of geometric information obtained is the key to making it possible to evaluate the data quantitatively in a straightforward manner. In this context, López et al. [57] employed 3D modeling in archaeology by analyzing the megalithic necropolis of Panoria using Structure from Motion techniques. The use of image-based modeling demonstrates how new recording approaches are more effective in comparison with traditional fieldwork approaches. However, the accuracy of the methods utilized for data recording is still a challenge to the qualities of 3D modeling. Recording systems must contain user-friendly software that accurately captures the site's archaeological elements to recreate an archaeological site as it was during excavation, Figure 3.

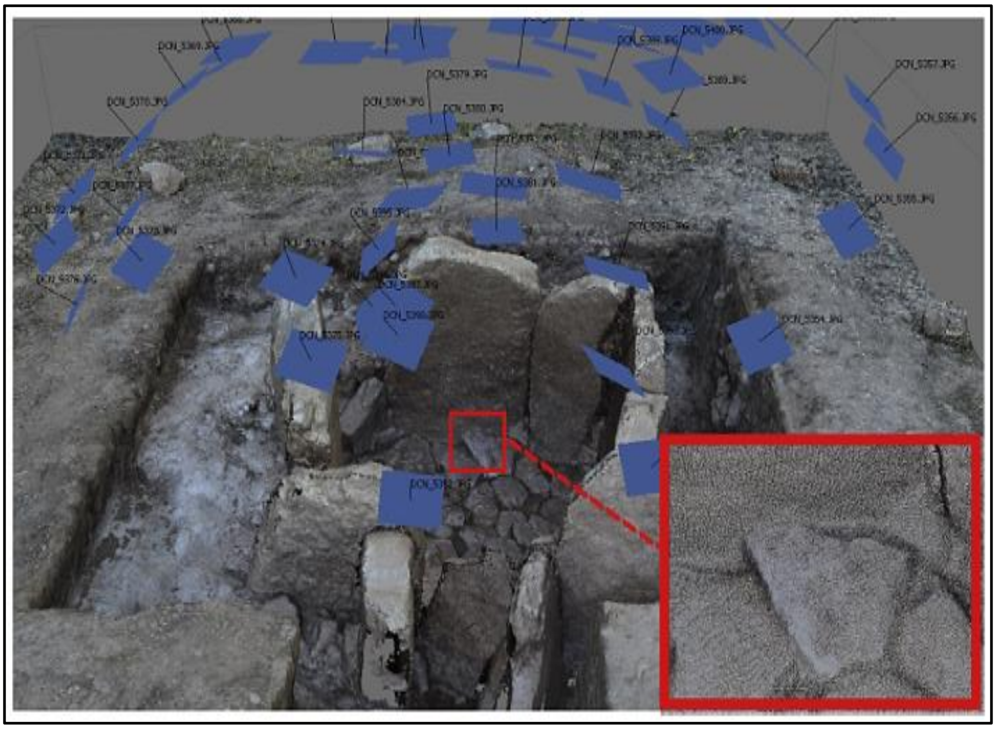

Figure 3: Dense point cloud derived by implementing DMVS algorithms [57].

On the other hand, Aicardi et al. [58] used a photogrammetry technique to co-register the multi-temporal UAV image dataset for DTM extraction. The research utilized two datasets from a construction site and an area damaged by a post-earthquake. They proved that the outcomes highly depend on the image quality and distribution across the entire block. Nevertheless, it has been demonstrated that using the same reference period is the most effective strategy for preventing the accumulation of processing mistakes. The provided approach makes it possible to co-register individual blocks with high-precision outcomes. Therefore, it can be considered the first step of an intuitive approach for change detection and monitoring of the orthophotos and Digital Surface Models (DSM) that have been generated.

Furthermore, Bianco et al. [59] analyzed the effectiveness of structure-from-motion pipelines in CH application. They showed that it is possible to produce synthetic datasets from which SfM reconstruction can effectively run and obtain satisfactory results. This allows the user to test the limitations of the pipelines and demonstrate how certain critical situations can harm the reconstruction process. To achieve this goal, they have created a plug-in for the Blender rendering software to produce synthetic datasets and evaluate the pipelines. In addition, it makes it easier to carry out the numerous stages of the evaluation process. Synthetic datasets allow the possibility of having exact and infinitely precise ground truths compared to genuine datasets, often gathered through physical imaging instruments. Figure 4 illustrates images captured from several observation points.

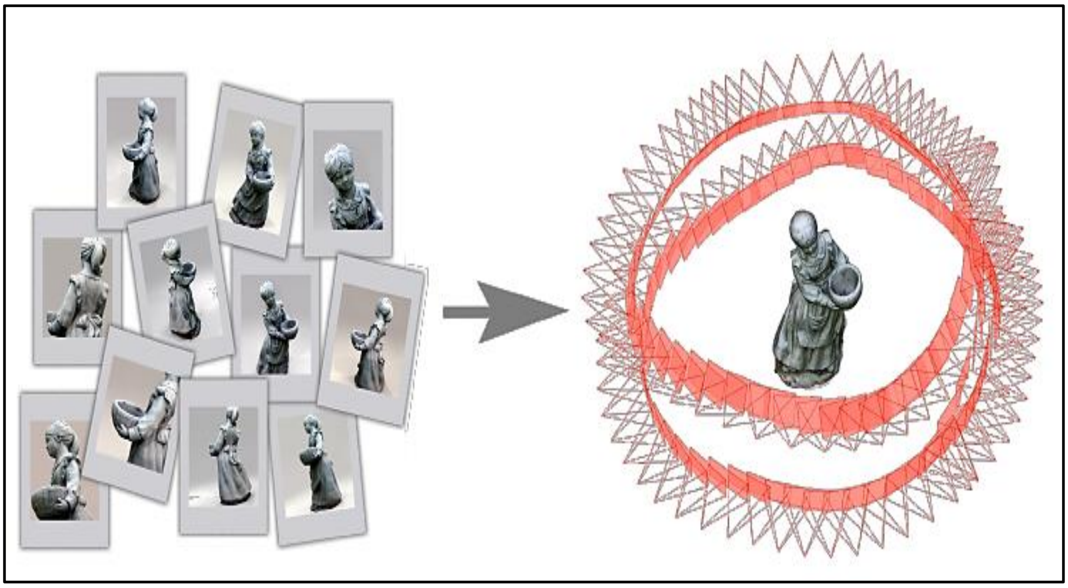

Figure 4: 3D reconstruction using Structure from Motion [59].

Later, Zrinjski et al. [60] studied the application of two different approaches for determining the structural geometrical parameters of an industrial masonry chimney using UAS photogrammetric surveys. Based on the results of their experiments, additional investigation into the application of the UAS photogrammetric survey is necessary. It is impossible to draw a definite conclusion regarding whether or not this method can be utilized to determine the correct values of the chimney geometry parameters. Because it serves as the basis for subsequent computations, the findings suggested that the quality and precision of the extracted point clouds formed photogrammetrically should get much attention.

2.2. Range-Based Modeling Approach

Range-based modeling approaches exploit emitted laser beams using designated active sensors to collect many points for the target object in a rapid manner. This technique, also called active scanning with non-contact of the object, measures the distance between many points in the target scene. The direct product is a "point cloud" that contains a tremendously accurate and helpful group of issues that may be utilized in engineering analysis [7]. Range-based approaches can be used for distance measurements, as-built infrastructures, 3D reconstructions, terrain mapping, city modeling, vegetation, and specialized applications like forestry, geophysics, or hydrology [10]. Data obtained from laser scanning devices can exhibit a wide range of characteristics, including point density, amount of noise, field-of-view (FOV), incidence angle, waveform, and information about texture [61].

A laser scanner can directly calculate the three-dimensional coordinates of any point in the scene, both horizontally and vertically, within its field of view (FOV) [62]. A study by [63] described how Lidar data could automatically generate photorealistic 3D models. They devised an automated method for registering 3D point clouds, presented an automatic target identification strategy for georeferencing, and presented an automatic plane recognition technique for texture mapping and surface modeling. Mohsin and Abed [64] analyzed the 3D laser point cloud registration to document cultural heritage objects using TLS. They demonstrated the potential of accurate 3D modeling applications by applying two fine registration methods: NN-ICP and LM-ICP. A comparison between both approaches has been used to evaluate the accuracy of the collected objects in such applications. The NN-ICP approach had an average registration error of 3.9 mm, while the LM-ICP method only had 2.6

mm. The documentation process was accomplished by utilizing the most precise registration approach. To evaluate the digital procedure, 21 and 25 reference points with an even distribution were attached around the body of two objects at individual locations. The results showed that the RMSE of the TLS close-range approach was 6 mm at the minimum range of 3.5 meters and 12 mm at the 7-meter range for the interior and outdoor cases, respectively.

On the other hand, Barazzetti et al. [65] provided an approach to assess verticality deviations of tall chimneys via TLS techniques. The method uses laser scanning point clouds acquired around the chimney to estimate vertical variations with a precision equivalent to millimeters. Point cloud-derived horizontal slices reveal the chimney's geometry at various heights. The center estimates were made at multiple levels using TLS techniques. The implemented approach was fully automatic, and in addition to center coordinates, it offers data that can be used to evaluate the quality of the metric measurements.

Maalek et al. [66] utilized the point cloud geometric primitives to develop a general and dependable framework for automatically extracting flange pairs and pipe in pre-fabricated modules in oil and gas refinery construction projects. They evaluated the approach on two-point cloud datasets with varying data quality and density gathered from different sites. Their method was able to extract all 49 pipes and flanges successfully, and it enhanced the precision of the estimated normal vectors and centers by 145% and 171%, respectively, when compared with the results obtained from commercially available verification tools. The findings of the trial point were of great potential for the suggested system in terms of its generic applicability for fabrication verification despite the limitations obtained regarding low coverage, data gaps, and time consumption, Figure 5.

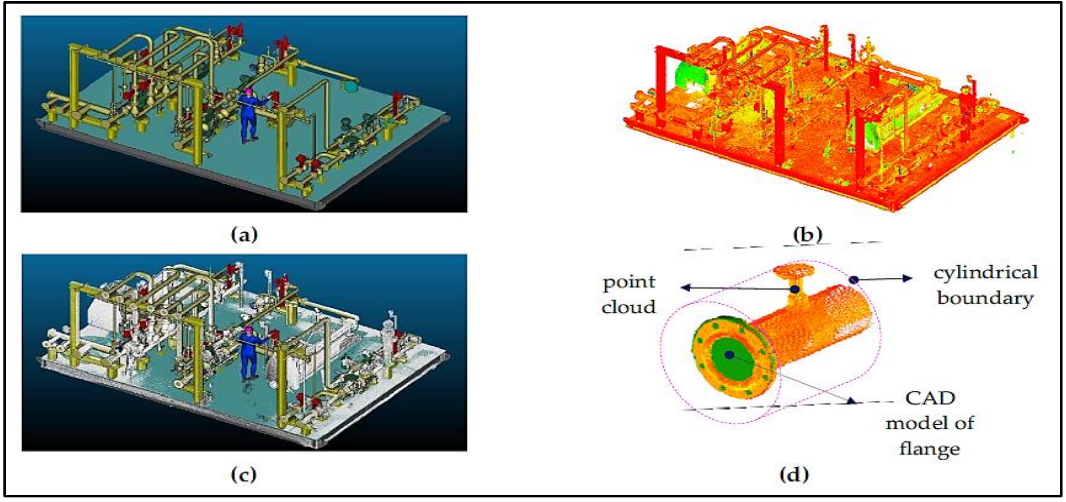

Figure 5: The planned 3D/4D model includes (a) a Pre-designed 3D model, (b) a 3D point cloud of the site, (c) an integrated scan and CAD, and (d) an extracted point cloud of one pipe and flange [66].

Moreover, Stenz et al. [67] showed the quality of investigating data obtained from static and kinematic TLS platforms, which should primarily focus on industrial applications. They investigate the relevance of sensors commonly implemented in a multi-sensor system and the appropriate data collection and acquisition methodologies. Such systems aim to examine the geometry and surface of the object being measured in an industrial setting to an accuracy of +/− 1–2 millimeters. However, Maalek et al.[68] provided a reliable framework for extracting common structural elements, like columns, from TLS point clouds acquired during standard rectangular concrete building projects. The framework compares the retrieved objects to the building information model (BIM) designed, automatically allowing it to discover as-built scheduling and dimensional discrepancies. Further, a novel approach was developed in the mentioned study for removing unnecessary points from a newly obtained scan in order to identify differences between successive scans. The framework was able to correctly extract 132 out of 133 columns and removed unnecessary surfaces with an accuracy of 98.79%. In addition, it was demonstrated that the measurements of 127 out of 132 columns have reached and all of the slabs complied with those planned in the BIM were extracted successfully as shown in Figure 6 which demonstrated classification and segmentation results.

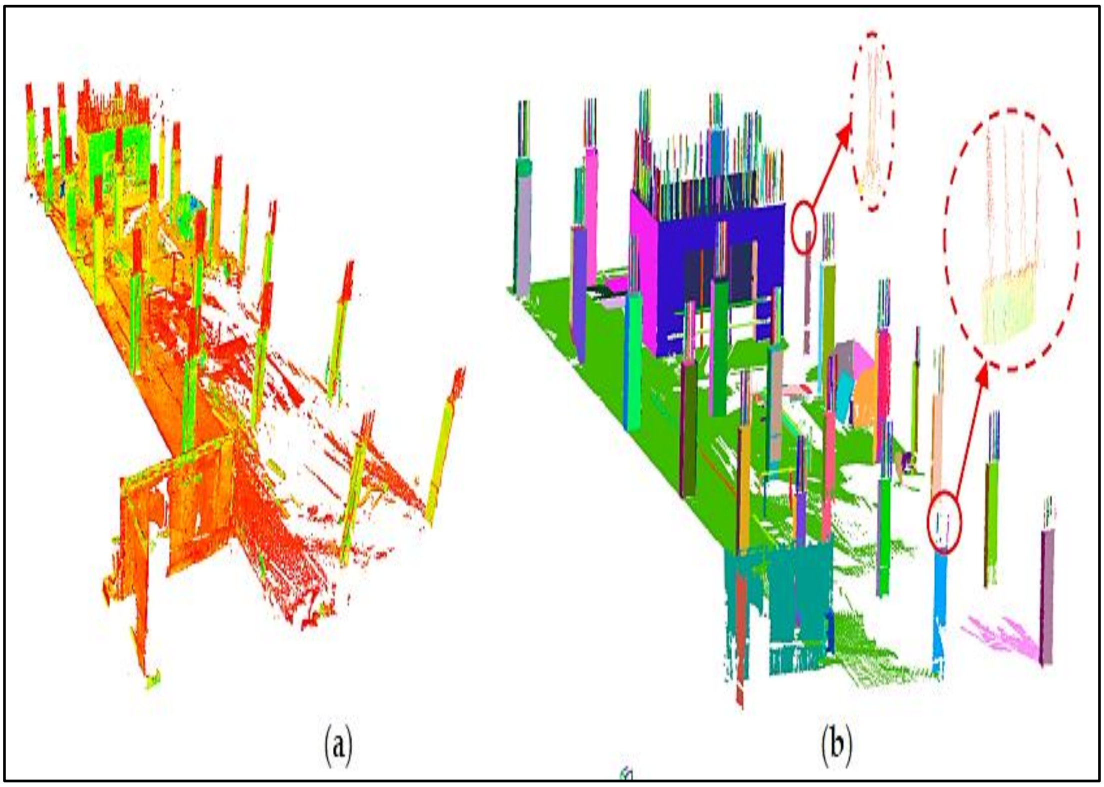

Figure 6: Epoch 1: (a) point cloud; (b) robust planar, linear classification and segmentation [68].

Later, Zhang et al. [69] provided a study on TLS technology for more sophisticated progress monitoring on construction projects involving infrastructure. They demonstrated that occlusions could be a real problem and a high challenge should be tackled. However, occlusion can be partially controlled, objects with various shapes can be modeled, registration can become more accessible, and the costs can be kept to a bare minimum. In addition, they concluded that all of this can be accomplished in an automated manner with a minimum amount of involvement from the user. It is expected that the duration of the inspection process, as well as the hard work involved in monitoring the progress of the building, will be cut down by the automation of the procedure. Additionally, automation can improve the personal security of construction managers and inspections. Their research revealed that the findings can be extrapolated to sizeable horizontal infrastructure projects, particularly those involving the construction of roads, bridges, and railroads, as shown in Figure 7.

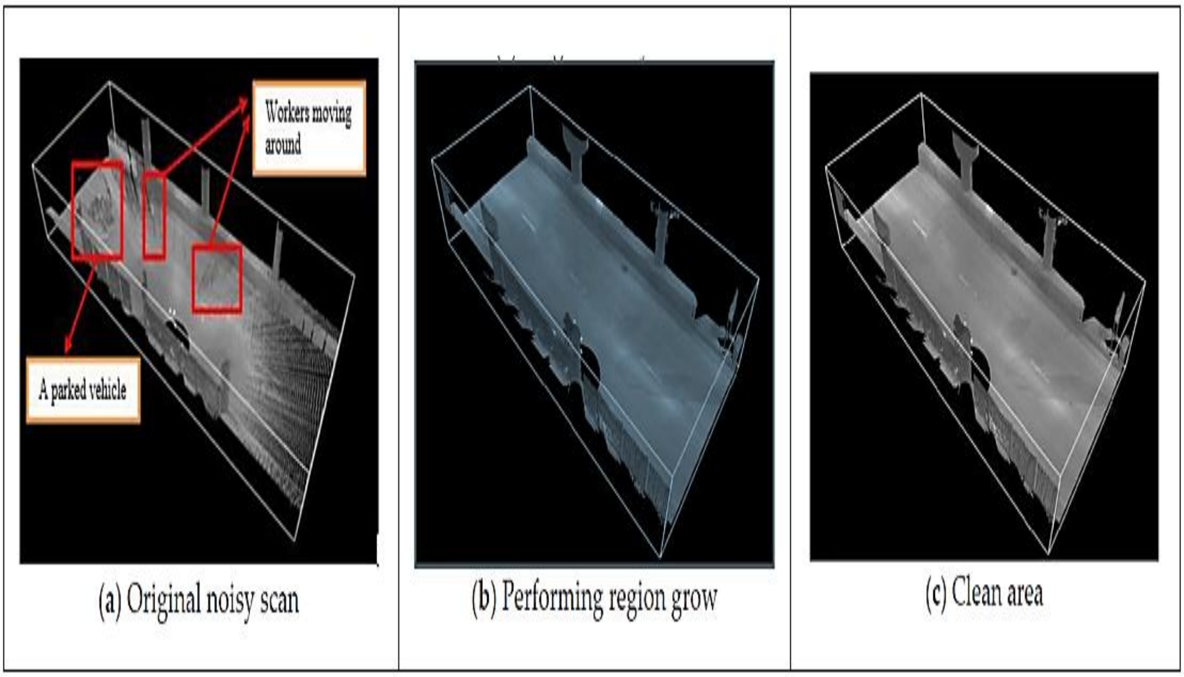

Figure 7: The region-growing process includes the original scan with the noisy, defined region-grow parameters and the results of the “region-grow” process [69].

Finally, Almukhtar et al. [1] studied the use of 3D laser scanners to capture buildings' reality. Using de-noising algorithms, they discovered that problems with the intensity and quality of point cloud data with the location of 3D laser stations could be uncovered using this technique. In addition, the results revealed issues about the capacity of laser beams to pass through various surface materials. This is a critical issue for automatically identifying different building elements, which might be employed for automatically monitoring the progress in construction and detecting variances in the building process. In conclusion, their research presented a framework for connecting the cloud-based model of the scan stations with the BIM system. Such an approach has the potential to significantly improve the management of building amenities, particularly in the case of historic structures.

3. Combination Approaches

There is substantial literature on using laser scanning and digital imagery as a survey approach for 3D modeling applications. The results demonstrated that these two technologies could work in tandem to provide high-quality 3D recordings and presentations [27]. The primary objective of combining various datasets is to overcome the limitations of standalone methods. The constraints are overcome by combining multi-datasets derived from the same sensors and multi-sensors datasets. Image-based or range-based individual modeling are examples of integrating data from the same sensors [70], [71]. In contrast, image-based and range-based modeling is an example of fusing or integrating data from multiple sensors [72].

3.1. Data Integration / Fusion Approach

Data integration, or data fusion, refers to the act of combining data coming from several sensors and, typically speaking, at different geometric resolutions – but still accurately portraying the same physical object in the real world to generate a representation that is consistent, accurate, and helpful for further processing [5]. To overcome the limits imposed by individual procedures, one solution frequently discussed is integrating different methods for geometric recording [73]–[75]. Thus, data fusion is required to combine the strengths of both data sources in one simultaneous solid solution.

In the context of a general multidisciplinary approach, the phrase "data fusion" refers to integrating data from several sources to increase the data's potential value, improve its interpretability, and make it possible to generate high-quality visual representations of the data. Data integration and Sensor fusion are similar things that often refer to the same concept [5]. However, "sensor fusion" will refer to only those approaches that utilize simultaneous data acquisition with multi-sensor configurations. This is done to differentiate these approaches from data fusion methods carried out during the post-acquisition processing stage.

It is now more apparent than ever that there are numerous benefits to combining optical data with LS. Despite the time and cost of the fusing process, it is considered a great benefit for industrial documentation as laser scanning data provides general coverage, and images complement the datasets to fill in gaps (voids) and resolve fine details. Images have many practical applications because they are analogous to the human visual system, have a well-understood geometry, are easily interpreted, can record texture and multi-channel reflectance information, can model moving objects, can be measured again, and use frame-based acquisition techniques [62], [76], [77]. Successful integration of both data sources will support operations such as surface reconstruction. It will simplify subsequent processing activities, such as developing 3D textured models. Combining the various data sets calls for an exact co-registration, which an algorithm for 2D-3D posture estimation must solve [78]. Integrating data from several sensors depends on several factors, including the spatial and radiometric data's resolution, positional accuracy, and the dimensionality of the fusion [79].

The step of the data processing pipeline at which fusion takes place is typically used as the criterion for categorizing approaches for data fusion [80]. However, you need a standard reference system with already-known parameters to register metric data and other metrics or qualitative information. This is so that their spatial integration can take place [81]. In addition, to integrate data from various sources at the pixel level, you need pictures (or orthoimage-mosaics) of the scene sampling distance and represent the same plane [81]. Registration, which involves aligning the data from the laser scanner with the image, is one of the essential steps in the integration process [7]. The registration process quality is crucial in determining how accurately combined processing is performed [7]. The methodologies currently being used for registration can be broken down into four distinct levels of integration, as suggested by [82]. These levels are as follows:

1. Integration at the object level.
2. The use of photogrammetry assisted by laser scanning.
3. The use of laser scanning assisted by photogrammetry.
4. Laser scanning and optical images that are tightly integrated.

In separate earlier investigations, integrating several datasets obtained from various sensors was applied for multiple reasons, depending on the particular study. In [73], the study combined Terrestrial Photogrammetry (TP) and TLS data to build realistic 3D models. Their research was conducted to formulate a geometric link between the 2D digital images-based Photogrammetry obtained from the LS 3D point clouds [83]. On the other hand, [84] investigates the differences between point clouds that are produced through the use of photographs and point clouds that are made via the use of a laser. They emphasize how the precision of photogrammetry is substantially higher than lidar technology's, as well as how the density of an object's surface is significantly higher when pictures are utilized rather than lidar. In addition, [70] looked at re-creating surface textures by combining digital Photogrammetry results with terrestrial laser scanning (TLS). These days, this is done with high-tech equipment that can collect precise and dense 3D point data from the surfaces of the objects. The utilization of the measurement ideas is maximized following the combination of these two sensors. In the same respect, Barreiro and Fritsch [85] work on 3D/4D photorealistic models and show their potential for many applications, including cultural heritage protection, urban planning, public management, etc. To get precise and trustworthy models, the geometries must be exact, and the textures must be of high-quality TLS systems to be among the most dependable approaches for capturing correct data. However, these methods include flaws such as missing data or the absence of texture information, dense image matching can build dense point clouds from photogrammetric images, etc. In this sense, employing photogrammetric image matching with laser system data is symbiosis to combine the benefits of both technologies in one approach.

Therefore, Zhang Lin [86] studied the fusion of optical images and LiDAR point clouds in one mathematical solution. They found that visual images and LiDAR data offer distinct advantages in specific situations. However, the drawback of one data source may be offset by the benefit of the other. Thus, data fusion is required to combine the strengths of both data sources in one simultaneous solid solution. Various fusion methods have been proposed. These applications include registration, actual ortho-photograph generation, pan-sharpening, classification, target recognition, three-dimensional reconstruction, change detection, and forest inventory. So, integrating optical images with LiDAR point clouds creates a link between the two independent data sources, allowing for improved surveying, mapping industry, and scientific research. In addition, [62] looked at re-creating the textures of objects by combining the results of digital Photogrammetry with terrestrial laser scanning (TLS). These days, this is achievable with high-tech equipment that can collect precise and accurate dense 3D point clouds following technical procedures to limit the effects of error sources as possible.

Furthermore, Chiabrando et al. [87] presented a multi-scale and multi-sensor approach to obtain (3D) data covering large and complex areas to acquire various metric information in a single 3D archive. The applications of these 3D georeferenced products are numerous. The merging or integrating of data from various sensors, scales, and resolutions is promising since it may aid in the construction of a hybrid model when they compare incorporated progress and outcomes from (TLS), (MMS), (UAV), Photogrammetry (TS), and (GNSS) for topographic surveys in their work. Later, Farella et al. [88] applied quality measures to enhance the combined terrestrial and UAV image processing in three dimensions. They noted that the results suggest the procedure is effective and reliable, verified using internal and external quality checks and visual qualitative comparisons.

Different approaches are available for fusing/integrating photogrammetric images and laser scanner data, depending on the desired outcome, the original data's nature, or the relative importance of the two integrated data sets. Data integration, or data fusion, approaches are used in many engineering disciplines. Examples include Cultural Heritage [62], [89], [90], Archaeological, Architecture surveying [91], Industrial applications, as well as monitoring [92], and construction monitoring [93]–[95]. For most of the mentioned applications, 3D object capturing in an accuracy range of several millimeters up to a few centimeters is sufficient. However, in engineering geodesy, particularly in industrial surveying or monitoring measurements, accuracy in a range of a few millimeters is required. The following sections review more detailed data integration studies in selective applications to highlight challenges, potential, and future insights.

3.1.1. Cultural Heritage and Archaeological Applications

In Cultural Heritage (CH) and archaeological engineering, Bastonero et al. [4] studied the ability to use the fusion approach of 3D models derived from Terrestrial Laser Scanning (TLS) and image-based techniques to enhance Cultural Heritage documentation. To define the problems and potential associated with combining or fusing metric data obtained through various survey methods. They demonstrated that the data integration allowed for time savings in the surface model processing phase because the data used in this workflow were equally plentiful on the entire object. Furthermore, they identified the possibility of increasing the radiometric information through the texture projection throughout the volume, from the front to the roofs. Depending on their results, they concluded that the geomatic approaches could satisfy various documentation requirements about cultural heritage. Balsa-Barreiro [96] presents a fusion methodology applied to historic cities and found are intrinsically valued due to their rarity. These cities represent the past, and they also offer excellent prospects. As a result, it is critical to understand how to conserve them and assess their extraction potential from various angles. Increasing understanding of these concepts is necessary and requested as 3D virtual representations are an excellent approach to introduce visitors to these valuable sites. However, some traits generated from irregular urban structures and distinctive human dynamics in ancient urban contexts may limit the usage of certain 3D data collecting systems.

In this context, Luhmann et al. [97] used the fusion of laser scanning with terrestrial and UAV photogrammetry for the 3D reconstruction of historic churches. According to what he reported, one advantage of laser scanning is the ability to capture point clouds reliably without requiring specialized engineering knowledge. In addition, photogrammetry aided by UAVs enables the measurement of roof and tower areas that cannot be seen by TLS or images acquired from terrestrial sources. They demonstrated that utilizing images and laser scan data simultaneously produced a 3D model with the highest completeness and quality possible to represent the original object. However, the highly parallel method used by Reality Capture demonstrates that optimized solutions with simultaneous TLS data fusion are viable and produce high-quality results, Figure 8.

Figure 8: The final 3D model is based on combined photogrammetry and laser scanning. [97]

Chiabrando et al. [87] studied the possibility of using a multi-scale and multi-sensor approach (e.g., TLS, UAV, and terrestrial photogrammetry) to collect and model three-dimensional data about expansive and intricate regions to acquire a range of metric information, included inside the same 3D archive, which is based on a single coordinate system. They showed that geomatics gives solutions to specific demands and purposes, favoring a strategy that draws from multiple disciplines while fostering the widespread diffusion of digital technologies. In these situations, the geomatics approach to the digitization of heritage covers the entire workflow to manage the idea of complexity that lies behind the difficulties of the building. Reality-based models, once they have been created from data collected and processed, offer a wide range of applications that react to specific needs of costs and goals, such as documenting, analyzing, and sharing information. Moreover, Hoon Jo and Hong [98] combined TLS and UAV photogrammetry to establish a 3D model and accurate digital documentation of a cultural heritage site named Magoksa Temple in Korea. On comparing the two technologies' accuracy, it was found that laser scanning offered more precise positioning than photogrammetry. The overall capability difference between the two systems was considered adequate for producing convergent data. The TLS and the UAV photogrammetry results were consequently aligned and combined. This research demonstrates how 3D digital documentation and spatial analysis of cultural heritage sites could benefit from integrating terrestrial laser scanning and UAV photogrammetry.

Ulvi [99] used Unmanned Aerial Vehicle (UAV) photogrammetry and terrestrial laser scanners to demonstrate the potential of the fusing approach in 3D modeling and visualization of cultural heritage objects and sites. He reasoned that the photogrammetric technique, which uses UAV technology to produce 3D models, is a low-cost but relatively fast methodology compared to other contemporary methods of protecting cultural heritage places. UAV photogrammetry is a much more suitable method for low-budget projects. He recorded that integrating oblique images in UAV photogrammetry is essential to recognize and record the small details of cultural heritage with high accuracy and precision derivable.

Alshawabkeh et al. [100], integrated photogrammetry and laser scanner for heritage BIM enhancement, proposed that a reliable approach for intelligent geometric feature detection and recognition is required to automate the parametric reconstruction of complex objects. In this scenario, new techniques based on color picture intensity values were utilized to automatically segment and measure the perimeter of an object's shape in the related point cloud. Figure 9 displays the finished textured model of the castle that resulted from integrating the two RS data.

Figure 9: UAV and TLS data-fusion of Asfan Castle 3D model. [100]

Buzón et al. [101] compared the limitations of (SfM) photogrammetry and (TLS) for archaeological excavations. They proved that the SfM approach offers a more significant performance level while remaining straightforward about TLS performance. In addition, the SfM method does not require the participant to have any prior technical knowledge because it just entails capturing images using a particular strategy without any initial preparation.

Therefore, they concluded that the SfM approach was the most accurate and had the fewest limitations when it came to its application in archaeological excavations of semi-buried sites.

Fabris et al. [102] applied low-cost SfM photogrammetry sensors and speedy TLS scans to construct credible 3D models of Illasi Castle, a historically significant building in northern Italy that has suffered considerable damage. The study concluded that, depending on the findings of the structural analysis, equivalent values for the linkages between the demand and capacity of global and local processes that affected the same area of the structure were detected. In conclusion, from most global analyses, the findings showed the link between the pattern of cracks in the systems and the concentrations of the principal strains and stresses in the finite element model, Figure 10.

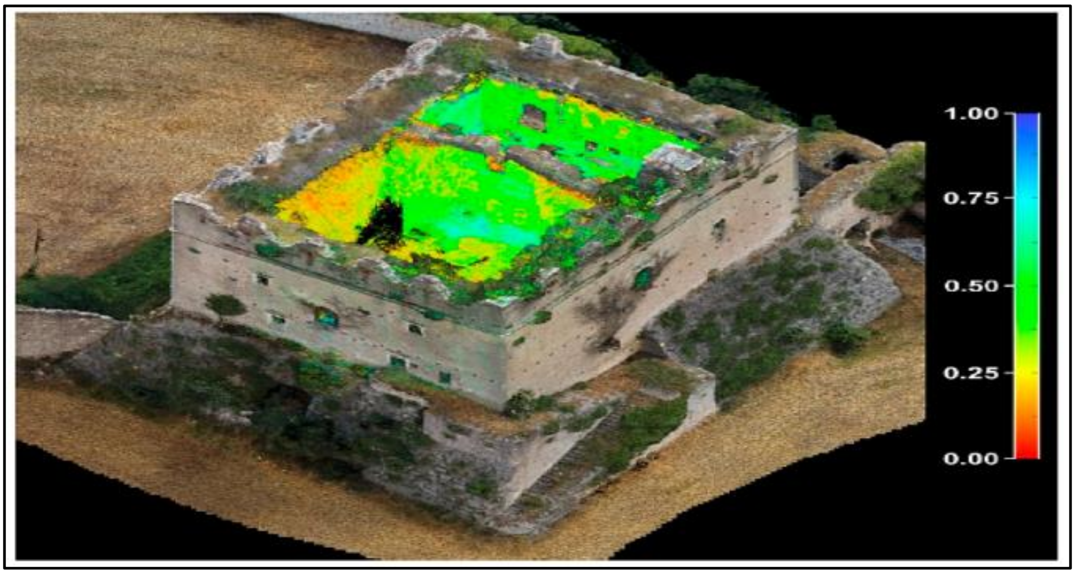

Figure 10: Integrating SfM and TLS data were used to create the palace's final 3D model. [102]

Kadhim and Abed [103] studied the potential of UAV photogrammetry and LiDAR data to evaluate the detection of new archaeological objects in Chun Castle - southwest of England. Their findings present several archaeological artifacts and relics on the investigation site that have been recognized. The utilization of various approaches and algorithms has successfully contributed to an improvement in the level of comprehension of the spatial characteristics of the landscape. The results illustrated how raster data derived from low-cost approaches may be used to discover archaeological remains and buried monuments, which has the potential to revolutionize our understanding of archaeological practices.

3.1.2. Industrial Applications

Partovi et al. [104] studied using TLS in combination with photogrammetric point clouds automatically in a complex industrial environment. Despite the challenging atmosphere, the primary results obtained in a complex industrial environment were promising. The outcome of the gap detection module demonstrates that the proposed method can identify areas with gaps successfully. Within the volumetric space, it was possible to make geometrical elements estimation for the gap areas, such as their size and volume. The suggested coarse registration of the TLS point clouds to the photogrammetric point clouds utilizing three-dimensional coordinates of the 2D features correspondences leads to accurate and reliable results. Later, the photogrammetric dense point clouds were combined with the TLS point clouds to fill the gap areas and reduce occlusions, Figure 11.

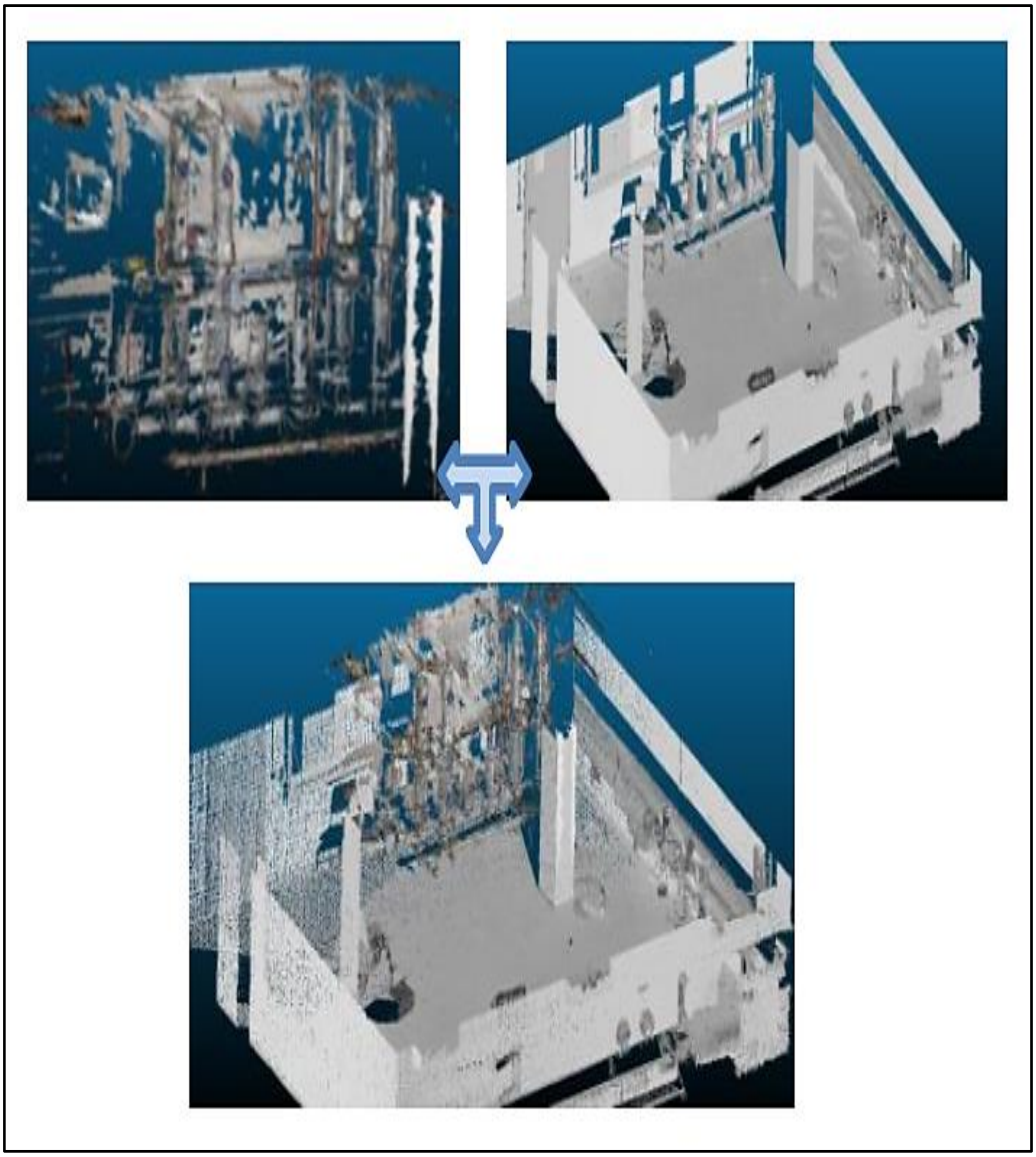

Figure 11: The integration of TLS and SfM photogrammetry in industrial sites [104].

Siwiec and Lenda [105] integrated SfM and TLS to evaluate industrial chimney geometry. They assumed the generated model would have accuracy and density comparable to the TLS measurements if the prerequisite conditions for SfM measurements were satisfied. Their findings demonstrated that it is possible to construct an accurate model of an industrial chimney using an integrated point cloud derived from TLS and SfM measurements, provided that certain conditions are satisfied. One of these conditions is the transformation function used in the co-registration approach into a standard system that can be carried out for partial coverage of the object with the point clouds at a given level for each technique. The integrated object model was recommended to be constructed from the TLS and SfM measurement components with complete point coverage at a specific height for individual techniques. To integrate the measurements for objects with smooth surfaces, it is necessary to have constraint points that are along and transverse to the object's axis, Figure 12.

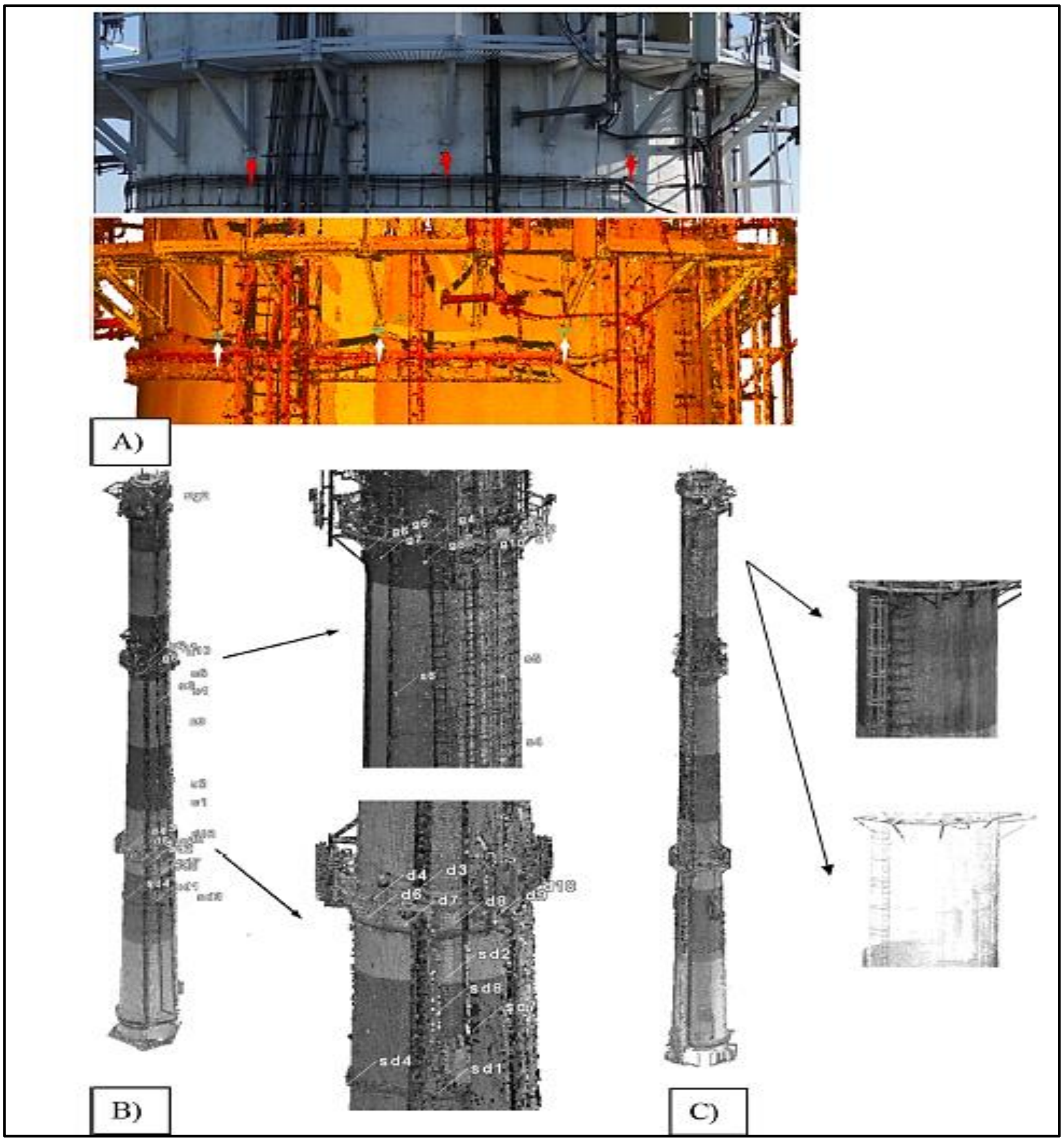

Figure 12: Integration of TLS and SfM photogrammetry of a chimney geometry [105].

Gumilar et al. [106] used a TLS and a handheld mobile 3D scanner for the 3D modeling of pipelines and instruments at an oil and gas company. Their findings demonstrated that integrating these two approaches produces an accurate 3D representation of the piping and instrumentation in industrial sites. The two data sets were merged using a cloud-to-cloud registration procedure based on the geometry of objects. This procedure considered the selection of reference data, the overlap of the two data sets, the similarity of the scale factor, and the unit of measure. Combining these two approaches resulted in a registration error far smaller than 3 mm, Figure 13.

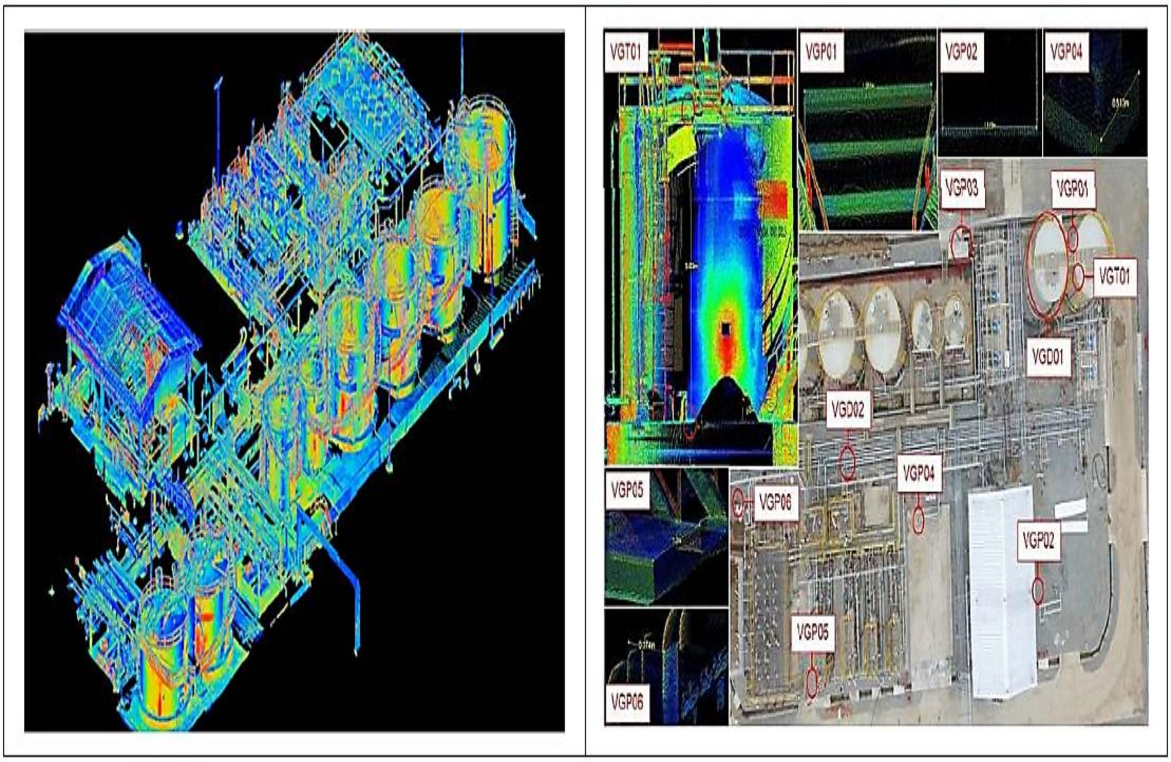

Figure 13: The objects used to validate and register TLS and handheld MLS point clouds. [106]

Finally, Zhumao et al. [107] investigated the method for determining the tilt condition of transmission towers using co-registering dense point clouds obtained from UAV-based LiDAR. Their results demonstrated that using (UAV) 3D laser scanning techniques for measuring the tilt of transmission towers can overcome the limitations of more conventional detection methods. This technique offers several benefits, including adaptability in terms of takeoff and landing, high accuracy and speed, low-altitude flight, and freedom from specific geographical constraints. They proposed a scheme for the automatic estimation and risk assessment of transmission tower inclination using data collected by unmanned aerial vehicles equipped with light detection and ranging (LiDAR) sensors. This would allow power grid operators and maintainers to keep tabs on transmission lines in real time, preventing accidents and minimizing losses due to deformation.

3.1.3. Other Applications

Zaragoza et al. [108] investigated the combination of UAV-based photogrammetry with terrestrial laser scanning, applied for a 3D-documentation in a hazardous situation; they proved that fusing TLS with UAV-based photogrammetry can be highly useful if it is necessary due to an emergency. It has been demonstrated that the accuracy of photogrammetry carried out using UAVs is on par with that achieved using laser scanning in areas practically orthogonal to the axis along which the shots are taken. The current case study demonstrates that it is possible to provide a helpful solution to combine the survey of gardens, roofs, and inner courts, for which access is restricted due to stability difficulties. Instead, using a UAV for photogrammetry along a nadiral axis yields lesser quality results for vertical components.

Moon et al. [109] compared point clouds produced by laser scanning with those produced from photogrammetry to create a 3D world model for intelligent heavy equipment planning.

In addition, they demonstrated that photogrammetry data may be utilized in various earthwork contexts. They proposed a mechanism for compiling and registering data that can supplement the geographical and physical constraints imposed by TLS technology. The study recommended a fusion approach against a standalone approach for producing high-quality models by generating hybrid point clouds co-registered datasets. Numerous applications, such as developing a 3D surface model, field surveys, and computations of the earth's volume, have become feasible due to this development.

Kordić et al. [110] integrated terrestrial laser scanning and UAS photogrammetry in geological studies, and they hypothesized that TLS and UAS photogrammetry might considerably reduce survey time during geological studies. At the same time, both technologies produce high-resolution data sets that may be studied in a virtual environment from either a sedimentological or a structural point of view. In addition, once obtained, these datasets can be stored and easily used for future multi-temporal spatial data comparisons at any timeframe and scale, hence boosting any target geological data gathering and analyses at the investigated sites. Once acquired, these datasets can be quickly compared at any timescale.

Later, Šašak et al. [111] compared the processes of terrestrial laser scanning (TLS) and (UAV) photogrammetry as individual approaches for mapping alpine terrain. They proved that the more accurate point cloud produced by TLS could be complemented by photogrammetry's point cloud in regions with insufficient data coverage from TLS. However, the standard deviation of the mutual orientation of TLS scans was on the order of millimeters. In contrast, the precision of the ICP adjustment of the UAV and the TLS point clouds was on the order of several centimeters. They also revealed that the generated (DEM) has a spatial resolution of 0.5 m (Figure 14), which makes it an invaluable resource for mapping any geomorphologic forms and shows the terrain effects of dynamic geomorphologic processes in this region. The product was suitable for the multiscale study and segmentation of land surfaces. Therefore, a highly accurate, comprehensive, and spatially consistent DEM is required to obtain reliable geomorphometric variables that describe the nested hierarchy of landforms and land surface processes.

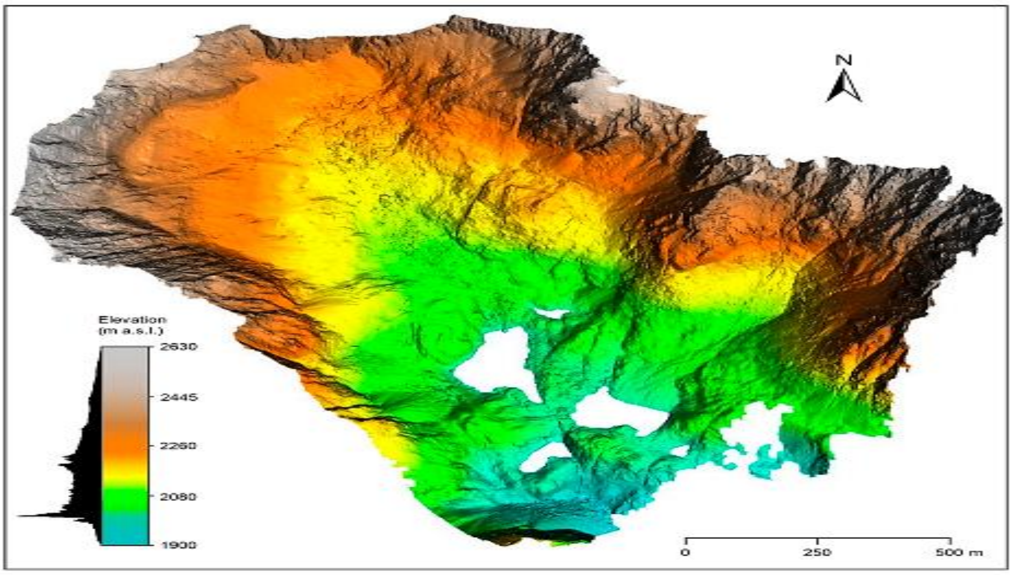

Figure 14: DEM from combined UAV–SfM and TLS. [111]

Cucchiaro et al. [112] studied the correlation between the multiplatform-SfM and TLS data fusion approaches for monitoring agricultural terraces in complex topographic and landcover conditions. They claimed that fusing data based on various methodologies and acquisition platforms is necessary to create accurate (DTMs) that reflect the actual surface roughness of terrace systems and have no gaps in the data, which is necessary to obtain these models. Furthermore, a mix of direct and indirect georeferencing was an excellent approach to reduce the significant annoyance and cost of GCP deployment in inaccessible or hazardous terrains. They showed that a comprehensive and individualized workflow is necessary to achieve accurate data fusion under these difficult circumstances. This workflow needs to consider all concerns with data merging and the land cover conditions. It also needs to include the step of survey planning, the process of co-registration, and the error analysis of the outputs. The high-resolution DTMs created can give a starting point for assessing the land degradation process in these agricultural areas. This information can be valuable to stakeholders for the improved management and protection of such significant heritage landscapes.

Blistan et al. [113] investigated the bulk density of the excavated heterogeneous raw materials, which was determined using the fusion between SfM and TLS approaches. They reported that by applying the developed methodological work frame, determining bulk density for the operative calculation of reserves in the deposit should be quicker. This was because the procedure had been devised. The method used for calculating the bulk density in situ should make the operative computation of stocks of the extracted material deposited in stockpiles easier and more accurate. The methodology was presented and evaluated using several technologies, methods, and procedures for the geodetic determination of volumes following fusing digital photogrammetry and terrestrial laser scanning. When appropriately utilized, these geodetic methods would produce highly accurate findings almost equal to the results obtained in the laboratory. They concluded that the provided in situ method is adequate for the laboratory assessment of bulk and loose bulk density since it is rapid, inexpensive, and precise. This is especially true for deposits that contain a variety of different raw materials. In addition to this, it applies to any other kind of deposit in the process of calculating operative reserves, as well as the calculation of stocks of extracted raw material stored in stockpiles, Figure 15.

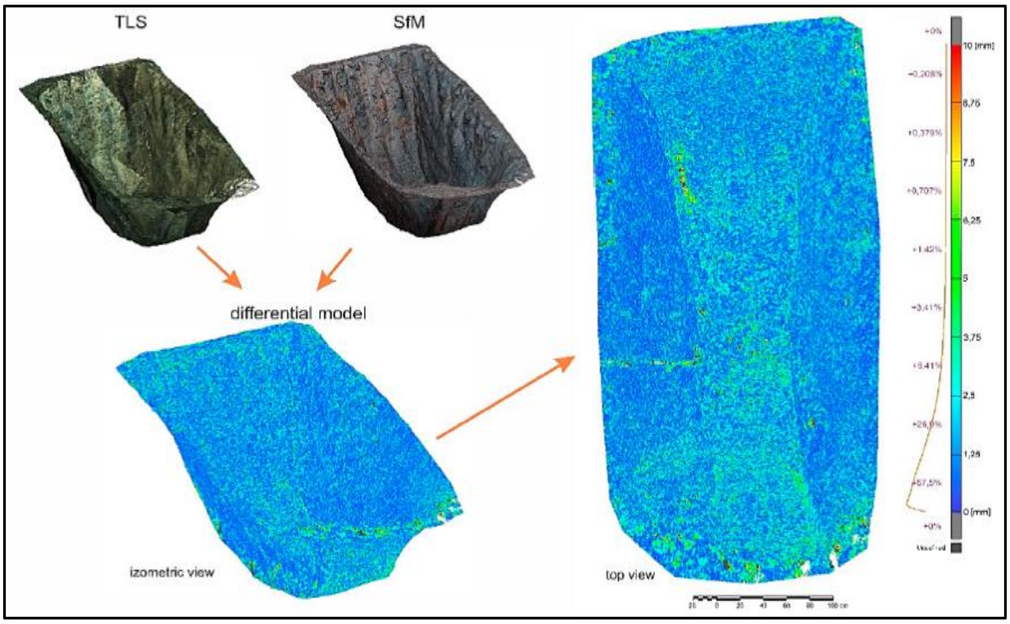

Figure 15: Difference model between point cloud from photogrammetric and TLS processing - probe1 [113].

Guerin et al. [114] quantified the rockfall activity in Yosemite Valley over the past 40 years using an integration model based on TLS and photogrammetry. They determined via change detection that 235 rockfalls occurred from the two monitored cliffs; more than twice as many incidents are recorded in the inventory database of Yosemite National Park. However, the individual rockfall volumes reported in the inventory database differ from those SfM-TLS measures; the cumulative volumes written are comparable to the actual measured volumes. This is likely because big-volume events, which are responsible for most of the cumulative volume, are typically observed by many people and thoroughly documented. According to volume frequency correlations, the cliffs are eroded mainly by rockfalls that occur less frequently but are of greater volume, with rates ranging from 0.9 to 1.7 mm/year. The research demonstrates how integrated SfM and TLS measurements, particularly those that utilize SfM models derived from historical imagery, make it possible to detect and quantify rockfalls that occurred over several decades. This helps improve inventory databases, inform rockfall hazard assessments, and provide longer-term cliff erosion rates.

Abdelazeem et al. [18] employed the multi-sensor point cloud data fusion for accurate 3D mapping, and they claimed that the formed point clouds from every sensor and the fusing point clouds are utilized in various formats, namely the original, de-noised, and subsampled point clouds. The de-noised point cloud dataset is produced by applying the (SOR) filter on the original point clouds. This process removes any outliers that might be present. The M3C2 approach is used to explore the multiscale model-to-model cloud comparison, which in turn helps investigate the relative accuracy of the 3D models. As a point of reference, the TLS-based 3D model was utilized. It has been discovered that the photogrammetric-based 3D model has a better level of precision than the other two models, both for the original and denoised datasets. The fusion photogrammetric/UAS-based model gives a comprehensive 3D model with higher accuracy than the UAS-based model, Figure 16.

Figure 16: Final 3D building model from fusing photogrammetric/UAS and TLS point clouds [18].

Table 1 summarizes the advantages of the applications of combination approaches (Laser Scanning and Photogrammetry) in the experimental and analysis setting, the approach's benefits, and the essential findings from previous studies.

Table 1: Outcomes of selected combination approaches from previous studies.

Study	Site	Data Source	Results / Conclusion
[62]	Temple Heliopolis in Egypt / Hirsau Abbey, Germany	Integration of digital Photogrammetry and TLS	(I) An effective way to overcome the constraints of the standalone data is to combine synthetic images created by TLS with digital photos. (II) The combination approach successfully resolved several difficulties, including occlusions in TLS point clouds, and provided 3D models with better details.
[98]	Magoksa Temple, Republic of Korea	TLS and UAV Photogrammetry	(I) Because of overlapping error estimates between the results of the photogrammetry and laser scanning, the RMS steadily decreases based on the alignment steps, and the effect of the RMS was 0.005 m.
[115]	Historic Churches in Georgia	Fusing TLS, aerial and terrestrial Photogrammetry	(I) The use of laser scanning data and photographs simultaneously resulted in the creation of a 3D model that was superior in terms of both its thoroughness and quality. The average residual error after registrations or photogrammetric assessments ranges from 4 to 16 millimeters. (II) The overall accuracy is about the same as laser scanning, which is approximately 5–10 millimeters.
[116]	Mosaic of Cantillana (Spain)	Compared (TLS) and (SfM) photogrammetry	(I) Photogrammetry with SfM is limited when the object is far from the camera. (II) A further significant restriction applies when the lighting conditions of the surrounding surroundings are unsuitable.
[102]	Illasi Castle in Italy	SfM Photogrammetry and TLS	(I) The results showed that employing the best approach (including drone and SLR shots) resulted in a standard deviation value for comparing point clouds of around 2–3 centimeters, whereas using smartphone images resulted in a matter of 4–7 centimeters.
[105]	industrial chimney in Poland	Integration of TLS and SfM Photogrammetry	(I) Both approaches covered point clouds above 55 m, allowing us to integrate them with an average inaccuracy of 13 mm. (II) TLS and SfM had an internal consistency of a few millimeters and an outward consistency of 10 mm when the scan data was fully covered.
[106]	Oil and Gas Company in Indonesia	TLS and Handheld 3D Scanner	(I) Combining these two techniques resulted in an overall registration error of less than 3 millimeters. (II) In geometrically validating the model's dimensions through reference data and in-situ measurements, the maximum absolute variation recorded was 3.4 millimeters, while the average absolute divergence measured 1.6 millimeters.
[108]	Harzburger Hof, a luxury hotel (Germany)	Integration of (TLS) and (SfM)	(I) point clouds for TLS and SfM photogrammetric were compared, and the results showed a mean difference of around 10 centimeters, with a standard deviation of approximately 1–2 centimeters on the ground. (II) On the roofs, the mean difference was approximately 3–4 centimeters, with a standard deviation of approximately 2 centimeters.
[109]	earthwork sites in the Republic of Korea	Fusing photogrammetry and laser scanning	(I) In the case of photogrammetry-based GCP using point matching registration only, the cloud-to-cloud distance (XYZ) were −0.054 m, −0.0675 m, −0.072m, and 0.0765 m. (II) After including the point matching registration and the ICP registration, the cloud-to-cloud distance (XYZ) was estimated to be 0.04 m, 0.065 m, and 0.117 m, respectively. (III) Following ICP registration, the accuracy was enhanced in three of the four coordinates (0.014, 0.0275, and 0.007), and it was improved by 0.002 in terms of the average of the four locations.
[111]	Alpine Terrain in Slovakia	Combined TLS and UAV Photogrammetry	(I) The mutual orientation of TLS scans had a standard deviation of millimeters. In contrast, the accuracy of the ICP adjustment between the TLS and UAV point clouds was on the order of several centimeters.

[113]	perlite deposit Lehôtka pod Brehmi (Slovakia)	TLS and SfM	(I) The findings of the field in situ measurements (1841 kgm3) and the laboratory measurements (1756 kgm3) revealed that there was only a 4.5% difference in results between the two methods for measuring the density of heterogeneous raw materials. This confirmed the accuracy of the in situ methods that were utilized. (I) The TLS and photogrammetry sensors used a distance of up to 5 meters between themselves and the measured distances. (II) By comparing TLS and photogrammetry models, they achieved RMSE of up to 3 mm.
[117]	Outcrops in the United Arab Emirates and North East England	Comparison of TLS and SfM	(I) When contrasted with the corresponding TLS data sets, it was discovered that the SfM data sets contained various systematic errors. (II) These errors are because the SfM method uses a triangulation methodology separate from the time-of-flight principle that TLS utilizes.

The above research studies reviewed in this article were compiled from the Scopus database (http: //www.scopus.com/). This information was accessed on December 15th, 2023. Two filters were used to identify previous studies: For the standalone approaches, the key terms of "Laser Scanning," "3D scan", "Photogrammetry," "Terrestrial Laser Scanning," "LiDAR," "Aerial Images," "UAV," "3D modeling", "3D Reconstruction", "GIS, "Remote sensing," "Hidden Features," "Digital Preservation," "civil engineering," "construction engineering," "structural engineering," "construction industry," "architecture, "and "Archaeology" were used. The second filter was related to the RS combination approaches. The key terms used were: "Combination Approaches," "Integration," "Fusion," "Merging," "3D modeling", "3D Reconstruction", "Remote Sensing," "Digital Preservations," "Documentation," "structural engineering," "construction industry," and "architecture." Scopus database was used to select scientific publications (Figures 17 and 18). The findings were separated into two categories: (1) standalone and (2) combination approaches.

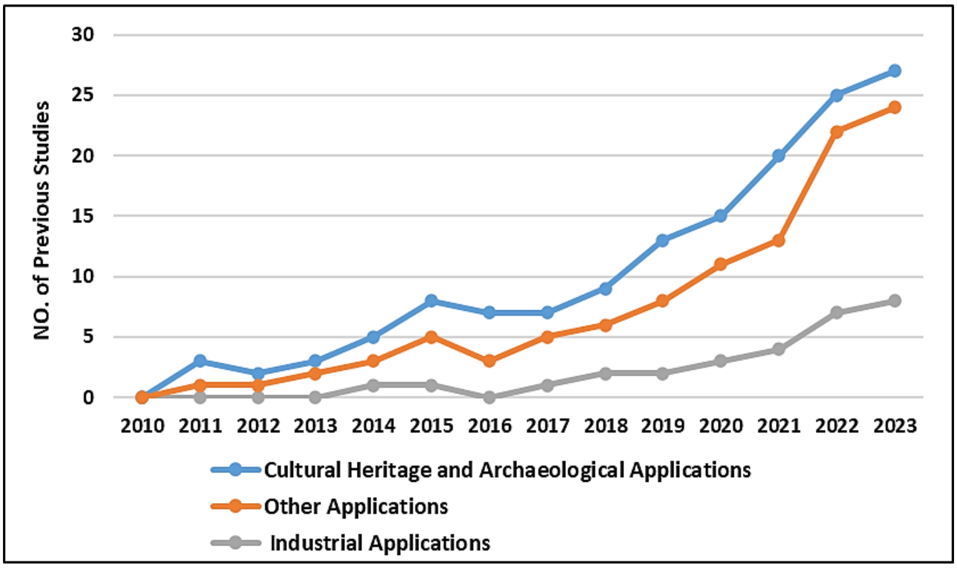

Figure 17: Literature count (2010–2023) extracted from the database Scopus (http://www.scopus.com/) for research that utilized Remote Sensing (RS) standalone and combining approaches (fusion/integration) from 2010 to 2023. The chart demonstrates that there has been a consistent rise in the number of research studies that make use of the applications of fusing LiDAR and photogrammetry.

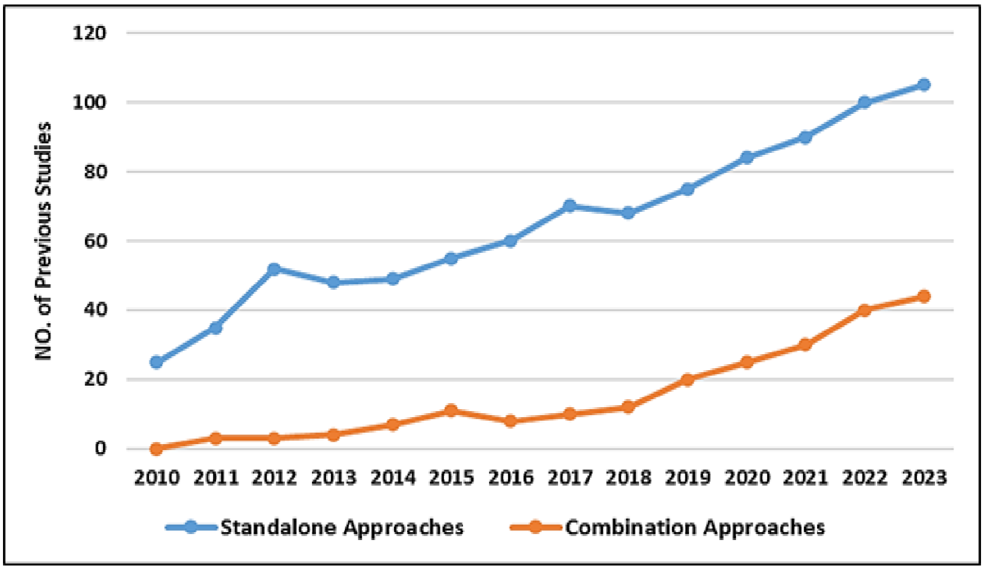

Figure 18: Literature count (2010–2023) extracted from the database Scopus (http://www.scopus.com/) for research that utilized Remote Sensing combining approaches (fusion/integration) in different applications.

4. Summary and Conclusions

This paper presented a general review of 3D modeling approaches from image-based to range-based and the fusion of both approaches. Laser scanning is an approach that focuses mainly on point clouds rather than paying particular attention to the corners and edges of the object being scanned. On the other hand, photogrammetric Dense Image Matching creates dense colored point clouds and focuses on the objects' representational structures. These technologies produce dense 3D point clouds; however, neither has higher quality results; instead, they can complement one another very well. This study reviews the existing integration methods of both output datasets from the two acquisition methodologies to optimize the geometric accuracy and the visual quality of the 3D data gathering for ground scenes.

However, there are limitations to the photogrammetry method that uses SfM-MVS algorithms. One limitation occurs when the distance at which the photographs are taken is not close to the object. In this particular scenario, the distance is comparable to the flight altitude of a photogrammetric aircraft. Another notable limitation is when the environmental illumination circumstances are not ideal; under these situations, the TLS technique is superior, such as in caverns or buildings. On the other hand, it is possible that the issues of modeling the obscured parts, edge borders, and plated surfaces will not be appropriately addressed when using laser data solely. In this regard, the work that has been proposed provides an effective workflow that combines TLS and photogrammetry point clouds to ensure that the whole geometrical reality of the structure is represented with the necessary level of detail.

TLS and SfM photogrammetry are considered complementary assets, as integrating the datasets from both sensors has shown promising results in improving the quality of the generated 3D models [118]. Additionally, TLS and SfM photogrammetry fulfill the 3D modeling requirements for inspection, building information modeling (BIM), multitemporal deformation monitoring, and numerical modeling [119], [120], in addition to enabling the extraction of surface features concerning degradation and physical defects. Compared to traditional remote sensing methods used on their own, co-registration based on remote sensing techniques offers many more solutions, as was shown in the studies highlighted in the previous studies. The integration between them illustrates the complementarity of geometric and color information.

Conflicts of Interest:

The authors declare that they have no conflicts of interest.

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