3D Laser Scanning: A Modern Technology for Optimizing Rehabilitation Solutions for Various Types of Constructions

Doctoral Thesis - Abstract
for obtaining the scientific title of doctor at
University Politehnica Timișoara
in the field of Civil Engineering and Installations
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Chapter 1 – Introduction and general considerations

This dissertation aims to mitigate risks and disasters with economic, ecological, and social impacts by implementing advanced laser scanning technologies to generate precise digital models of various construction types. The reliability of geomatic technologies lies in their ability to acquire, process, and deliver data in a digital format, enabling a wide range of applications. The doctoral research examines the precision modeling of digital constructs using the topo-photogrammetric laser scanning method, exploring the organization and utilization of these devices, the capabilities of associated software, and the structuring of data inventories to support and complement routine inspections, develop a digital database, and review specific applications.

Understanding the sources and mechanisms of hazard formation is crucial for ensuring safe operation parameters for constructions throughout their service life, maintaining economic efficiency and maximum safety. Throughout the study, analyses were conducted on the Herculane Dam, the Wrought Iron Bridge in front of the Imperial Austrian Baths in Herculane, the Huniade Castle in Timișoara, and the Iuliu Maniu Bridge (formerly the Muncii Bridge) in Timișoara to evaluate the effectiveness of UAS (Unmanned Aerial Systems) and TLS (Terrestrial Laser Scanning).

To design a systematic and efficient approach, a technique for quantifying damage through 3D imagery and models was proposed, encompassing image quality assessment and damage measurement based on imagery.

Remote sensing technologies have become indispensable tools in infrastructure assessment, allowing for comprehensive and precise evaluations of various civil structures. These methods enable non-contact data collection, providing detailed insights into the condition, geometry, and behavior of infrastructural elements. By applying remote sensing techniques, infrastructure evaluators can surpass the limitations of traditional methods and gain a more profound understanding of structural health [1].

TLS and UAS provide complementary data collection capabilities, optimizing the precision of infrastructure evaluations. TLS excels in capturing detailed point cloud data, offering millimetric precision regarding geometry and structure [2]. Conversely, UAS equipped with aerial sensors capture high-resolution images, covering larger areas and providing valuable contextual information [3].

Many areas of interest are challenging to access due to their location. TLS is typically employed at ground level, allowing close-range scanning of structures, while UAS offers aerial mobility, accessing hard-to-reach areas on foot. The combined TLS-UAS methods enable the evaluation of structural elements from multiple perspectives and angles, overcoming accessibility constraints and providing a comprehensive understanding of the structure [4].

By automating data collection and reducing the need for labor-intensive fieldwork, the integration of TLS and UAS provides an efficient alternative for obtaining data over extensive areas. This reduces the overall project duration and costs [5].Traditional visual inspections of hydrotechnical infrastructure often require manual measurements and visual observations, which are time-consuming and prone to human error [6]. TLS and UAS technologies significantly enhance data collection efficiency.

Chapter 2 – Emerging TLS and UAS technologies

TLS systems operate by emitting laser pulses and measuring the time required for the pulses to return after reflecting off targeted surfaces. These measurements are utilized to generate highly detailed three-dimensional models, capturing the geometry and spatial characteristics of the infrastructure [7]. TLS systems offer exceptional precision, long-range scanning capabilities, and the ability to capture intricate details of structures, making them invaluable tools for evaluating geometric properties and detecting structural defects in infrastructure [9].

UAS have gained significant traction in recent years due to their versatility and accessibility [10]. Equipped with various sensors and imaging devices, including cameras, LiDAR systems, and hyperspectral sensors, UAS can capture high-resolution imagery, LiDAR data, and spectral information about infrastructure from an aerial perspective. Their advantages include the ability to access hard-to-reach areas, efficiently cover larger surfaces, and rapidly acquire data, making them particularly suited for inspection and monitoring tasks [10].

The integration of remote sensing data with Geographic Information Systems (GIS) involves combining diverse data sources, formats, and scales to create a comprehensive and accurate representation of infrastructure [12]. This integration merges remote sensing imagery, LiDAR point clouds, and other geospatial datasets with structural attribute information, such as construction materials, age, and maintenance history [13].

One of the critical research gaps in hydrotechnical infrastructure is the development of reliable and efficient structural health monitoring techniques. Traditional visual monitoring methods often rely on manual inspections and measurements, which are time-consuming and fail to provide a comprehensive understanding of the structure's condition [14]. The integration of TLS and UAS enables automated and remote monitoring, delivering real-time data on deformation, displacement, and structural integrity.

Hydrotechnical infrastructure is frequently subjected to geomorphological changes caused by sedimentation, erosion, and hydrological processes [15]. Assessing these changes is essential to maintaining the performance and safety of such structures. TLS and UAS provide the capability to capture high-resolution topographic data, facilitating precise and detailed analysis of geomorphological transformations. Further research is necessary to develop algorithms and methodologies for detecting and analyzing changes using TLS and UAS data, aiding in the identification of erosion zones, sedimentation patterns, and their impact on hydrotechnical infrastructure [16,17].

The practical implementation of TLS and UAS integration for real-world infrastructure assessment projects requires addressing numerous challenges to ensure efficient data acquisition and processing. These challenges arise from technical considerations, operational constraints, data management issues, and legal and regulatory requirements. This section examines some of the primary challenges encountered in integrating TLS and UAS systems and presents strategies and solutions proposed by researchers and practitioners to overcome them.

One of the most significant difficulties lies in the compatibility and synchronization of hardware and software components. TLS systems and UAS platforms are typically manufactured by different vendors and may employ disparate data formats and communication protocols. As a result, integrating these systems necessitates careful selection and configuration of compatible equipment and software. Ensuring seamless communication between TLS and UAS systems is essential for synchronized data acquisition and accurate data fusion [17].

Chapter 3 – Types of platforms, hardware and software utilized in the research

The Leica C10 Laser Scanner stands out as a high-precision TLS device extensively applied across diverse fields, including engineering, architecture, archaeology, and cultural heritage conservation. Its advanced technical features make it a reliable and efficient solution for projects demanding detailed and precise documentation of the surrounding environment [18].

From a technical perspective, the Leica C10 offers a scanning range of up to 300 meters, achieving measurement precision within 4 millimeters at a 50-meter distance [5]. Its angular resolution, set at 60 microradians, facilitates the acquisition of highly detailed data from scanned surfaces [19]. Additionally, the scanner achieves a scanning speed of up to 50,000 points per second, ensuring rapid and efficient data capture [20].

Another noteworthy TLS device is the Z+F Imager 5010C, which integrates a calibrated camera for combining vibrant colors with high-resolution scanning data. The High Dynamic Range (HDR) technology incorporated ensures uniform illumination across the scanned target, producing balanced and high-quality color images. This scanner is capable of an impressive scanning rate exceeding 1 million points per second, enabling rapid data collection over extensive distances—capabilities previously achievable only with pulse-based scanners [21].

The Z+F Imager 5010C utilizes a time-of-flight measurement principle, enabling it to calculate precise distances and generate dense point cloud representations of the scanned environment [22]. The scanner's technical specifications include a high scanning rate of up to 1 million points per second, a range extending up to 1875 meters, and a 360-degree field of view. These features facilitate comprehensive and efficient data acquisition, even in complex and diverse environments [23].

The DJI Phantom 4 Pro, a high-performance Unmanned Aerial System (UAS), has become a vital tool in various research fields due to its advanced data-capturing capabilities. It is equipped with a 20-megapixel camera capable of recording 4K resolution images, enabling the collection of visual data with exceptional quality and detail. These attributes make the DJI Phantom 4 Pro particularly suitable for applications requiring high-resolution imagery, such as environmental monitoring, land mapping, and infrastructure inspection [24].

Chapter 4 – Acquisition and processing of data

In Romania, the operation of drones is governed by a series of laws and regulations that ensure airspace safety and respect for privacy and public security.

The Romanian Ministry of Transport’s Order No. 8/2014 regulates the use of UAVs in Romanian airspace, specifying requirements for registration, certification, and operation. This regulation aims to align national legislation with European standards and ensure a high level of safety and security in drone usage [25].

The use of terrestrial laser scanners (TLS) in Romania is governed by a legislative framework that ensures both the precision and reliability of measurements and compliance with data protection and privacy standards. TLS use is regulated by several normative acts that oversee surveying and mapping activities as well as the protection of collected data. These include Law No. 7/1996 on cadastre and real estate advertising, updated through multiple amendments, and Law No. 190/2018 on measures to implement EU Regulation 2016/679 (GDPR). Law No. 7/1996 stipulates that surveying and mapping activities must be performed by authorized personnel and in accordance with technical standards established by the National Agency for Cadastre and Real Estate Advertising (ANCPI) [26].

One approach to planning data acquisition involves dividing the infrastructure into smaller sections and designing scanning and flight paths for each section. This ensures adequate coverage and reduces the potential for data gaps or redundancies. Additionally, consideration of the limitations of TLS and UAV systems, such as scanning range and flight autonomy, is essential for determining the number and arrangement of scanning positions and flight paths [27]. A common optimization goal is to maximize coverage while minimizing flight distance and time. This can be achieved by considering factors such as flight altitude, camera field of view, and image overlap requirements. Optimization algorithms and their variations can be used to determine the most efficient flight path that covers the infrastructure area with minimal redundancy [28].

To achieve the most accurate dataset, it is crucial to select optimal scanning positions. This process relies on analyzing coverage and point density requirements, taking into account factors such as the size, complexity, and geometry of the structure, thereby ensuring adequate data acquisition. Selecting appropriate scanning angles is a critical step for capturing desired information and minimizing occlusions.

To ensure precise alignment and registration of aerial images, georeferencing is a vital stage. Georeferencing involves assigning spatial coordinates to images by referencing known ground control points (GCPs). Control points are identifiable ground features with precisely measured coordinates. The use of GCPs allows for correcting geometric distortions and ensures that each pixel in the image corresponds to an exact location on the terrain.

Noise removal or error correction is an essential step in point cloud processing to enhance data quality and accuracy. Point cloud data can be affected by various types of noise that may arise during the data acquisition process. Noise can be introduced by sensors, environmental factors, or errors in the measurement process.

Noise removal algorithms identify and eliminate points that significantly deviate from the expected point distribution. These algorithms can be based on statistical measures, such as the median absolute deviation (MAD), or on distance-based approaches, such as statistical outlier removal filters [26].

Algorithms to remove erroneous points identify and remove those that deviate significantly from the expected distribution of points. These can be based on statistical measures such as the median absolute deviation (MAD) or on distance-based approaches such as the statistical dropout filter [26].

Chapter 5 - Case studies

5.1 Using terrestrial laser scanning for the documentation and preservation of Huniade Castle

The conservation of cultural heritage, such as Huniade Castle in Timișoara, is imperative due to natural degradation and human-induced factors. In the early project planning stages, a detailed assessment of the castle is conducted to identify optimal scanning areas. The Leica C10 scanner is employed for data acquisition, with calibration and georeferencing processes ensuring precision.


Fig 1. Visible signs of damage

The focus is placed on critical sections requiring rehabilitation, involving collaboration with stakeholders to align project objectives with the conservation and restoration needs of the castle. The scanned data is processed using Leica Cyclone software for scan alignment and the creation of a cohesive model, employing RGB color values to enhance object identification and analysis.


Fig 2. Huniade Castle - current status and point cloud data (Cuzic O.Ș. 2016)

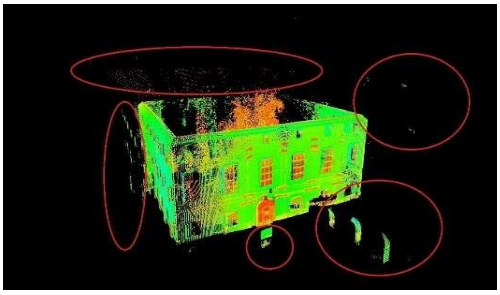


Fig 3. Residual noise (Cuzic O.Ș 2016)

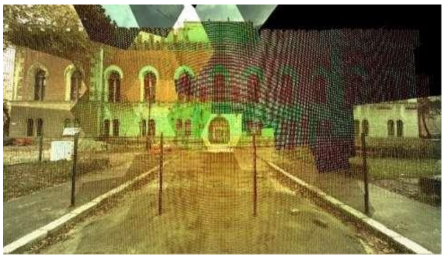


Fig 4. The images captured by the scanner C10 superimposed on the point cloud (Cuzic O.Ș. 2016) (Cuzic O.Ș. 2016)


Fig 5. Limitations of TLS capture in areas with dense vegetation

A point cloud obtained with TLS can be converted into a textured 3D polygonal mesh. Typically, a 3D polygonal mesh consists of triangles, but in certain applications, it may include quadrilaterals, simple convex polygons, concave polygons, or polygons with holes. These 3D polygonal meshes can be overlaid with colors recreated from the images of the object captured by the laser scanner.

The rehabilitation of Huniade Castle has involved various consolidation interventions over the years, but the soft soil has led to unsatisfactory results. Rehabilitation projects have been revised multiple times, and a new project initiated in 2006 is currently ongoing, supported by the Ministry of Culture. Given the architectural and historical complexity of Huniade Castle, detailed and precise documentation is essential, making 3D laser scanning an indispensable tool.

Thus, integrating 3D laser scanning into the documentation and conservation process of Huniade Castle represents not only an evolution in architectural research technology but also a means of preserving and passing on the historical and cultural richness of this emblematic monument. By employing this advanced technology, new perspectives are opened for understanding and safeguarding cultural heritage.

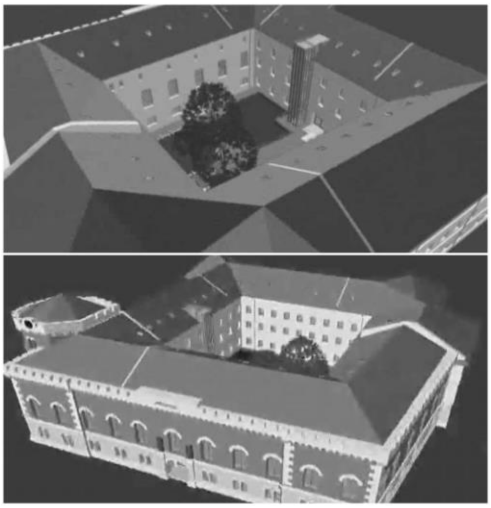


Fig 6. The 3D model of the building (Cuzic O.Ș. 2016)

This approach not only optimizes the process of documenting and preserving cultural heritage but also unlocks new opportunities for researching and interpreting the history and evolution of architectural structures. Consequently, 3D laser scanning has become a valuable tool in the field of cultural heritage conservation, providing an efficient and precise method for documenting complex historical and architectural sites such as Huniade Castle. These technologies enable the creation of detailed 3D models while contributing to the protection and enhancement of cultural heritage for future generations.

5.2 Using TLS technology for the evaluation and restoration of the Wrought Iron Bridge of Herculane

The conservation of cultural heritage and the rehabilitation processes of iconic structures such as the Imperial Neptune Baths and the cast iron bridge reflect past engineering achievements, ensuring their longevity and honoring their historical significance. Data acquisition involved utilizing six strategically positioned measurement stations around the bridge to achieve a comprehensive representation. The density of the point cloud is crucial for identifying essential elements such as edges, corners, joints, and architectural details. The spacing between neighboring points is adjusted according to the project objective to ensure accurate rendering.

Fig 7. The degree of degradation of the bridge

Fig 8. The current condition of the bridge

High-resolution scanning captures extremely detailed images of the metal structure, including ornaments and specific architectural elements. However, this process is time-intensive, resource-demanding, and requires specialized equipment to ensure data accuracy. The substantial volume of data generated imposes high demands on storage and processing, which can pose challenges for efficient data management. While the absence of targets may affect data precision, subsequent analysis demonstrated that the results were reliable and provided a solid foundation for infrastructure management.

Fig 9. Scanning the facade and the bridge of iron Herculane

Fig 10. Establishing the optimal locations of the laser scanner (Cuzic O.Ș. 2022)

The application of TLS scanning to evaluate the cast iron bridge represents a modern and effective method, applicable to various civil engineering and built heritage restoration projects. Capturing data at six stations using the Z+F 5010 scanner at maximum resolution took approximately six hours, including equipment relocation and preparation time for each scan. Data alignment was performed in Z+F LaserControl software using the point-to-point method, eliminating the need for targets. This method is efficient and rapid, ensuring precise alignment of raw data while eliminating systemic errors.

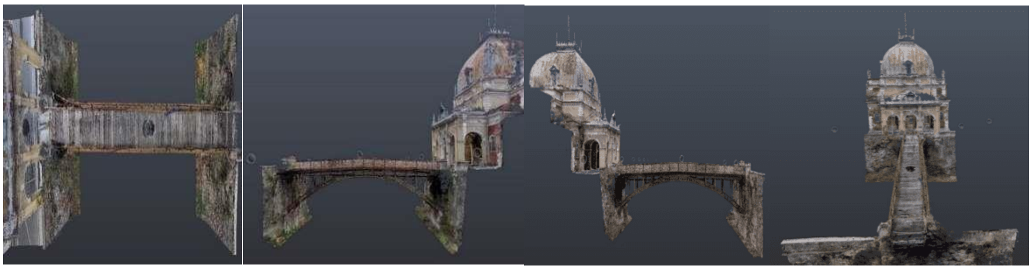


Fig 11. Rendering in the form of a dense point cloud of the iron bridge and the main entrance (Cuzic O.Ș. 2022)

Periodic TLS scans can identify and compare changes in the bridge surface conditions, structural deformations, or signs of deterioration over time. This monitoring process aids in evaluating the success of conservation interventions, informs adjustments to maintenance strategies, and ensures the long-term durability of the bridge. By capturing detailed point cloud data, TLS enables comprehensive visual evaluation, precise documentation, structural analysis, and monitoring of conservation efforts. Additionally, integrating TLS enhances public engagement and education, promoting the appreciation and conservation of these cultural treasures [27].

5.3 Application of UAS technology to the Iuliu Maniu Bridge (Muncii Bridge) in Timișoara as decision support in the rehabilitation of the structure

Over time, the structural elements of the bridge, including the infrastructure, riverbanks, riverbed, roadway, and sidewalks, have undergone significant degradation. Given the advanced state of deterioration and the current and future traffic demands, rehabilitating the bridge is essential to ensure traffic continuity while enhancing safety and functionality.

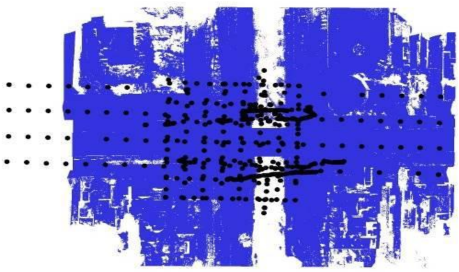


Fig 12. Camera locations and flight plan (Cuzic O.Ș. 2022)

Fig 13. Point cloud extracted from captured images (Cuzic O.Ș. 2022)

To accurately reflect the current condition of the structure and facilitate the planning and execution of rehabilitation work, a detailed digital model of the bridge was created. Due to the large size of the bridge, high traffic volumes, and hard-to-access areas, an appropriate UAS system, specifically a DJI Phantom 4 Pro quadcopter equipped with an FC330 12-megapixel camera, was used. Image capture involved multiple carefully planned flights to cover the entire bridge, each flight lasting approximately 30 minutes due to battery limitations.

Image processing included importing and organizing the photos in a logical sequence, automatically detecting common reference points between overlapping frames, and performing geometric camera calibration. This process corrected optical and geometric distortions, ensuring accurate reconstruction of the structure. The final 3D model reflects all structural details of the bridge and is essential for structural analysis and planning rehabilitation work.

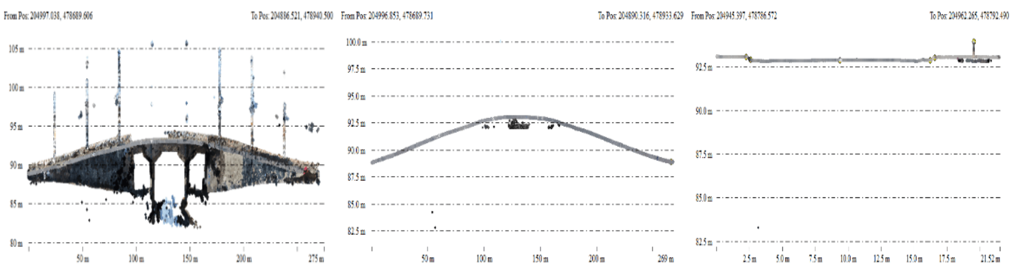


Fig 14. Longitudinal section of the bridge and highlighting of the roadway

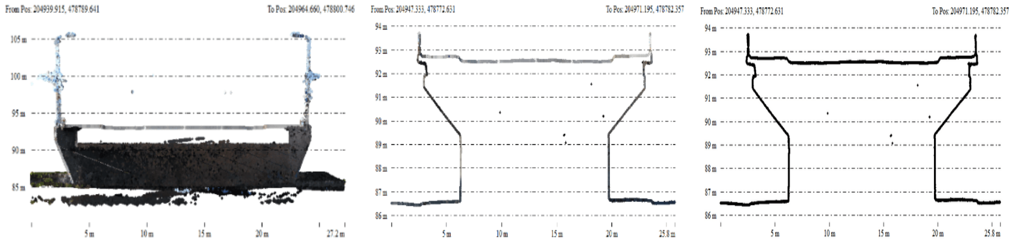


Fig 15. Cross-sections of piers and superstructure

In total, 495 images were obtained from various distances during all flights. The entire data processing took 18 hours, including image alignment, point cloud densification, 3D model construction, and texturing. The resulting digital model provides a faithful representation of the bridge's current state, serving as an essential tool for structural inspection, condition assessment, and planning maintenance and rehabilitation efforts.

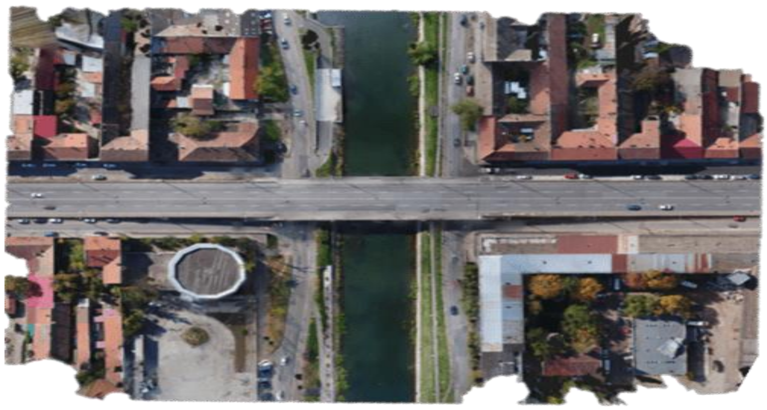


Fig 16. Orthophotoplan of the Iuliu Maniu bridge (Cuzic O.Ș. 2022)

Ensuring data quality guides the selection of equipment and techniques based on project objectives. Deteriorated components can be meticulously documented and extracted from 3D models, facilitating in-depth studies with centimeter-level accuracy. Applying high-resolution images for 3D polygon mesh texturing allows for both geometric and visual inspection directly on the generated 3D model. Despite technological advancements, a standardized approach for evaluating specific monitoring and inspection criteria is lacking. Implementing a systematic methodology is crucial for providing diverse perspectives on quality and assessing 3D measurements in terms of potential errors.

5.4 Optimizing the visual inspection of the Herculane Dam using TLS technology

Massive concrete dams require regular evaluation and monitoring to ensure structural integrity and safety. These complex structures are subject to significant stress factors, making constant evaluation essential for preventing defects and major risks. Integrating TLS and UAS scanning technologies provides a robust solution for obtaining detailed data and conducting precise analyses of such structures. The studied dam has significant height and spans a wide valley, making it challenging to evaluate and monitor using traditional methods. By integrating TLS-UAS, high-resolution data were captured, enabling the analysis of the dam's condition, deformations, and vulnerabilities.

For the evaluation and monitoring of the concrete arch dam, a combination of TLS and UAS platforms was used.

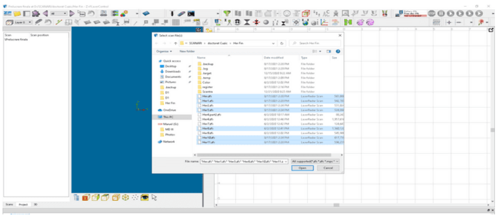


Fig 17. Loading scanning stations

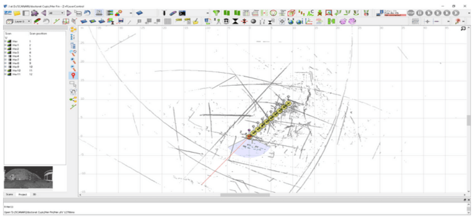


Fig 18. Display of data capture stations without geofencing

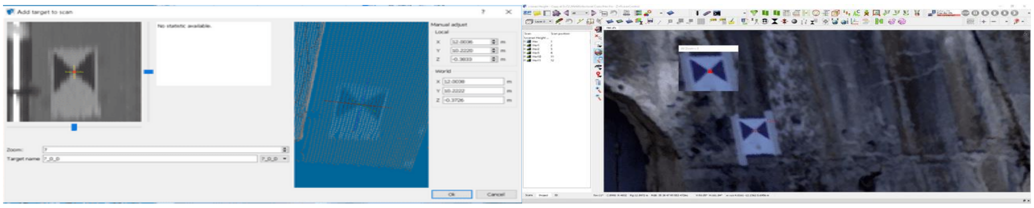


Fig 19. Georeferencing based on determined targets

The point cloud data obtained through TLS were registered and aligned to generate a comprehensive 3D model of the dam structure. This data provided a multi-level set of information, facilitating detailed analysis and visualization of the dam's condition, deformations, and potential defects. Integrating these technologies allowed for much more precise and detailed evaluation compared to traditional monitoring methods.

Based on the analysis of data obtained through TLS and UAS, a comprehensive risk assessment was performed, identifying potential vulnerabilities of the concrete arch dam. Quantitative information obtained from data analysis, including crack dimensions, surface defect measurements, and deformation patterns, facilitated an accurate risk evaluation. This information, combined with expert knowledge and safety guidelines, enabled engineers and decision-makers to prioritize maintenance and repair actions, efficiently allocate resources, and implement preventive measures to reduce risks and ensure the dam's long-term stability. Thus, this technology has demonstrated its utility in enhancing the safety and operational efficiency of large dams.

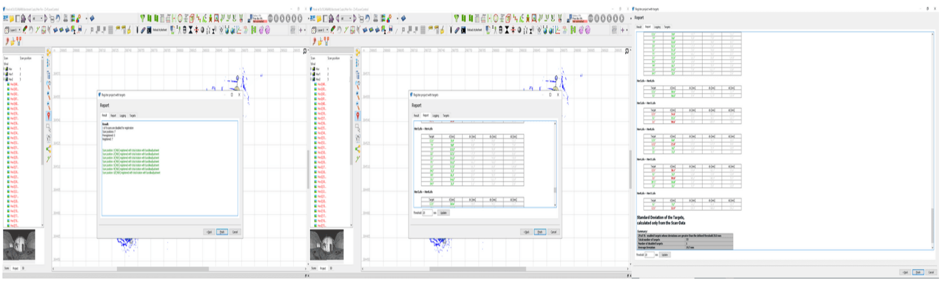


Fig 20. Generation of alignment report and analysis of existing errors

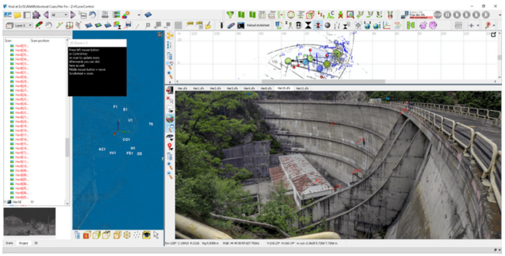


Fig 21. Previewing a scan

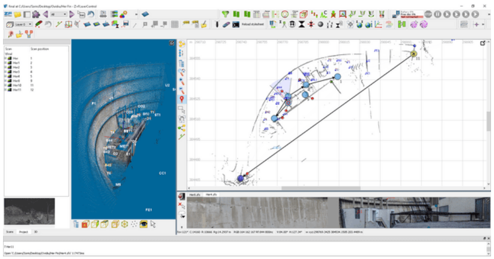
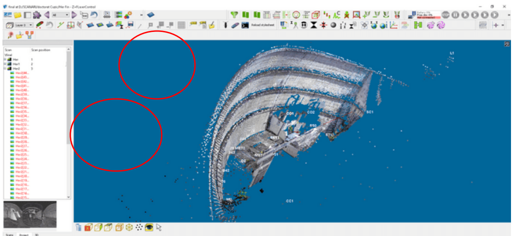


Fig 22. Georeferencing of all stations through GCP

The rugged terrain and dense vegetation required scans from multiple positions, linked using precise targets for efficient connection of scanning stations. Scanning positions were precisely established before starting fieldwork, considering topography, operator safety, and scanner characteristics.

To ensure georeferencing accuracy, 17 reference points (GCPs) were placed. The scans were conducted in August 2021, under favorable weather conditions and with a low reservoir water level. The scanning process involved 8 different positions and lasted approximately 14 hours. The raw data were imported and processed, and the point cloud was cleaned of errors and noise to obtain an accurate 3D model. Filtering and cleaning the point cloud involved using median and bilateral filters, removing isolated points and speckle noise. This complex process demonstrated the effectiveness of 3D laser scanning technology in dam monitoring and evaluation, contributing to improved safety and maintenance.



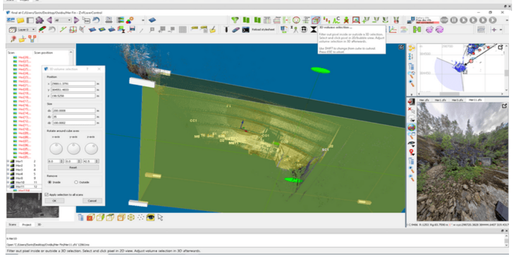


Fig 23. Laser propagation errors Fig 24. Creating a bounding box

The scanning study of a concrete dam using a laser scanner demonstrated the efficiency and utility of advanced technology in documenting and analyzing massive and complex structures.

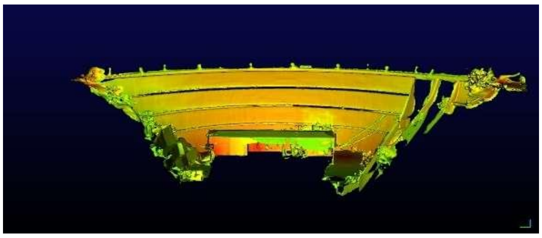


Fig 25. Poisson type surface

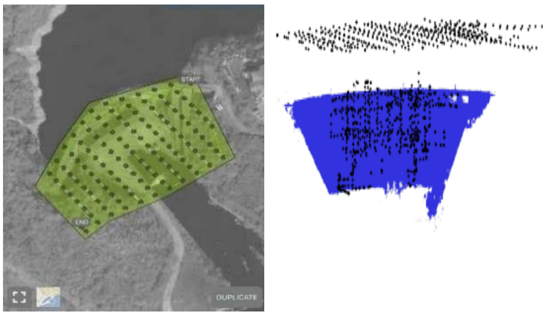
Fig 26. The final 3D model

reconstruction

The results highlighted the advantages of 3D laser scanning in civil engineering and structural conservation, offering an efficient way to monitor the dam's evolution over time and plan maintenance or repair measures. Moreover, the precision and details obtained through scanning with the Z+F 5010 Imager opened new perspectives in structural analysis and risk assessment associated with hydrotechnical infrastructures. Evaluating the total scanning error is essential to ensure the accuracy and reliability of collected data and to avoid undesired consequences, incorrect structural design, or irregularities in subsequent monitoring and maintenance of the dam. To minimize the total scanning error, careful planning and implementation of the scanning process, along with rigorous data analysis and obtained results, are necessary.

5.5 Optimizing the visual inspection of the Herculane Dam using UAS technology

In the same data capture session of the Herculane Dam using TLS scanning technology, a UAS drone was also employed to generate a detailed 3D model of the structure. The proximity photogrammetry technique was essential for data acquisition and processing, capturing the entire structure of the dam through high-resolution images taken from various angles. The flight plan and image capture zones were developed to ensure complete coverage, and the flight report was prepared to document the conditions and results.



Number of images:	1,089	Camera stations:	1,069
Flying altitude:	48.8 m	Tie points:	509,758
Ground resolution:	1.17 cm/pix	Projections:	3,132,548
Coverage area:	5.12e+003 m²	Reprojection error:	0.779 pix

Camera Model	Resolution	Focal Length	Pixel Size	Precalibrated
FC6310 (8.8mm)	5472 x 3078	8.8 mm	2.53 x 2.53 μm	No
FC6310 (8.8mm)	5472 x 3648	8.8 mm	2.41 x 2.41 μm	No

Table 1. Cameras.

Fig 27. Flight plan, image capture zones and flight report

The first two flights were preset in the DJI software, at an altitude of 30 meters, with the camera oriented at a 90-degree angle. The third flight was manually conducted to cover the entire complex structure of the dam. During the third flight, images were captured at intervals of 3 seconds, both vertically and horizontally, to ensure full coverage.

The georeferencing network initially established for the TLS scan was also used for the data captured by the UAS drone. The 17 control points identified on-site with GPS and used for TLS were also utilized for the UAS data collection. The goal of having a single georeferencing network was to obtain accurate digital models and facilitate the merging of the two digital models captured with different techniques. Of the 17 control points, 7 were placed on the ground and 10 on the structure at different heights. The GPS positions were determined in real-time (RTK) using the Stereo 70 projection system. Ground control points were marked with black-and-white models and had an overall accuracy of 0.5-1 cm, and were used to convert data into national coordinates.

Fig 28. Classification of errors according to location

The 3D geometry reconstruction of the dam uses information about the position and orientation of each image to determine the shape and structure of the object. After generating the base 3D model, the software adds textures and details to improve the visual appearance of the model.

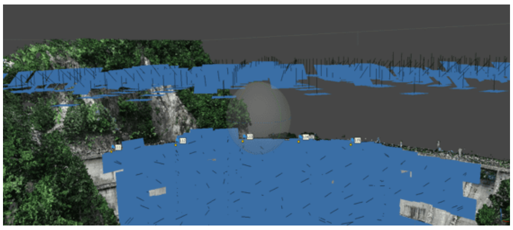


Fig 29. Visualizing the UAS image set on the 3D model of the Herculane dam.

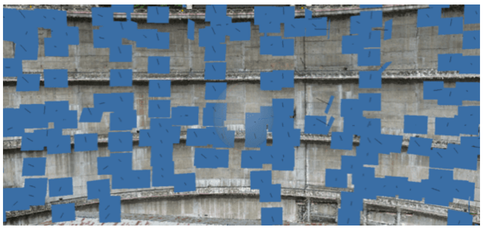


Fig 30. An aerial perspective obtained from manually guided flight

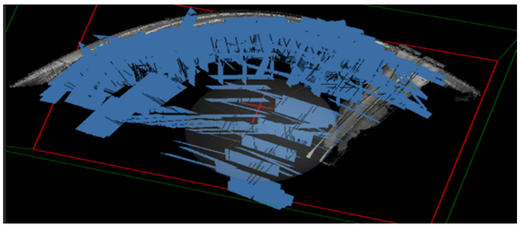


Fig 31. Visualizing the obtained photo set providing a detailed perspective

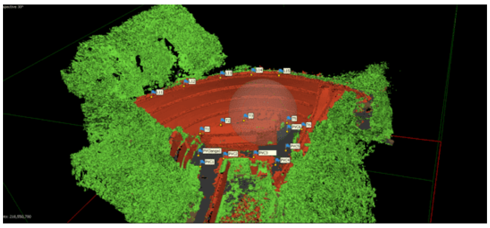


Fig 32. Selecting the dam from the point cloud and separating it from the entire scene

The point cloud densification phase adds additional points in regions with reduced detail, improving the quality and accuracy of the data. Densification can be achieved using interpolation or extrapolation algorithms, filling in the gaps in the point cloud. The mesh generation process transforms the point cloud into a 3D model or a network of polygons representing the surface of objects and terrain. This process can include triangulation of the points, model texturing, and adding additional details to obtain an accurate and detailed representation.

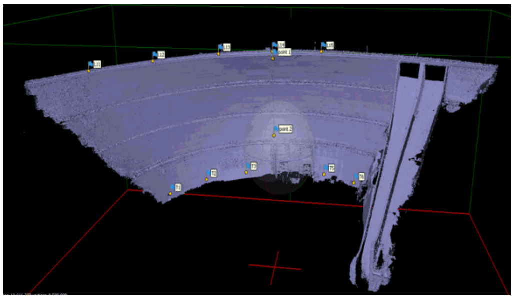


Fig 33. The process of transforming a set of 3D points in to a tetrahedra mesh

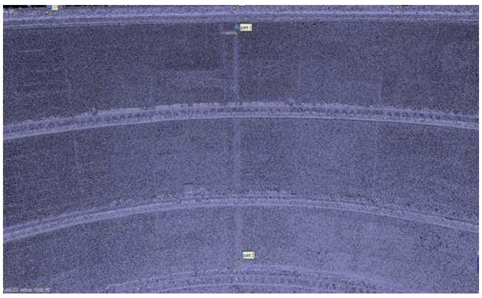


Fig 34. Mesh into wireframe mode

A total of 1,089 photographs were captured from the three flights, resulting in approximately 20 GB of raw and processed data. The processing timeline involved 41 hours and 25 minutes, including image matching and alignment, depth map generation, point cloud densification, and texturing. The hardware resources required included 64 GB of RAM, an Intel Core i7-6700K processor, and a GeForce GTX 970 GPU.

Fig 35. The 3D model of the Herculane dam without texture

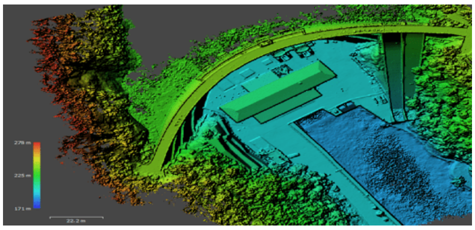


Fig 36. DEM-Digital Elevation Model (11699x10128, 2.34cm/pen)

Fig 37. Orthophoto plan of the dam

In the pursuit of developing a comprehensive and detailed 3D model, the data acquisition process plays a crucial role, influencing the richness of the final result. Therefore, optimizing scan locations, using targets and GCPs, considering camera resolution, and understanding the optimal operating parameters of the equipment are valuable steps to achieve optimal results.

Challenges related to data acquisition and collection, improving noise removal techniques, and optimization algorithms for 3D reconstruction in post-processing can influence the quality of point clouds. Key concerns include weak or absent GPS signals, calibration degradation, battery-life-limited flights, dependence on weather factors, lack of image overlap in UAS-based photogrammetry, and poor laser beam diffusion or reflection in TLS. These factors can lead to the production of low-quality point clouds, along with defects such as inaccurate geometric positioning and noisy datasets with uneven point densities. Ensuring data quality for civil infrastructure inspection guides the choice of appropriate equipment and techniques based on objectives. Damaged components can be meticulously documented and extracted from 3D models, facilitating in-depth studies with centimeter accuracy.

5.6 Generation of a hybrid 3D model by merging UAS and TLS datasets

By combining data captured by the Z+F 5010 Imager, known for its accuracy in capturing fine details, with high-resolution aerial images obtained using the DJI Phantom 4 Pro, which offers extensive perspective and coverage, it is possible to create a comprehensive 3D model of the arch dam at Herculane. This synergistic approach brings significant benefits to the detailed analysis of the dam structure, identifying potential problems or damages, and planning and monitoring maintenance or improvement works. It also provides valuable information for assessing and monitoring the health and integrity of the dam. By integrating data from these two complementary sources, a comprehensive three-dimensional model is obtained, serving as a valuable tool for engineers and specialists involved in managing and preserving the arch dam at Herculane.

This initiative represents a significant step toward achieving a deeper and more precise understanding of the structure and topographical features of this vital construction. This hybrid approach combines the strengths of both data acquisition methods, offering a comprehensive solution for documenting and analyzing complex structures. The 3D models obtained through the two methods were aligned and integrated using the open-source software CloudCompare, resulting in a complete hybrid 3D model.

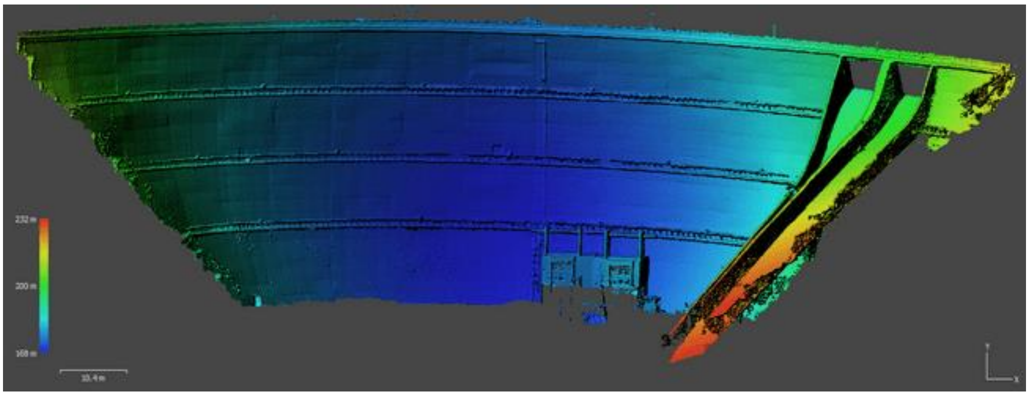


Fig 38. Merging the two data sets

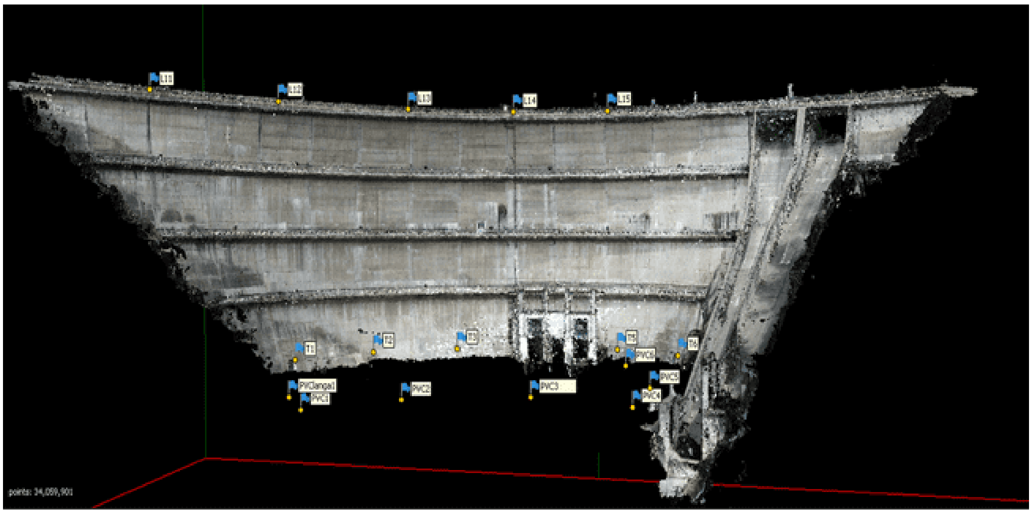
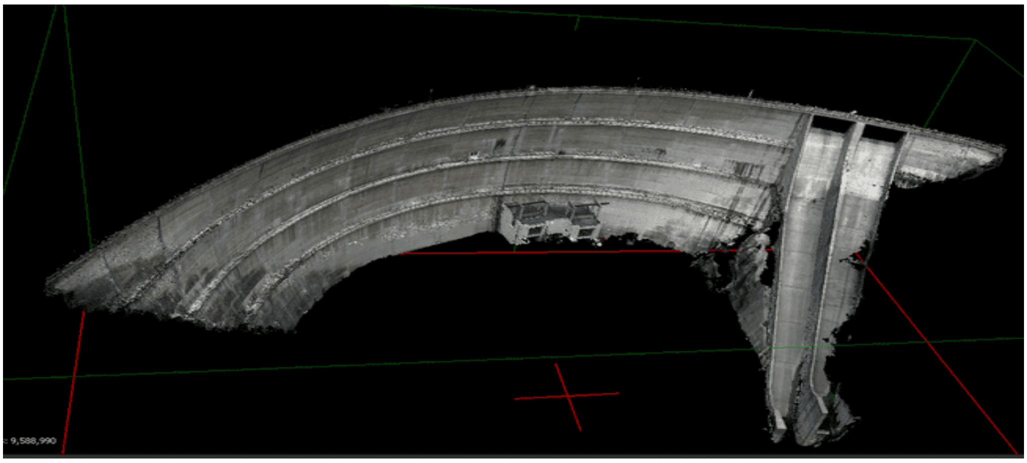


Fig 39. The resulting 3D model

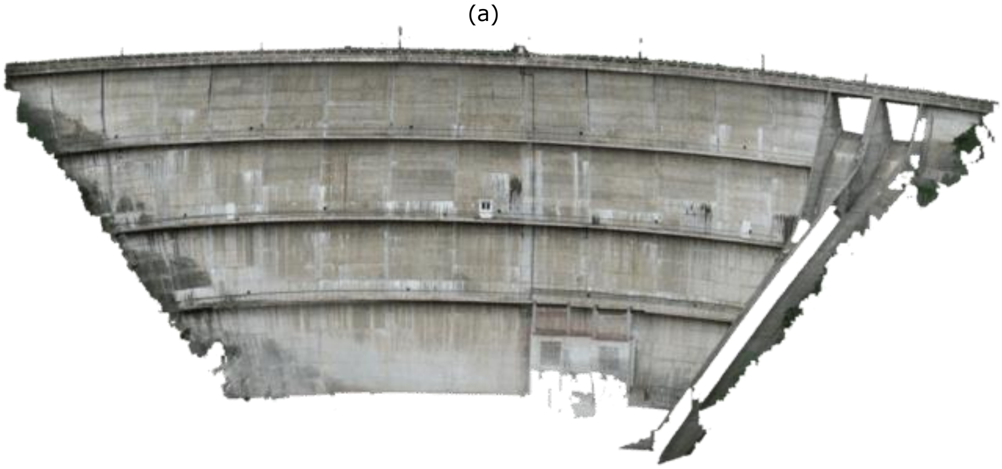
The 3D model provides a detailed and accurate representation of the dam with the following benefits: geometric accuracy through the combination of laser scanning and photogrammetry data, which allows millimeter accuracy of the 3D model; rich texture obtained from aerial photography that adds realism and detail to the 3D model; full hybrid 3D model information integrating details from both data sources providing a comprehensive picture of the dam and surrounding area.

The hybrid 3D model of the Herculane dam can be used for a variety of applications including structural monitoring, detection and analysis of deformations, cracks or other damage to the dam structure; maintenance planning that facilitates the organization of repairs, maintenance work and modernization projects; simulation and modeling through hydraulic applications and dam stability analyses.

Processing and fusing data from independently collected TLS and UAS technologies, each technique providing unique terrain and structure information, involved several critical steps from data capture to obtaining a unified and accurate 3D model of the dam in the arch of Herculane.



(a)



(b)

Fig. 40 (a, b). The resulting 3D model after data fusion

After aligning the two sets of points, the position of the 3D UAS model was adjusted to perfectly match the TLS point cloud. Using the iterative method that minimizes the distance between points more precisely the ICP algorithm. Data from both sources were fused by minimizing the distance between the corresponding points between the two models and merging the data from both sources. To remove duplicate or redundant points, statistical filters or distance-based filters and density-based filters were applied that combine points from both point clouds by weighting the contribution of each point according to its quality. After applying the filters, the resulting data were inspected and analyzed to check the quality of the fusion and the integration of details from both sources to extract useful information about the Herculane Dam. Each data capture technique comes with specific advantages and limitations, and combining data from multiple sources allows us to compensate for these limitations and obtain a more complete representation of the terrain. It is the result of a complex combination of technologies and data processing methods that help improve our understanding of this important engineering goal. This integrated three-dimensional representation allows us to explore the structure of the dam in detail, identify possible defects or damage, and assess its overall state of preservation. It can also be used for planning and managing dam maintenance and rehabilitation projects, helping to improve its safety and sustainability. It is an eloquent example of how modern data capture technologies can be used to support the conservation and management of civil infrastructure in a more efficient and sustainable way.

The efficiency of each method is determined by the expected results and will be based on criteria such as the nature of the object, the operating conditions, the size of the objective, etc. Considerations regarding functionality and operability by applying the two methods in certain circumstances highlight the limitations, weaknesses and strengths of each technology.

Total annual costs for the TLS Z+F 5010 Imager are significantly higher than those for the DJI Phantom 4 Pro UAS. This major difference is largely due to upfront equipment costs, software and data costs, and long-term maintenance and operating costs. Although the cost of the DJI Phantom 4 Pro UAS is lower, the accuracy and resolution achieved with the TLS Z+F 5010 Imager can justify the extra expense for projects that require maximum accuracy and fine detail. The choice between the two technologies must take into account the available budget, the specific requirements of the project and the level of detail and precision required in the data obtained. For projects that do not require such high accuracy or fine detail, the DJI Phantom 4 Pro UAS may be a more economical and cost-effective option.

Current laser scanning data acquisition practice relies on human intuition for planning scan locations and acquisition parameter settings at each selected location. However, construction sites are complex and ever-changing environments, making it impossible, even for experienced surveyors, to guarantee that the acquired point clouds fully cover all scan targets with the specified quality levels.

The complexity is further increased by the fact that scanners have different technical performance, and all targets captured from an entire construction site may have different data quality requirements.

The results indicate that the integration of TLS and UAS offers significant advantages in the field of civil infrastructure assessment. By combining the strengths of TLS and UAS technologies, it becomes possible to capture high-resolution data, create detailed three-dimensional models, and visualize complex structures with high precision. This enables a comprehensive and multi-scale representation of the infrastructure, enabling the identification of structural defects, the assessment of structural integrity, the detection of damage and deterioration, the analysis of deformations and displacements, and the quantitative assessment of structural health. In addition, the case studies presented in this research demonstrated the effectiveness of integrating TLS and UAS technologies in support of visual inspection, cultural conservation and the rehabilitation process.

Chapter 6 - Global Conclusions, Original Contributions and Future Trends in Modern Technologies

6.1 Original contributions and future developments regarding the use of modern technologies

The original contributions to this study are summarized as follows:

1. Development of a methodology for integrating data from multiple sources, including terrestrial laser scanning (TLS), aerial imagery, and field data, to create more complete and accurate 3D models.
2. Implementation of advanced data processing technologies for dynamic monitoring of structural conditions and the use of drones with multispectral

cameras to identify and monitor areas with potential stability or structural deterioration issues.

3. Application of augmented reality technologies to facilitate inspection processes and diagnose structural issues.
4. Development of predictive models based on chronological and current data to assess the risks of structural failure.
5. Introduction of cloud-based data management solutions for the efficient storage and access of large datasets from diverse sources.
6. Integration of geomatic technologies into the planning and design processes for the maintenance and repair of civil infrastructure.
7. Use of geospatial technologies for detailed monitoring of hard-to-reach areas within hydrotechnical structures.
8. Creation of customizable and interactive 3D models to help engineers and designers visualize and analyze relevant structural data intuitively.
9. Evaluation of the effectiveness and accuracy of each technology depending on the type and characteristics of the analyzed structures, including dams, bridges, and other infrastructures.
10. Assessment of the performance of combined scanning systems under varying weather and lighting conditions to identify optimal operational conditions and potential limitations.
11. Optimization of scanning parameters such as altitude, tilt angle, scan density, and image resolution to achieve the best results based on specific project objectives.
12. Development of data capture mission planning strategies using UAS to optimize flight paths and ensure complete and uniform surface coverage.
13. Assessment of the feasibility and effectiveness of UAS technology for detailed documentation of civil structures such as bridges, dams, and cultural heritage sites, highlighting its advantages and limitations.
14. Investigation of environmental factors such as wind, temperature, and humidity on data capture systems' performance, particularly their impact on image stability and quality.
15. Development of strategies for efficient data storage, processing, and analysis of large datasets generated by 3D scanning of complex structures.
16. Evaluation of the financial impact of using UAS and TLS systems for detailed infrastructure documentation, including initial acquisition costs, operational costs, and long-term benefits.
17. Implementation of calibration and error correction systems to ensure accuracy and consistency in data obtained from TLS and UAS, especially for large and complex structures.
18. Highlighting the performance of combined scanning systems compared to traditional inspection and monitoring methods to determine the advantages and limitations of each approach.
19. Feasibility study on using drones and laser scanners for continuous monitoring of infrastructure conditions to identify potential problems early and schedule interventions effectively.
20. Analysis of the impact of 3D scanning technologies on the safety and reliability of infrastructures, aiming to identify and eliminate potential deficiencies and vulnerabilities.

21. Examination of how 3D scanning impacts the efficiency and cost-effectiveness of rehabilitation and maintenance processes to optimize costs and productivity.
22. Exploration of the applicability of 3D scanning technologies in architectural and urban planning to improve precision and detail in project development.
23. Investigation of the role of 3D scanning technologies in the design and rehabilitation of critical infrastructures such as roads, bridges, and dams to enhance durability and reduce risks.
24. Analysis of decision-making and project management processes in civil engineering and construction to optimize efficiency and performance.
25. Development of technologies and strategies for disseminating 3D scanning research outcomes to promote its adoption among industry professionals and the public.
26. Optimization of alignment and registration processes for data obtained from UAS and TLS to ensure coherence and accuracy in the generated digital models.
27. Examination of education and professional training in civil engineering to promote a better understanding of modern concepts and techniques.
28. Application of 3D scanning technologies in archiving and conserving cultural and historical heritage to preserve and promote their value for future generations.

6.2 Future perspectives in the field of research

Future research directions in civil engineering include integrating underwater scanning technologies with terrestrial laser scanning to create detailed 3D models of hydrotechnical infrastructures, developing risk simulation and analysis tools for evaluating the impact of extreme events, and creating hybrid models for structural performance analysis. Advanced communication technologies and machine learning applications are also critical for automatic defect detection.

Additional research domains focus on leveraging advanced monitoring technologies for natural risk management and developing predictive and decision-making systems based on artificial intelligence performance. These trends aim to improve the durability, resilience, and sustainability of civil infrastructure while adapting to climate change challenges.

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