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Remote Sensing Method In Cultural Heritage Analysis And Constructive Pathology Diagnosis

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Abstract

Terrestrial laser scanning (TLS) techniques have been tested by both academic and commercial communities since the early 2000s to digitize architectural, archaeological, and cultural assets. However, most applications have adopted a descriptive approach, creating documentation and cataloguing of cultural heritage (CH). After more than two decades of pioneering research, a three-dimensional (3D) acquisition process has been developed. The use of digital restoration models has been difficult, and their goals have remained unclear for a long time. Current approaches are increasingly developing model-based comparison methodologies, either for detecting building pathology or for architectural and archaeological investigation. This study falls into the latter category. The technique and method presented in this work have the particularity that they are not based on comparison, but solely on the analysis of the surveyed model.

The method was tested on the oldest minaret in Algeria and the 1,000-year-old Agadir Mosque minaret in the Province of Tlemcen, where the geometric differences between the vertical parts, which are equal by definition, were identified and analysed. In addition, potential lesions and deformations of the structures were studied. This means that the technique can be used on any other vertical structure of any type, and can be replicated.

Keywords: Terrestrial Lidar, Survey, Building Pathology, Analysis, Diagnostic, Cultural Heritage.

1 Introduction

The digital preservation of heritage has become a key issue in the years to come. Besides, the digital tools are focused on the growing concerns to bring new spatial and digital mapping, data analysis and modelling technologies to the architectural and cultural heritage discipline

1. The increasing destruction of historical monuments and sites is taking place in countless forms. Documenting our cultural legacy has been shown to be more necessary than ever. The entire 3D digitization process involves the reproduction of digital data. Currently, the most accurate and rapid method is the application and development of 3D Laser Scanning Technology (TLS), which is particularly effective for the exterior space of historic buildings (Ullrich et al., 1999; Raimondi et al., 2015; Vacca, 2022; Doneus et al.,2020).

This research is being put up as a contribution to the discussion surrounding reverse modelling in the context of cultural heritage. In addition, the advancement of data-capturing methods in recent years, particularly Terrestrial Light Detection and Ranging (TLS), offers the opportunity to create new processes for the research and diagnosis of architectural heritage (Boardman,2018). A variety of integrated methodologies and non-invasive methods have been used to examine vertical constructions from point clouds and gather pertinent data. Similarly, this work involves an inquiry using several integrated approaches for geometric information extraction, data analysis, and the creation of a 3D mathematical model that is trustworthy from a formal and cultural standpoint.

TLS is an active remote sensing method used for 3D data gathering. Light Detection and Ranging (LiDAR) is an active sensing method. More than 20 years have developed a 3D acquisition method based on TLS, which has been shown to be an effective instrument for the reconstruction and preservation of structures (Costa-Jover et al., 2018; Costa-Jover et al.,2017). Terrestrial laser scanning (TLS) is an efficient technology for gathering 3D data and texturing structures, with little involvement of the structure itself.

The goals of employing 3D digital models, which demand costly tools and a lot of labour, beyond recording and preservation, or descriptive approaches, remained obscure for a very long time (Davis et al.,2017; Pesci et al.,2012; Berndt, 2000; Shih, 2000; Rahaman et al.,2019).

Geometrical deformation assessment is critical in CH, and many studies have devised simple strategies to address the deformation of ancient structures using point-cloud data.

However, methods for comparison, assessment, and analysis based on digital models have recently been developed (Fryskowska, 2018 Kushwaha et al., 2020). Evaluation of geometric distortions is crucial for preserving the architectural past. Numerous studies have devised procedures using point-cloud data to deal with the deformations of ancient structures. Finding pathologies in cultural assets is also part of its focus on architectural and archaeological inquiry. This study falls into the latter category.

Similar work on assessing the mechanical behaviour and constructive and structural deformations of constructions is essentially based on a comparative study between two digital surveys, T0 and T1. Subsequently, we performed fusion of the two models using software such as Cloud-Compare or 3DReshaper. We then identified points of wear and differences (Arias et al.,2022). This method is used in engineering to identify points of wear in mechanical parts.

Another method compares a digital mock-up that acts as a reference model and displays geometric reference qualities with the model created by the TLS survey. It is necessary to merge the two surveys and reference models before identifying the points and axes of deviation (Cheng, 2012).

The final method, which is comparable to ours, is based on survey model sections that are only used in their geometric centers. This enables the evaluation of Y- and

Z-axis deviations (Ali Khodja et al.,2019; Mechiche, 2020).

The case study demonstrated in this research is the minaret of the Agadir Mosque, located in the city of Tlemcen, Algeria (latitude 34.88942 N Longitude -1.30013 W).

The term Agadir, which in the Berber language means "the fortress" on the ruins of Pomaria, an ancient Roman military post. In reality, this mosque was built between AD 789 and AD 790 on the remains of an old basilica by Idriss 1st, and it is considered one of the oldest mosques in Algeria. Furthermore, the mosque has been shown to be in ruins (by progressive abandonment since the 14th century), which could not cross the centuries by imposing minarets together with some traces of walls. The minaret built later was attributed to Yaghmoracen, a king of the Zianides dynasty in the 13th century (Yahya, 1913).

The Minaret is quadrangular in shape (Lafer, 2023) with a square base, 26.60 m high, and consists of a foundation made of stones, which is a re-employment of Roman stone bearing Latin inscriptions, up to a height of 6 meters (Figure 1). Moreover, above this brick tower, the four façades are decorated with arcatures. In addition, small openings were intended for the enlightenment of the staircase. The upper platform is a lantern that crowns the whole. Being square in shape, it is 4.70 m high and 2.40 m wide, and it is square in shape. It is crowned by a small cupola, the top of which is decorated with a diamond-shaped decoration and multifoil-arch, alongside a green ceramic frame that completes the whole (Merzoug, 2012).

In fact, a terrestrial laser scanner is an appropriate tool for the entire 3D digitization process. Subsequently, we resorted to the same during our study to be put into digital form the Agadir Mosque in Tlemcen, particularly its minarets. Above and beyond, this non-invasive technique allows the digitization of built cultural heritage. However, it is concerned with the process of data acquisition in the form of point clouds and then in the form of 3D modelling. In virtue of this, the entire digitization process involves the three-dimensional scanning and reproduction of digital data. Currently, 3D laser scanning technology has been shown to be the most accurate and fast-performing technology, mainly for the exterior space of historic buildings.

Additionally, geomatics applications in the field of cultural heritage have several objectives, such as the study and documentation of objects, structural monitoring in support of restoration, integration with non-invasive diagnostic techniques, high-precision replication, creation of databases, and anastomosis for visualization and exploration.

Figure 1. Picture of the Minaret of Agadir.

Materials and methods

Digital surveying, LIDAR technology, and computer modelling techniques have replaced conventional methods of surveying and sketching as a result of recent technological advancements. However, these new approaches provide fresh possibilities in areas such as autonomous orientation and measurement processes, point cloud-based 3D data production, digital surface modelling, and WEB representation of cultural heritage.

Much construction data needs to be captured on the site because heritage conservation is a continual activity that requires a large amount of data to be integrated, obtained, and examined. Surveying, drafting, engineering design, follow-up, and analysis are other workflow and procedures included (Santagati et al.,2013; Bertocci et al., 2019).

The significance of an analytical methodology in the examination and appraisal of architectural elements, particularly vertical elements, was explored in this study. The study was initially centred on the acquisition of data at the site using both Terrestrial LIDAR and standard measurement methods with a Leica Scan Station P16 Laser Scanner. The selection of an object is based on its characteristics, including its shape, longevity, and resistance to natural occurrences (earthquake, rain, material wear, etc.).

Indeed, the survey methodology proposes the use of simple procedures for assessing surface alterations with regard to the minaret, based on an on-site TLS survey. It should be emphasized that this study avoided studies on material properties and focused on architectural information and structural diagnosis. Above and beyond, the scanner used in this case is a Leica P16, a model that allows a very simple and fast survey process, main technical features delivering the highest quality 3D data and High-Dynamic Range (HDR) imaging at an extremely fast scan rate of 01 million points per second at a range of up to 270 m.

Using trigonometric triangulation, laser scanners can precisely record 3D shapes with millions of points. To put it more properly, they operated the reflection and projection of the laser beam. Nevertheless, the 3D scanner measures the distance between various locations on the object and the focal point, as it scans it with a laser beam. In addition, the scanner recorded the cloud points of the actual space. In addition, a 3D laser scanner similar to a top-notch digital camera was used in this study. However, the uncertainty of the derived model was less than 01 mm at 60 m. We employed an integrated and planned scanning job for the entire building that originated from several separate scanning stations and could combine a set of multiple view perspectives (scanning mode) to acquire 3D data related to the structure.

To recreate the body of the minaret from the exterior and vestiges of the Agadir Mosque, twenty-two (22) scan positions were necessary.

In light of the above facts, this work for Minaret totalled more than 22 survey stations on the site. The assembly of different point cloud stations into a workstation and merging them into a single model of the data generated a digital model of more than 185 million points (Figure 3). In Meshing's operation using the 3Dresharper software, more than 60 million triangles were generated in a mesh. However, the accuracy of the mesh was less than 1.5 mm. These results can be improved by multiplying the number of stations.

The methodology refers to the application of digital techniques to analyse data obtained from TLS surveys. The software used was Leica Cyclone, 3Dreshaper and Cloud-compare.

The objective is to identify a workflow to verify the initial hypotheses regarding structural and constructive deformations of the building that are not visible to the naked eye and cannot be obtained with traditional measurement systems. This was achieved through an exploratory data analysis. Finally, the identified technique must be easy and reproducible on elements identical to the object of study.

This study was divided into three stages.

The first step in documenting-built heritage is the difficulty in the classical surveying of complex architectural forms and structures with difficult access. The advantages of TLS techniques in terms of surveying are no longer questionable.

The second stage of documentation with a simplified workflow using specific software tends to render the object in 3D (digital restitution process).

The third and most important step is to conduct an evaluation of the geometric and architectural components of an object. With an understanding of constructive and structural problems, tools and processes.

Discussion and Results

The workflow based on TLS generally consists of four phases for initiating digitization]. Hence, the process starts with the generation of a point cloud by terrestrial LIDAR technology, followed by a cleaning process on the workstation and merging of the different stations to generate meshes (meshing process), in addition to a phase of reconstitution of the object's surfaces by digital rendering. The other processing phases represent the model production. The diagnostic workflow (Figure 2) is demonstrated with the following explanations.

- The first phase that uses TLS is the acquisition of raw point-cloud data to reconstruct the surfaces of the case study across several stations. To acquire raw data via TLS, the integrated scan job must plan for the entire object originating from several different scanner stations that can combine a set of multiple view orders (scan worlds). Moreover, the major steps in combining multiple views are positioning, planning, and accurate registration. Such information is organized in the form of a token ring or star topology.

- The second phase is performed by a computer through cleaning, merging, and recording of the different workstations operated on the site to generate the minaret in a single unified point cloud in raw data.

- The third phase represents the modelling of the point cloud (meshing) to generate surfaces by using reverse engineering software to process these raw data (cloud points), such as "Meshlab" (open source), "Cloud-Compare" (open source), and "3DReshaper." Above and beyond, this consists of using a triangulation algorithm to transform the point clouds into a 3D mesh and then converting them into a 3D model. In light of which, this phase implies mainly the transformation of the data and the reconstruction of the 3D geometry of the object.

- In closing, the digital expertise works on the object (the minaret of Agadir) to analyse the architecture and dimensions thereof and to diagnose the deteriorations suffered by its structure.

The survey examined how straightforward methods, based on a TLS survey, worked to analyse the state of conservation of masonry walls, with an emphasis on the exterior surface. Some of the damage was obvious, but the method used made it possible to swiftly, easily, and without contact to identify and quantify damage that was not visible to the naked eye. This method is based on a comparison of the number of vertical and horizontal portions of the object on the created mesh model.

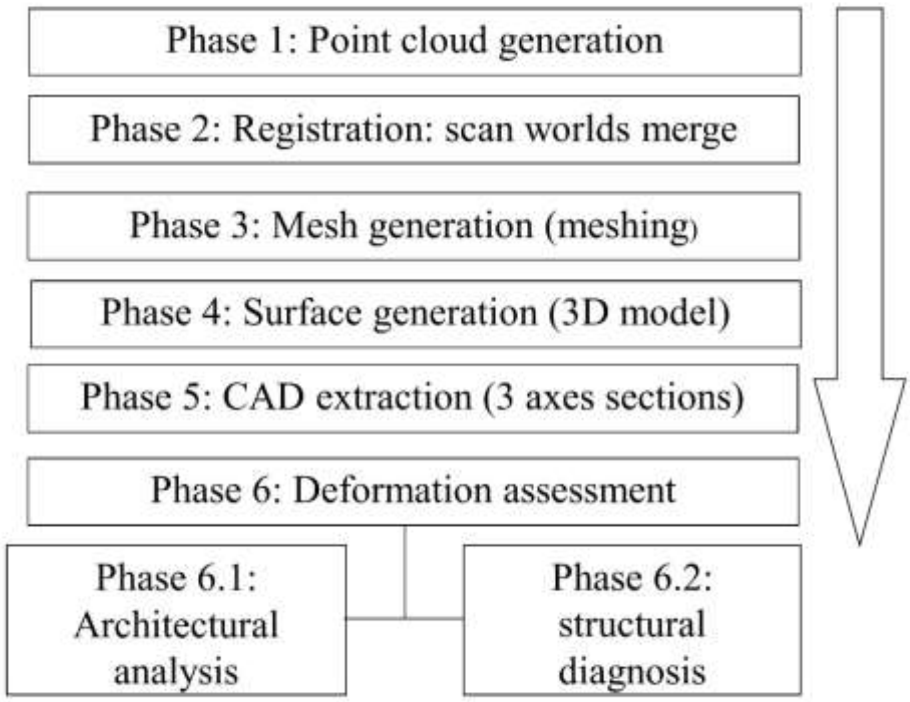

Figure 2. Methodology for capturing, modelling, and workflow.

During this workflow phase, the interest consists of choosing the control sections of the 2D geometry in the three axes (X, Y, Z) by placing a section of the plan on the textured object (Figure 4), the number of sections (53 sections, each half a metre in our case); their spacing depends, for sure, on the nature of the object treated, but also on the precision required, particularly for restoration or diagnostic operations. Likewise, it is possible to extract the geometry of a 2D section from a point cloud instead of the object in the mesh, using a section of the plan; however, in this case, the precision of the edges and contours is not useful for precise diagnostic work.

In the next step, once the 2D geometry of the sectional plan is created on the object, it is mandatory to isolate them for use in a 2D computer-aided design (CAD) representation. After colouring the sections separately, they were merged. Additionally, once a series of sections (the number and spacing of which depend on the precision of the work) has been obtained along the three axes (X, Y, Z), it is essential to merge the 2D representation. At this stage, we can distinguish the differences between situation 01 in 2D and situation 02 on the predefined XYZ axis.

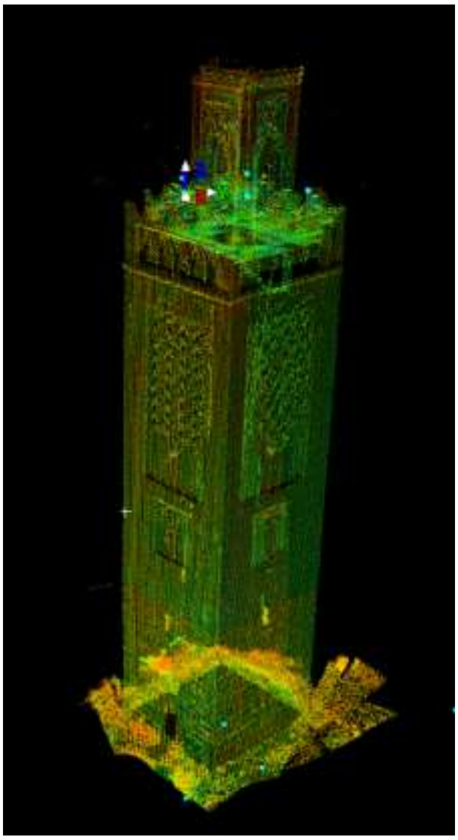

Figure 3. Cloud. point rendering of Minaret.

As for the architectural analysis work, it has alike been based on orthophoto plans generated by the object and the 3D dimensional calculation on the object produced by the workflow. Thus, this work made it possible to check all dimensions with great accuracy and inspect the verticality and deformation of the monument.

The Mesh elevation allows the entire surface of the minaret to be represented in a single-metric-scale image. Thus, the inspection map complements this information and reveals the different textures identifiable on the wall. Based on these two documents, it is easy to accurately identify and identify the main problems and degradations pertaining to the structure, such as differential settlements and torsion at the top.

In addition to diagnosing constructional pathologies, digital surveys via TLS can illustrate unknown facets of the implementation of historic structures and provide valuable documentation on the techniques under use.

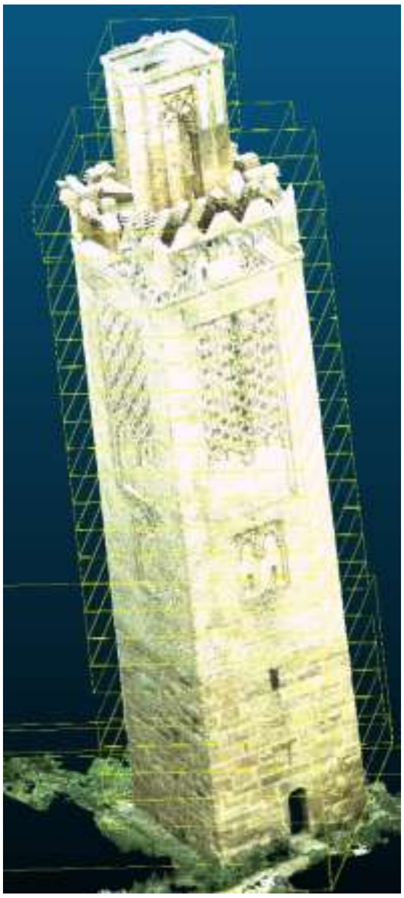

Figure 4. Cross-sections of minaret.

1.Architectural analysis: The study of the object has allowed the identification of elements that have not been addressed in previous studies on this heritage object, as well as on its construction. Nevertheless, the fact of this analysis work is that the minaret is really not a quadrangular shape as assumed in many works, but the study of the sections on the Z axis and Y axis have demonstrated that from the stone base at the height of 6.73 m, the minaret has a pyramidal shape with a deviation of 0.08 m on each side, in total reduction of 0.16 m on both sides corresponding to an angle of 0.8 degrees per vertical corner (Figure 5).

Another important fact is the construction of a stone base in sandstone at exactly the third of the height, and then the rest of the pyramidal form with full baked brick; this provision is already known in Roman architecture (Tronquoy, 1880; Delagardette, 1823).

The shaft is typically shaped like a truncated cone, but it is solid with the largest bulge around the first third of its height. It can be monolithic, formed from a single piece of granite, stone, or marble, but it can also be composed of two different materials (Jones, 2003; Adam, 2005; Summerson 2023). This shaft shape was frequently reused in Muslim architecture at the time, consisting of vertical elements to provide a foundation in a dense material in the base (sandstone with a density of 2100 to 2350 kg/m3), and the rest of the height with a less dense material (full baked brick has a density between 1500 and 1800 kg/m3). This building method lowers the compound centre of gravity relative to the geometrical centre of gravity (Figure 5). Because of this, the layout provides monument stability in the medium seismically active Tlemcen region.

2. Diagnosis of constructional pathologies: Evaluation of the sections of the three axes illustrates the main formal differences between the minaret and reference forms. Consequently, the results must be interpreted, as most of them may be related to deviations during the construction processes rather than to stability problems. In this regard, comparison with a reference plan has been shown to be indispensable, as well as a comparison between the different plans of the obtained sections. Nevertheless, torsions at the top of the minarets were observed in this study, accompanied by a slight settlement on the western side. This remains minimal for monuments that are over 800 years old. Also, these slight deformations affect in no way the durability of the structure of the object which, it must be said, has a solid foundation, which is the secret of its stability.

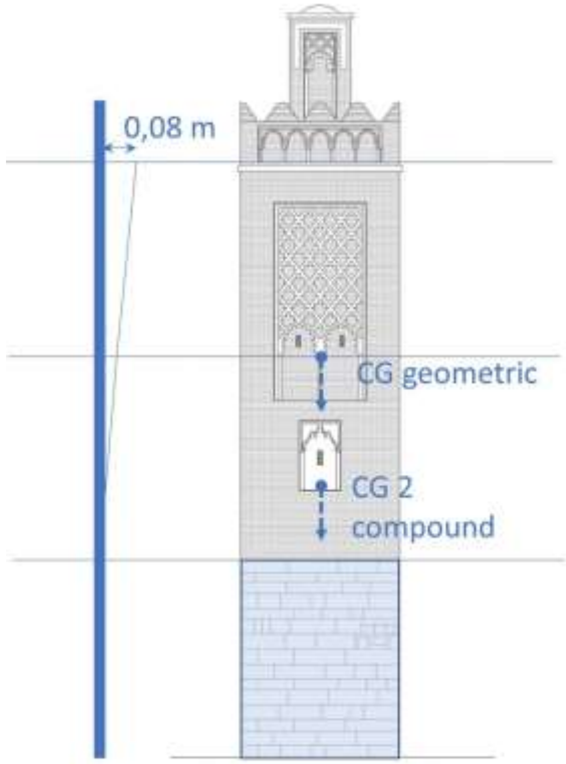

Figure 5. This figure shows the lowering of the centre of gravity and pyramidal shape of the minaret, which allows for better stability.

Conclusion

In this study, a technique was used to analyse the architecture of a cultural asset and diagnose constructional pathologies. It focuses on a double level of discussion: on the one hand, it contributes to the debate on the whole process of remote sensing applied to CH in the field of architecture and cultural heritage, and on the use of the technique for the documentation of the cultural object and its restitution in a digital model; on the other hand, it is a study on the possible uses of the model for its analysis and diagnosis.

In conclusion, the procedures tested made it possible to identify unknown constructive elements and to recognize degradation processes in the outer wall and formal deviations. These time-consuming procedures were performed manually using the CAD software, and further research will focus on automating these diagnostics using digital readings.

In this work, point clouds through the modelling of a historical monument with a particular geometry have proven to be an information model framework offering the potential for documentation, expertise, protection, and conservation of monuments. In addition, the techniques tested have allowed for easy characterization of the degradation processes of the minaret exterior wall, particularly with regard to its stability (which is now quantified with accuracy) and its features (which have not been noticed). Future research will focus on automating the procedures and testing other useful data that can be obtained from TLS for diagnostic purposes.

There is no single method that is best in general, as this depends on the specific needs in terms of accuracy, surface quality, cost, and time. Hence, it is recommended that different methods be tested to determine which method is most suitable for specific needs.

Despite the fact that 3D digitization procedures are heterogeneous and complex, including those that take place in computer laboratories, this technology has been shown to be an open door to specialists working on all forms of tangible cultural heritage. In light of this, this research paper does not present details of algorithms or implementation technologies, but sheds light on the framework and benefits of this approach for cultural heritage through TLS, not only for documentation and archiving purposes but also for analysis and diagnosis.

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