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Automated Structural Analysis for Historic Building Preservation Using Point Cloud Data and Parametric Design

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Abstract The maintenance and compliance assessment of historic buildings' structural health plays a crucial role in the conservation and preservation of the built heritage. The conformity inspections of the existing structures are conducted using traditional and manual methods. The latter can be susceptible to error, time-consuming, and labour-intensive, frequently relying on manual checks and measurements. The present paper proposes a work methodology that combines 3D scan technology and parametric design tools. This combination aims to develop an automated point cloud-based script responding to the efficient evaluation and analysis of the construction structural elements. The script is also expected to provide ease of use and reduce the cost and effort associated with structural maintenance. The initial focus of our investigation is on the portal frame selected as the first structural element of analysis, with particular attention given to the phenomenon of lateral displacement as a deformation type. The process mainly consists of the collection of point clouds representing the current state of the supporting element, which are then uploaded to the Grasshopper visual programming language. This results in creating a custom workflow and an automatic algorithm that begins with processing the point clouds and culminates in identifying the deviation and the displacement value. Following application to a 0.5cm displacement prototype, the methodology is validated as highly accurate, suitable for decision-making, and simple to use with an intuitive interface relying principally on point cloud uploading.

Keywords Structural Analysis, Displacement Detection Automation, Historic Building, Point Clouds, Parametric Design

1. Introduction

It is a fundamental tenet of historical and cultural studies that buildings with intrinsic cultural, architectural, and historical features constitute the collective memory, identity, and wealth of every civilization. The preservation of built heritage not only ensures the perpetuation of these values for future generations but also enhances the functionality of contemporary urban infrastructure. This, in turn, contributes to the sustainability of cities [1]. The effective maintenance of these buildings requires the implementation of ongoing architectural and structural maintenance measures. Architectural features must be maintained in accordance with their traditional uniqueness and complex character. The structural elements must also be capable of withstanding the effects of various climatic changes, the passage of time, and natural events. It is of great importance to undertake regular monitoring of the structure of the historic building to ensure its longevity, safety, and durability. This enables the various changes undergone by the construction to be identified, including displacements and cracks [2]. Indications of deterioration are thus discerned, enabling intervention over time to avoid serious structural damage.

For deformation detection, several research projects have been conducted employing a variety of methods for the assessment of the structural integrity of historic buildings. Direct contact methods, including displacement detectors, GPS, levelling techniques, plumb line methods, and visual inspection [3], require a considerable degree of manual intervention and effort. These methods are perceived as traditional due to their time-consuming nature and susceptibility to human error. Conventional surveying instruments, such as total stations, have also been employed for static angle and distance measurements, yet their dynamic performance remains limited [3]. Conversely, advanced techniques, such as laser scanning (TLS) and photogrammetry, are becoming increasingly preferred and adopted, as they facilitate the detailed capture of multiple points of the structure [4] and the generation of more accurate 3D models for structural anomalies detection. Comparative studies between modern and traditional technologies concluded that modern methods provide accurate and reliable results. One such study was conducted in the context of monitoring cracks in reinforced concrete structures [5].

The integration of advanced algorithms with imaging technologies serves to improve the accuracy and efficiency of deformation detection in structural assessment [6, 7, 8, 9]. This enables real-time analysis and facilitates proactive maintenance strategies through the addition of automation to the process. By employing advanced algorithms, the research can efficiently automate the processing of large-scale point clouds, thereby enabling rapid analysis [10]. Moreover, the results can be noise-reduced, leading to a cleaner and more reliable output, and the magnitude of building height changes can be detected [11]. Additionally, a detailed examination of the building over time can be established by enhancing the change detection [1], and the workflow of deformation detection can be streamlined by automating the tasks [11].

In the context of automating deformation detection based on point clouds, the following paper proposes an automated script combining the two approaches, 3D scanning and parametric design, to determine the displacement value of a structural element. Utilizing this methodology, the deformation of a representative wooden portico prototype was determined through a case study. Porticos in traditional Moroccan riads, a type of historic Moroccan building (Figure 1), constitute structurally significant elements supporting upper floors and redistributing loads around the central courtyard. Due to their exposure to environmental effects and material ageing, these elements are particularly vulnerable to deformation such as bending, tilting, and differential displacement. The proposed methodology is thus designed with direct applicability to such historic structures, justifying the choice of a portico as the element of study. This approach uses advanced algorithms to analyse the scanned data, speeding up the process and providing accurate measurements. The data was first captured using the photogrammetry principle in a powerful mobile phone application. It was then exported automatically to the Grasshopper plugin, a visual programming language, to create a customized algorithm that went through five basic steps to obtain the final result of the displacement calculation. As an outcome, the displacement obtained was 92% accurate to the real one, demonstrating the high precision and accuracy of the script.

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Figure 1. Post-and-beam galleries in Moroccan historic courtyards: examples from (a) Cherratine Madrasa and (b) Bahia Palace, representative of portico-type structures commonly found in traditional Moroccan riads

2. Literature Review

A significant number of research papers [12, 13, 14] focused on the use of point clouds as a basis for structural analysis and deformation detection. Several studies addressed building quality assessment and structural compliance inspection by comparing point cloud-based models with BIM or synthetic models to identify geometric deviations and imperfections in structural members [15]. PC have also been employed for damage detection in building facades, including the identification of spalling and cracks, using UAV-derived data and the fusion of infrared and visible imagery for effective evaluation [16, 17].

In terms of structural deformation and integrity assessment, a digital twin integrating point clouds and images was developed to evaluate the performance of buildings after damage [18], while advanced data-driven models combining PC data with signal processing and machine learning techniques have been proposed for large-scale structures such as concrete dams [19]. Post-earthquake structural assessment was also addressed, using UAV point clouds to estimate structural inclination and residual drift [13]. Additionally, rock discontinuity analysis was conducted, with comparative studies demonstrating the accuracy of TLS over SFM techniques and proposing efficient segmentation methods for large datasets [20, 21].

Building on this diversity of approaches, Sanchez-Aparicio et al. proposed a classification of the uses of 3D PC coordinates for damage detection under a single category, referred to as geometric-based methods [22]. The later includes six principal strategies: (a) manual mapping, relying on sections extraction from raw PC and visual inspection of the deformation patterns; (b) sections and curve fitting, which fits curves (polynomials) to PC sections using algorithms to quantify inclination, adding automation to section analysis; (c) Point-to-point distance, where temporal deformations are tracked by computing distances between corresponding points of PC from different periods; (d) Point-to-primitive distance, analysing deformation by measuring distances from PC data to fitted geometric primitives, defined manually or through semi-automatic fitting algorithms; (e) Point to 3D model distance, which detects local or global deformations by comparing the PC with an ideal or reconstructed 3D CAD model; and (f) Strategies based on geometric features, focusing on local information at the point level by analysing each point and its neighbourhood to determine descriptive features. While these approaches provide valuable insights, most are limited in automation, necessitating human guidance, rely on existing algorithms in commercial or open-source software, require significant user input, and depend on prior models. And only a limited number of studies develop custom scripts or methodologies for damage detection. These limitations reinforce the need for more autonomous, accessible, and adaptable solutions.

In this study, the suggested method does not strictly align with previously defined categories. However, it combines principles from multiple approaches, introducing features that address the existing limitations. Contrary to the point-to-primitive and point-to-model strategies, which depend on predefined geometries or reference models and necessitate a significant amount of manual input, the developed methodology operates directly on the raw PC. The key geometric feature of the structural element can be automatically extracted through the use of parametric design, eliminating the necessity for previous modelling. Additionally, unlike using external CAD or BIM data, the method generates its own optimal reference geometry from the scan, increasing the workflow's flexibility and autonomy. Furthermore, the integration of Grasshopper's visual programming environment facilitates the automatic quantification and visualization of deformations in real-time, displayed in an intuitive interface that is accessible to users with limited expertise. Consequently, this approach decreases manual intervention, eliminates dependency on predefined models, minimizes processing time, and improves access to deformation monitoring tools for heritage conservation. Accordingly, it can serve as a plugin or extension within the context of HBIM workflows.

As the proposed approach is based on Parametric Design (PD), it is necessary to examine its principles and applications more closely. The PD is a computational framework based on algorithms that link different variables and parameters, enabling the generation and control of shapes and objects. This approach, implemented in the Architecture, Engineering, and Construction (AEC) field, has undergone progressive development and has had a notable impact on applications ranging from design to the construction process. The capacity to modify architectural drawings by developing automatic inspection algorithms represents a significant advancement in the field of parametric design, as it effectively reduces human error and improves the overall quality of the work [23]. PD has also been widely applied to the exploration and modelling of complex geometries and structural analysis [24]. Furthermore, it involves simulating the environment and natural processes, thereby helping to optimize energy use [25] and developing new materials and innovative construction techniques [26].

For historic buildings, the implementation of this innovative approach based on automatic algorithms has proved highly beneficial, facilitating the automation of modelling processes and the detailed representation of complex architectural elements [27, 28]. This approach enables real-time modifications based on survey data acquired and supports the integration of contemporary analysis into the restoration process while retaining the historic value of the structure [29].

The integration of parametric design with the structural analysis of historic buildings has been shown to yield several benefits, including enhanced detection of structural deformation. This approach improves visualization of structural behaviour, transparency between design and analysis, and direct interaction with finite element environments through parametric toolboxes [30, 31]. In order to achieve an accurate structural analysis of a heritage building and efficient deformation detection, it is necessary to transition from a static to a dynamic model to take into account dynamic changes and factors over time. To achieve this aim, it is necessary to integrate imaging data acquisition techniques with parametric design methodologies. The latter is still an interesting and active field necessitating more research and improvements; this paper is a contribution to it.

Against this background, the combination of parametric design and point clouds has led to significant advancements in the field of the AEC industry, particularly in preserving the architectural elements of built heritage [6, 8, 32]. This approach enables the utilization of PC high-resolution capturing to document the real and current state of the structure, and the PD flexible analysis, visualization, and automated optimization. In pursuit of this research, our paper employs this integration approach using different tools to serve the structural side in terms of deformation detection and assessment, offering ease of use and cost reduction, while maintaining an elevated level of efficiency. The present study was developed through the combination of the capabilities of the Grasshopper plugin, as a PD program, with those of an iPhone 3D scan application. The main contributions of this work are the following:

→ The automation of point cloud processing
→ The elaboration of a Grasshopper algorithm for lateral displacement identification and calculation of its value
→ The application of the script to a prototype with the verification of the results
→ The development of a user-friendly interface that is intuitive to operate

3. Materials and Methods

The following section outlines the methodology employed to address the scientific issue presented in this paper. This manuscript aims to introduce a practical methodology that can be applied on-site with minimal cost, quick results, and acceptable accuracy. The study can be divided into two main phases: the scanning phase and the script development phase, which are linked through the use of Cloud Compare. The process began with the 3D scanning, resulting in 3D point clouds. These point clouds were then exported to Cloud Compare to convert the file format to E57. Finally, the automated script development process was initiated by transferring the generated file to Grasshopper.

To operationalize this framework, a conceptual workflow was adopted following five consecutive steps (Figure 2). First, the 3D data was acquired. Second, a key geometric feature is extracted from the structural element, forming the basis for deformation analysis. It is then automatically compared against a theoretically ideal reference geometry generated from the PC, and based on that, the displacement is calculated. Finally, the results are directly displayed within the Grasshopper interface, allowing for immediate interpretation and making the tool accessible even to non-expert users.

3.1. 3D Scan Acquisition

The monitoring of historical construction requires the use of survey and representation tools such as laser scanners, digital and professional cameras, etc. These always pose the problem of high costs, technical training, specialized staff, and time consumption. As a low-cost, easy-to-deploy, and accessible alternative to the advancements in 3D scanning and construction in recent years, high-performance digital cameras and Light Detection and Ranging (LIDAR) sensors have been integrated into the PRO versions of the Apple iPhone and iPad. Performance comparisons in the research have shown reasonable results in terms of accuracy and speed [33], especially when used with mobile survey applications. Nevertheless, the scans remain sensitive to the lighting conditions, surface texture, and the distance between the scanner and the object.

The Polycam mobile app, rated as the best performing, was chosen for our case. The latter showed better reconstruction accuracy and data completeness, and produced less noisy point clouds compared to others [34]. However, its accuracy is always comparatively lower than that of a laser scanner. Its precision is affected by the dimensions of the object, the user techniques, and the conditions of the scanning environment. The choice of the use of mobile scanning was justified by its accessibility and cost-effectiveness compared to other expensive devices, and the objective of the study was to provide a sufficiently detailed point cloud to test and validate the automated deformation-detection script. The expansion of our work and its application to large-scale real-world heritage cases will require the use of high-precision devices.

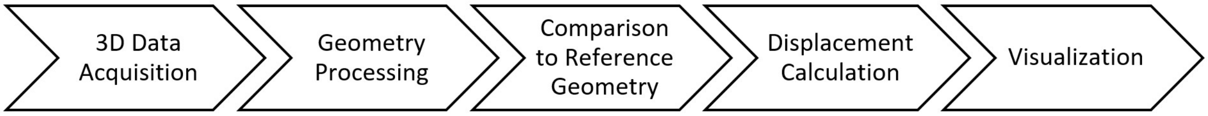

Figure 2. The conceptual workflow of the adopted methodology

The selected application was installed on an iPhone 13 Pro, which is equipped with advanced features that offer superior photographic and video performance. The iPhone 13 Pro is fitted with LiDAR technology, permitting the scanning of objects through the use of light pulses to measure distances and detect complex surfaces. Additionally, it is accompanied by 12-megapixel cameras and advanced computational photography functionalities. The portico was captured using the mobile app's auto mode, which facilitated the comprehensive capture of the object in a single recording session. After data capture, the images were processed employing the Structure from Motion (SfM) method to generate the 3D model. Upon construction of the 3D model, the mobile app provides multiple options for exporting the model, depending on the desired file type (mesh, point cloud, images, video, blueprint). In this instance, the point clouds were saved as a LAS (LASer) file, a file format that is widely supported by CloudCompare. Following transfer to CloudCompare, the conversion tool ensures that the data is in its appropriate format (E57) for further analysis and manipulation. Among the other formats accepted by Rhinoceros, such as LAS, XYZ, PTS, and PLY, the E57 format has been selected for use. This is the most advanced and versatile file format, providing interoperability, a large amount of data (coordinates, colours, references, classification information, etc.), compression, and optimization of file size. By that, the cloud compare facilitates the transition between the scanning phase and the script development phase.

3.2. Script Development

After the first phase of data acquisition, the second phase of script elaboration was launched. The writing of the automated algorithm was realized in Grasshopper, a plugin that operates within the Rhinoceros software. Rhinoceros is an effective and adaptable 3D modelling tool, known for its precision and various uses in different domains. It provides the functionality required to convert concepts into realistic 3D models. Grasshopper, conversely, is a visual programming language based on Rhino, designed for parametric modelling and design. It allows creation and manipulation of complex geometries algorithmically, using a parameter-based environment and a user-friendly interface. This language has enabled us to create a workflow and a customized algorithm for automatically detecting structural element deformation based on point clouds.

The algorithm was structured in five primary interconnected stages, as shown in Figure 3:

- → Point Clouds Uploading
- → Point Clouds Processing
- → Structural Element Profile Generation
- → Profiles Superimposition
- → Displacement Calculation

3.2.1. Point Clouds Uploading

The initial stage in the script's development involves retrieving the relevant point cloud data, which is represented in the E57 file format. This is accomplished via the "Load E57" component in Grasshopper, which enables the seamless integration of the data through direct file path connection without the necessity of intermediate processing. The latter provides the cloud on which the subsequent script stages will be based.

3.2.2. Point Clouds Processing

The script implements a series of processing steps on the point cloud data to accelerate processing speed while maintaining the necessary information. First, a random subsampling was applied to enhance performance and mitigate noise by reducing the number and size of points. As a result, the voxel subsampling was achieved by defining the distance between the points to guarantee the meaningful geometrical distribution of points. Additionally, the process of cropping was completed to delimit the precise area of interest. Consequently, a transformation was implemented to displace the modified cloud from its initial position, thus facilitating the subsequent processing steps.

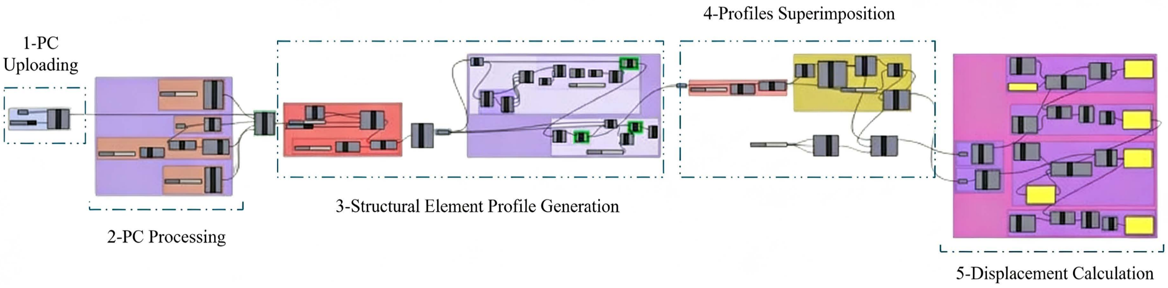

Figure 3. The general workflow of the Grasshopper-developed script

3.2.3. Structural Element Profile Generation

The creation of a section from the cloud is the first step in creating a structural element profile, based on the desired section plane and the maximum distance of projected points to the plane. This produces a new cloud, which is deconstructed to extract points from it. The points are triangulated to generate a mesh based on the Delaunay triangulation. The latter is a method of dividing a set of points into triangles such that no point lies inside the circumcircle of any triangle, frequently applied in mesh generation, surface reconstruction, and 3D modelling. Using various commands, only the outer boundaries were left, which are connected by a curve to generate the deformed profile considered as the principal geometric feature.

3.2.4. Profiles Superimposition and Displacement Calculation

Once the deformed profile is extracted, it is superimposed on an automatically generated reference curve representing the ideal geometry. This reference, derived directly from the point clouds in the form of a bounding rectangle, provides the theoretically ideal geometry. Based on the superposition, the distance between the two curves in the X direction is calculated, allowing the degree of deformation of the element to be determined.

4. Experiments and Results

To apply, test, evaluate, and validate the functionality and liability of the proposed method, a prototype was adopted. The first section describes the selected structural element and the deformation treated. The second section presents the results obtained from all the stages of the process.

4.1. Prototype

For this case study, a prototype portal frame structure was selected, as this architectural feature frequently appears in historic buildings, such as arches, porticos, arcades, and door frames. These elements are often vulnerable to critical deformations, especially lateral displacement and buckling effects caused by age-related deterioration and natural factors.

A preliminary prototype with small dimensions and features and controllable deformation (Figure 4) was chosen for initial verification to accurately test the detection of small displacement, for reasons of cost, faster iterations, and to detect and correct script errors. Once the adopted method is validated, it can be applied to larger and real structures when higher-resolution scans are available.

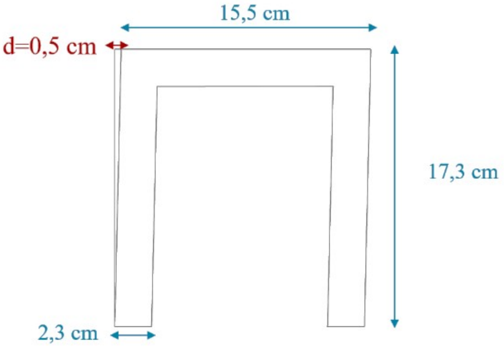

Figure 4. The dimensions of the wooden gantry

The proof-of-concept chosen for the application is a wooden portal 15.5 cm wide and 17.3 cm long, with beams and posts measuring 2.3 x 2.3 cm. The latter were subjected to a buckling deformation, which caused a displacement of the element of 0.5 cm in the X-direction.

In the scanning phase, the chosen mobile application captures images using the iPhone 13 Pro camera, processes this data to generate an accurate 3D model, and exports this model for later use. In our case, the principle used is that of photogrammetry. A series of 194 photos was taken from different angles, processed by aligning the images and extracting their characteristics to generate a 3D point cloud. This was converted into a mesh to produce a realistic visual representation, as shown in Figure 5 below.

Figure 5. The 3D model generated by the mobile app

Once a three-dimensional point cloud has been obtained, it is transferred to the CloudCompare software, which facilitates the transition from the scanning phase to the algorithm development phase. Afterward, the software offers the option to align the obtained point cloud along the XZ plane, thereby facilitating future use and simplifying the next operations. Furthermore, the data is saved in E57 format, which is rich in data, optimizes file size, and ensures good interoperability. This prepares the scan for further processing by the developed script.

The E57 file is then uploaded via the Grasshopper interface, after which the script is executed to complete the designated tasks.

4.2. Results

The script's launch generated many results throughout the process, ultimately leading to the final and primary outcome, namely the value of the displacement. Each stage yielded concrete results, which were then visualized in the 3D interface. This allowed for comprehensive monitoring and understanding of the process at each stage. The ensuing figure illustrates these stages in detail.

After the successful upload of the point cloud file path, the intricately constructed point cloud model that was generated through the sophisticated functionalities of the application was initially conceptualized within the visualization interface, which effectively showcased the entirety of the portico that had been meticulously scanned, as can be observed in Figure 6(a). Following the comprehensive processing of the point clouds and the careful delineation of the specific area of interest upon which all subsequent steps will be contingent, we successfully acquired a newly reframed point cloud, which is illustrated in Figure 6(b). Thereafter, the extraction process for the vertical section, which represents the front view, was completed efficiently, culminating in the resultant depiction found in Figure 6(c). Based on this outcome, a meticulous series of tasks was executed to facilitate the automatic generation of the vertical profile of the portico, and the curve contour obtained from this process is presented in Figure 6(d). This newly created profile was then superimposed onto the reference geometry, representing the theoretical undeformed state, to calculate the final displacement, ultimately leading to the visual representation illustrated in Figure 6(e). Upon initiating the algorithm specifically designed for calculating the displacement between the two curves, the result was efficiently obtained within just a few seconds, as displayed in the panel found in Figure 6(f).

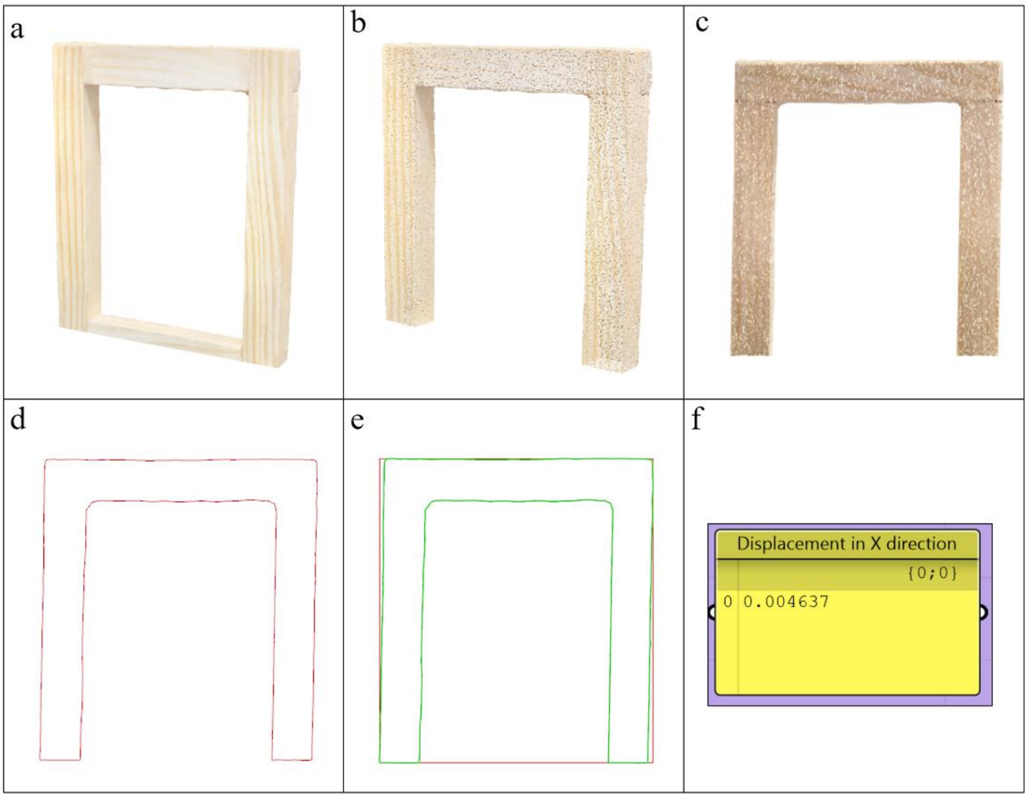

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Figure 6. The results of applying the workflow to the prototype

5. Discussion

This paper puts forth a methodology for developing an automated script utilizing 3D scanning and parametric design tools. The objective is to create a tool that can efficiently evaluate and analyse construction structural elements, while also providing simplicity of usage and reducing the costs and efforts associated with structural maintenance. Based on the core experiment performed, the following results and conclusions can be drawn.

Regarding the verification results, the actual measured displacement is 0.5 cm, while the displacement result calculated by the developed Grasshopper script is 0.464 cm. A comparison of the two values reveals a minor discrepancy of 0.036 cm between the actual and calculated displacements, with an accuracy of 92%. Based on the aforementioned calculations and to establish a general estimation of the displacement in question, it is reasonable to conclude that the script has a high degree of accuracy in detecting a displacement of 0.5 cm. This is especially true when considering the inherent margins of error that can arise from the scanning process, digitization, and the calculations performed. It can be concluded that the level of accuracy demonstrated by the script is sufficient for decision-making purposes. Furthermore, the Grasshopper script developed for detecting displacement occurring from buckling instability, as a first case of deformation based on point cloud, has the potential to be a valuable tool in historic and existing building maintenance, once high-precision 3D scans are provided.

The ultimate outcome of our methodology and the process developed is a script that offers several key qualities. In addition to automating the detection of portal buckling deformation from a scan, ensuring speed, efficiency, and accuracy, it provides a user-friendly interface that is intuitive and straightforward to manipulate. The aforementioned components of the script are incorporated into the programmer interface, encompassing all operations and configurations performed. The user interface (UI) is designed with the operator in consideration and features only sections for activation, input, and output operations. This interface offers groups of components, each with a name instructing the user on its intended use. The groups are divided into two principal sections, namely inputs and outputs. The Inputs section is divided into two sub-groups. The initial stage involves downloading the E57 file by entering the file path on the user's computer and launching the process by pressing the True button. The second step is to define the precise area to be considered using the Box component. Once this has been completed, the user will obtain the value of the displacement along the x-axis in a few seconds in the Output section. Figure 7 depicts the user interface.

Compared to existing point cloud-based deformation detection methods, the proposed approach provides multiple advantages. It enables full automation, reducing reliance on the operator’s manual intervention while decreasing processing time. The script generates the ideal reference and operates directly on raw point cloud data, without requiring primitive geometries or CAD models. In addition, the present methodology provides immediate and interpretable displacement results through an intuitive and user-friendly interface. However, there are some limitations to mention related to the validation on a minimal prototype.

While our method marks a significant advancement, it currently focuses on targeted structural elements and remains optimized for specific deformation types like lateral displacement in portals. Its performance is directly influenced by the point clouds' resolution, and the following factors should be acknowledged. When processing large-scale point clouds or entire buildings, increased data density can lead to longer processing time, and further optimizations of the script would be required for large-scale monitoring. In addition, many environmental conditions can influence the completeness of point clouds and introduce local noise, such as lighting variation, occlusions, and accessibility constraints in heritage sites. Consequently, the accuracy range of the method depends on the resolution of the acquired point cloud and the reliability of the geometric feature extraction, affecting the deformation and displacement quantification. Accuracy levels also depend on the data acquisition settings; higher point densities, for example, improve the exactitude of geometric features, while noise has a negative effect on local measurements and boundary definition. The chosen scanning method plays a crucial role in this respect: mobile photogrammetry or scanning provides flexibility and accessibility, while higher-precision systems offer improved geometric consistency, especially for large-scale structures. These factors highlight the importance of controlled acquisition processes and motivate further validation using large-scale monitoring datasets.

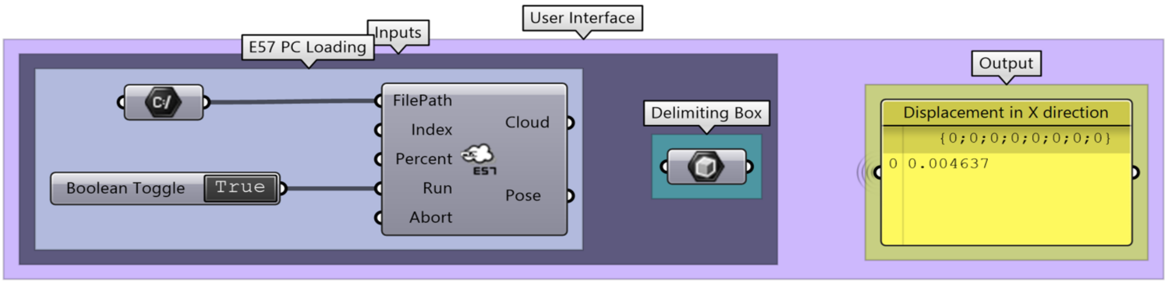

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Figure 7. The UI provided by the Grasshopper script

6. Conclusions

The objective of this research paper is to present a novel methodology for detecting structural deformation. The methodology is designed to respond to the specific features of automation, efficiency, ease of use, and time and cost savings. The methodology employed was a combination of two effective technologies: the 3D scan and the parametric design. The 3D scan enabled the actual condition of the structural element to be captured using the mobile phone application. An automatic script was then developed in Grasshopper, a visual programming language and environment specifically designed for parametric design and modelling, to respond to the aforementioned objectives. In order to assess the functionality of the proposed method, a prototype was constructed. This comprised a wooden portico as the supporting element, with the deformation in question being the displacement of the latter resulting from buckling. Upon completion of the proposed methodology, the script demonstrated an important degree of precision, identifying a displacement of 0.5 cm. This is particularly noteworthy when considering the inherent margin of error associated with the scanning, digitization, and calculation processes. Consequently, it can be concluded that the precision of the methodology is perfectly adequate for decision-making purposes.

In conclusion, the methodology presented above is designed to serve the structural maintenance of buildings and effectively addresses the challenge of automating buckling detection as initial deformation. This approach demonstrates superior performance compared to traditional tools in terms of usability, speed, and adaptability. In addition, the developed workflow's nature is adaptable to meet specific needs and can be extended to integrate additional plugins and customized components. To further develop our approach and contribute to developing scalable and cost-effective monitoring solutions for heritage conservation, several perspectives are identified. Beyond the controlled experimental validation presented in this paper, the methodology has been expanded to a larger-scale application involving a real slab in an existing building. This ongoing work addresses increased geometric complexity and real-site constraints. Future developments include:

→ Expanding the process to other load-bearing structural elements
→ Applying the methodology to additional real-world case studies using higher-accuracy acquisition technologies
→ Processing the entire construction scan for the systematic verification of all elements
→ Integrating the developed workflow into HBIM environments

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The authors have no acknowledgments to declare.

Data and Code Availability

The Grasshopper script and key algorithmic components developed in this study are not publicly available at this stage, but are accessible from the corresponding author upon reasonable request for academic and research purposes.

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