Parameterization of structural faults in large historical constructions for further structural modelling thanks to laser scanning technology and computer vision algorithms

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Abstract. Laser scanning technology has evolved significantly in the last decade, particularly, in those applications in terrestrial environments dealing with the documentation and inspection of civil engineering and architectural constructions. Even though there exist mature procedures to convert the so-called LiDAR point clouds in CAD models or even FEM models, the current trends in the technology are related to the automation of these operations. The development of robust automatic procedures for data segmentation and interpretation it is a key aspect so that the technology can definitely be accepted as a basic, accurate, and robust tool for reverse engineering of existing constructions. This paper presents the application of laser scanning technology to the structural evaluation of the Medieval Wall of Guimarães (Portugal). This laser scanning survey was conducted with the aim of having an accurate and detailed geometrical model of the large masonry construction that includes the existing deformations and structural faults. The parameterization of structural damages was possible thanks to the highly detailed point cloud collected, and its processing using computer vision algorithms. The geometric models obtained could be used for further structural analysis of the entire wall.

Keywords: laser scanning, masonry wall, geometric investigation, automated data processing, openings.

1 Introduction

The conservation of cultural heritage is one of the fundamental concerns and challenges of modern society. Historical constructions present a cultural legacy that needs to be preserved [1]. This generic term includes a wide range of constructions such as residential buildings, religious buildings, or even civil structures such as bridges. For assessing components of historic constructions, current practice is based on experience, which has been widely utilized with some success as a basis for identifying efficient strategies for health monitoring and

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extension of service life. However, this approach has important drawbacks. The three main problems associated with experience-based protocols for historical constructions are: first, many structures are unique, so they demand particular strategies for mapping and structural monitoring; second, experience does not enable new monitoring technologies to be qualified with respect to their performance prior to their implementation; and third, the dependence upon experience does not contribute to the smart and efficient management of such valuable constructions and infrastructures.

Close-Range Remote Sensing has evolved importantly in the last decades in terrestrial environments: new technologies such as Laser Scanning have significantly contributed to this growth. The main advantage of these technologies is their non-destructive nature, together with the crosscutting applications of the technologies to many different fields. Although there is great potential in the data provided by Remote Sensing systems, it should be noted that, to date, the data have to be interpreted by human operators, i.e. technicians trained to read and manually convert the model created into a specific product to be implemented for further applications. As this is the principal bottleneck in the adoption of remote sensing for structural engineering applications, the last trends in the usage of remotely sensed data focus on automation of data processing.

This work aims to present the potential of laser scanning technology to accurately document and offer a diagnosis of the structural performance of a large masonry structure, the Medieval Wall of Guimarães (Portugal). This laser scanning survey was conducted with the aim of having an accurate and detailed geometrical model of the large masonry construction, including deformations and existing structural damage. The parameterization of structural damages was possible thanks to the highly detailed point cloud collected, and its processing using computer vision algorithms.

2 The Medieval Wall of Guimarães

The survey presented in this paper was done in a Mediaeval masonry wall placed in the Portuguese city of Guimarães. In the 13th century, during the reign of Afonso III, the defense walls were extended to the village of Guimarães so it turned into a walled village, so that the bailey moved outside the keep. After several centuries as a walled village, the wall was partially destroyed during the 17th century in order to obtain money for the restoration of Dukes Braganza Palace. The survey presented in this article was performed over a stretch of the wall with a straight direction. This stretch is located in the city center, namely in a sloped street with pedestrian and vehicular traffic from the external face. On the other side, the wall is closing the gardens of the Museum and the parking area of the Council House. The surveyed stretch has a total length of 230 m, and the height in the external face varies between 9.7 and 7.3 m along the wall, approximately. The wall is made of regular granitic ashlars whose averaged dimensions are 76 cm and 50 cm for length and height, respectively [2]. The wall contains battlements with merlons with an average height of 1.5 m. Part of the walls still preserve the Romanesque architecture, where ashlars were disposed and organized, maintaining a constant height for the pieces of each course and slightly different height among different courses.

3 Laser scanning survey

3.1 Laser scanning technology

Laser scanning is a remote sensing technology that allows collecting 3D geometry of objects' surface in an automatic way by using LiDAR technology. Laser scanning instruments can be classified attending to the different principles used for distance measurement [3]. For civil engineering applications, the most common principle is based on measuring the time of flight (TOF) of the laser beam. This principle allows distances to be remotely computed by measuring the time delay between the emission and return of a laser beam that travels from the instrument (a laser scanner) to the object. Terrestrial laser scanners (TLS) (static scanners) contain mirrors and rotating mechanisms to deflect the laser beam in different directions. Thus, TLS covers efficiently the entire field of view around the instrument. The mirror that deflects the laser beam in the vertical direction (around horizontal axis) can rotate at a very high speed, which usually corresponds to a prism that rotates 360º. As a result, a very dense point cloud is obtained. This point cloud basically contains the X, Y and Z coordinates of each surface point, and some other attributes such as amplitude of the laser beam or RGB data.

3.2 Survey of the Medieval Wall of Guimarães

The survey of the of the Medieval Wall was performed using the terrestrial laser scanner Faro Focus X330. This phase-shift laser scanner has an operating range of 0.6-120 m, with a nominal precision of ±2 mm at 25 m distance in normal reflectivity and illumination conditions. The field of view is 360º horizontally and 305º vertically and the maximum angular resolution is 0.009º. This instrument is able to register 10^6 points/s when working at maximum rate. Artificial targets were used as tie points to allow the alignment of the 31 point clouds collected all along the wall to complete the external and internal faces of the masonry structure. These targets were also measured using a total station with the aim of using these marks as control points. Furthermore, they allow to reduce registration errors of such a large number of scans. Another important issue is that it was possible to accurately level the point cloud using the total station. For the topographic survey, a total station Leica TCR1102 was used. Technical features of the instrument are: long-range measurements (up to 100 m); 3mm+2ppm accuracy; 20cc typical average measurement in angles deviation, 5cc angular accuracy, 20´´ sensitivity of levels.

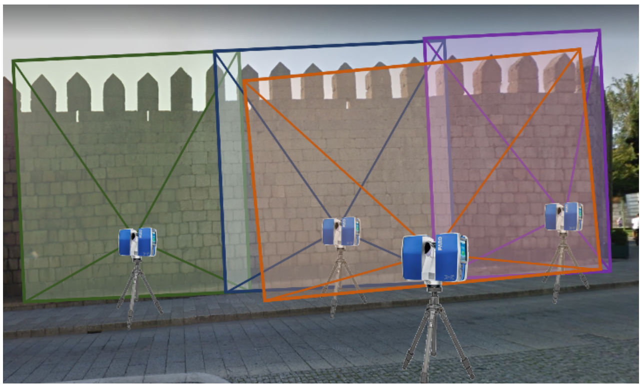

Figure 1. Network of scanner position that was repeated all along the entire wall.

As mentioned, a large number of scanner positions were required to complete the point cloud of the entire wall. To optimize the quality and size of the point cloud, the scans were acquired consecutively and with a 100% overlap, as depicted in Fig. 1. Furthermore, they were aligned in a common coordinate system using the aforementioned targets.

3.3 Point Cloud pre-processing

The main objective of the proposed methodology was to automatically process the external and internal face point clouds of the wall and to obtain the damages that it could be suffering. *CloudCompare* is a 3D point cloud processing software and it was used to pre-process the Guimarães Wall data due to the big amount of points contained in the point clouds.

The first filter applied was the Statistical Outlier Removal (SOR), used to minimize measurement errors. It is a statistic algorithm for deleting outliers. It is in charge of computing the mean distance between each point (P_j) and each of its neighbors (considering P_i with $i=1...k$ the closest k neighbors of P_j, being 10 the first parameter used for these data). It can be said that the resulting distribution is Gaussian. Therefore, the algorithm reject points farthest than the mean distance plus a number n of times the standard deviation σ (n = 0.5 in this case, second parameter), being those considered as outliers (Eq. (1)).

$$d_{max} = \frac{\sum_{i=1}^{k} \|P_j - P_i\|_2}{k} + n \cdot \sigma \; ; \quad j = 1 \ldots N_{pts} \qquad \textbf{(1)}$$

being N_{pts} the number of points in the cloud.

The next tool used in this software estimates the roughness of a point cloud. The program only needs the kernel size value as input, which is the radius of a sphere centered at each point. For each point in the cloud, the roughness value is equal to the distance between that point and the best fitted plane to the nearest neighbors. In this case, the entry parameter has been fixed as 0.02. As a result, the density of data has been considerably reduced. Two point clouds were also obtained with a separation of approximately 0.05 centimeters between neighboring points.

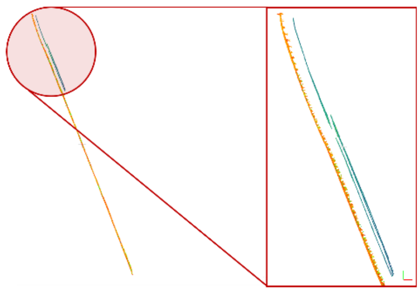

Figure 2. Separation between internal and external wall. Top view.

4 Results: Dimensional analysis

The method starts with the two LiDAR point clouds pre-processed in the previous steps, namely one representing the external and another one the internal part of the medieval wall of Guimarães (Fig. 2). First, unnecessary data were deleted, hence the ground has been removed from the point clouds. Subsequently, each point cloud was reoriented based on the longitudinal direction of the set of points, and the best fitting plane of the joined clouds was obtained. Taking all these data into account, the Euclidean distances between each point and the aforementioned plane were computed. As a result, a structural diagnosis of the wall has been made, considering the deviations detected in the point clouds. These results and the corresponding explanations are shown in subsequent sections.

4.1 Automated processing

4.1.1 Ground extraction

The first step for making the point clouds suitable for this work was to extract points belonging to the ground because of their futility in this work. The method starts with two point clouds, one belonging to the external $C_1 = (x, y, z)$, and another one belonging to the internal face of the wall $C_2 = (x, y, z, I)$, where (x, y, z) are the 3D spatial coordinates of each point forming the clouds and I the reflected laser pulse intensity. The set of both of the clouds was voxelized [4] having as base the same grid. With voxelization, the point clouds were reduced, and the membership to a voxel of a given size was assigned to each point as an ID, being able with that to recover full resolution when needed. Points belonging to the ground were detected following the methodology proposed by [5], consisting on a saliency analysis. With this method it was possible to evaluate whether a candidate (point) belongs to the ground or not.

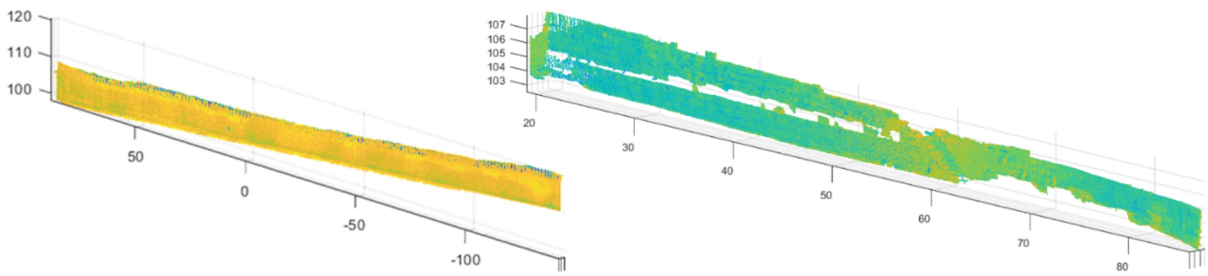

Figure 3. (a) Rotated external face of the Guimarães wall. **(b)** Rotated internal face of the Guimarães wall. (Dimensions in meters)

4.1.2 Point cloud rotation

The point clouds of the wall were rotated in such a way that their points resulted aligned to the longitudinal axis of the 3D space. This was done in order to accelerate the distance calculation process. The rotation process started by searching the plane that better fitted the cluster of points using orthogonal regression. Subsequently, both the external and internal faces of the wall were rotated with the same angle, accordingly to the rotation matrix computed with the previous data (Fig. 3 (a) and (b)).

4.1.3 Damage detection: Transverse opening of the walls

The damages that were taken into consideration in this work were the transverse openings of the Guimarães Wall faces. In order to detect these pathologies, it was necessary to study the geometry of this structure. In the measurement of transverse opening, the distances between each point forming the point cloud and a plane were computed. Due to the big amount of data forming the clouds, it was necessary to work with them voxelized (one point every 10 centimeters). The measurement of transverse opening in the wall has been done working with the Euclidean distance (Fig. 4) between each voxel point and the best plane fitted (π) to the set of points containing both the external and the internal point cloud. The results are two column vectors with those distances stored inside, being each row corresponding to its respective point.

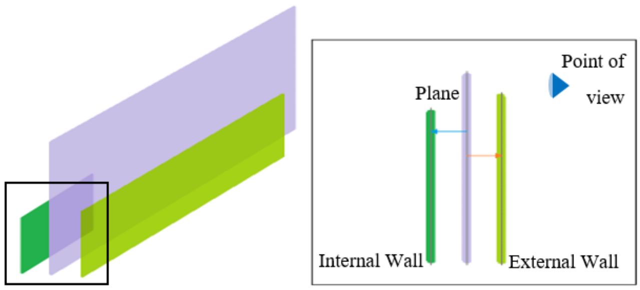

Figure 4. Scheme of the Euclidean distances calculation

Each voxel was transformed into a pixel in the *XZ* plane, and each pixel value was computed as the mean of Euclidean distances of each point inside the corresponding voxels, calculated beforehand. Therefore, the desired result was formed by two images, namely one for the external and another one for the internal face of the wall. It was fundamental that both images had the same size, so that they could be directly compared. In this case, the images extracted from the point clouds of the Guimarães Wall are formed by 524628 pixels, distributed as 228 rows and 2301 columns (Fig. 5).

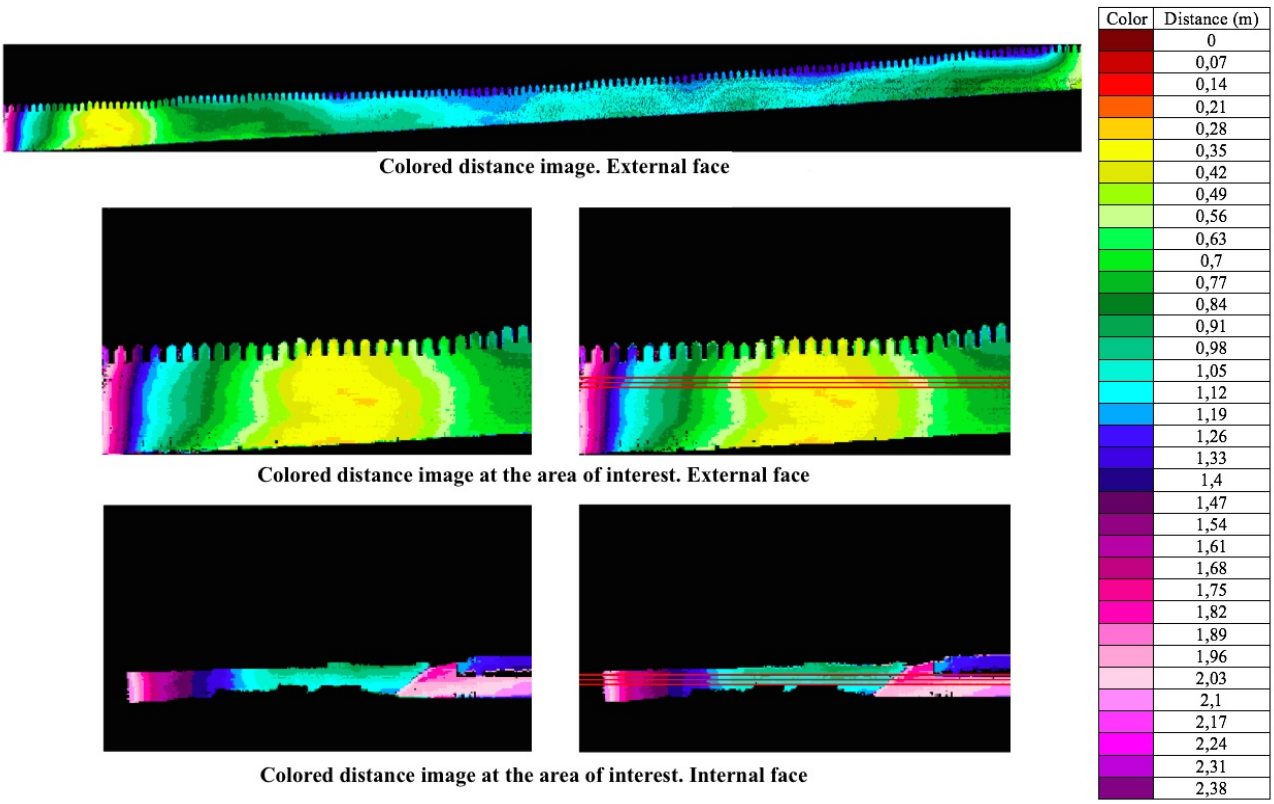

Figure 5. Distance images of external and internal faces of the Guimarães Wall

4.2 Structural diagnosis

From the results shown in Fig. 5, it is observed that the external face of the wall is suffering a clear deformation in its left extreme (increasing distances). Focusing the attention on this clearly affected area, a comparison between both faces of the wall (internal and external) has been performed. It has been verified if the distance between points belonging to the same pixel of both images was increasing or decreasing simultaneously. This has been done in order to get to know if the structure is suffering from transversal opening externally or also over its internal face. The images' rows selected to do that are the ones marked in red color in Fig. 5.

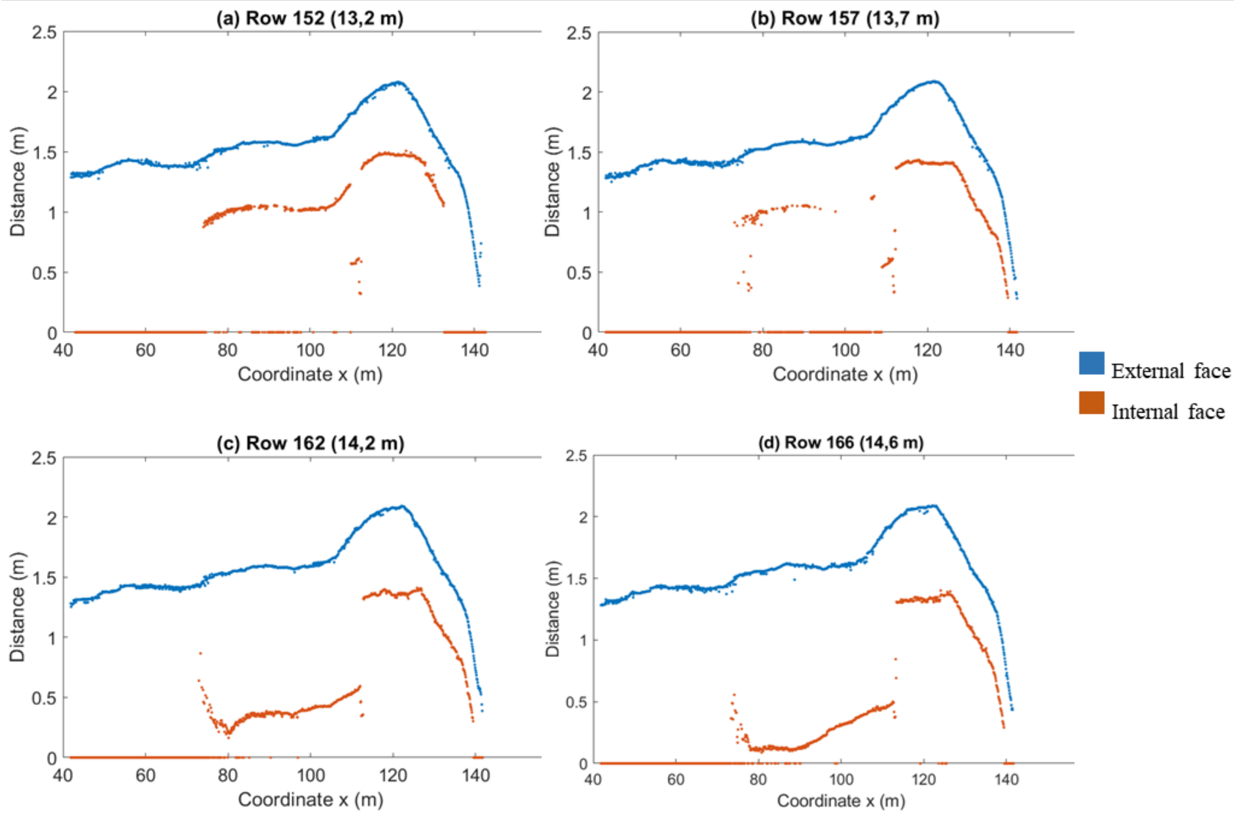

Figure 6. Distances between external and internal faces to reference plane plotted at different heights.

From the graphics in Fig. 6, it can be deducted that the external face is farther from the averaged plane than the internal face of the wall. Both faces start to open following almost the same curve, but the external face suddenly suffer a peak of increasing distances along the structure, which might be caused by the curved form of the wall in this area. This pattern is observed at different heights in the wall, as depicted in Fig. 6 (a)-(d). On the other hand, it can be seen that, in general, distances from inner face and outer face of the wall to the averaged plane follow the same pattern in all its length. However, Fig. 6.d corresponding to the upper profile analyzed, the pattern of parallelism is not maintained in the central regions of the wall (between meters 70 and 110).

5 Conclusions

This paper presented a methodology for the automated geometric analysis of a large masonry construction. It was demonstrated how laser scanning technology can be used for a massive, detailed and accurate investigation of geometric anomalies in historical constructions. Moreover, the data can be easily interpreted by non-experts in geomatics thanks to the development of computer vision algorithms that automatically handle and produce maps with the searched pathologies. Particularly, point cloud segmentation, voxelization and distance computations to a reference plane allowed to create images where geometric anomalies can be detected. The comparison of the images obtained from both faces of the wall permitted detecting transverse openings in some areas of the wall. Further analysis such as out-of-plane deformations can be done using the same algorithms and the point's normal. This is very useful not only to detect areas of the wall with significant deformations, but also to accurately map and determine how the deformation is occurring.

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