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DOCUMENTATION OF BRIDGES BY TERRESTRIAL LASER SCANNER

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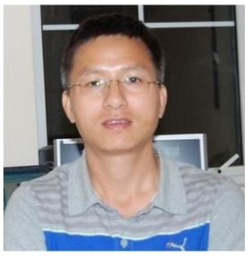

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Abstract:

Bridge structures are subjected to deterioration due to excessive usage, overloading, and aging material. For the last two decades, a significant amount research has been developed for collecting data for structural health monitoring. Yet, visual investigation with an on-site inspector remains the predominant method. This is true despite the highly subjective and time consuming aspects of this approach. Alternatively, terrestrial laser scanning can acquire surface details of structures quickly and accurately and is, thus, an emerging means to overcome the shortcomings of direct visual inspection. This paper presents a procedure for data collection for bridge inspection documentation and proposes a “cell-based method” for determination of structure deterioration (involving vertical deformation and lateral distortion), as well as surface loss due to corrosion. The Guinness Bridge built in 1880s located in Dublin council, Ireland is selected as a case study to illustrate the efficacy of the proposed method.

Keywords: Terrestrial Laser Scanning, Point Cloud, Historic Mental Bridge, Deflection, Lateral Distortion, Volume /Surface Loss, Damage, Documentation

1. INTRODUCTION

A bridge’s performance life can be reduced unintentionally by excessive loading and environmental impacts. To counter this, knowledge of a bridge’s performance level is needed to schedule timely and sufficient maintenance, otherwise catastrophic damage may occur, particularly for aging bridges. The predominant inspection method is visual, as it has the advantage of being simple [1]. However, the process is subjective and highly dependent upon an inspectors’ experience, especially when working in adverse conditions (whether and access) [2,3]. Visual inspection may also require rather heavy logistics and bridge closure [2, 3]. Thus, obtaining the relevant information for bridge assessment is complex and time consuming when using traditional methods [4].

The current generation of terrestrial laser scanning (TLS) is a non-contact method that has the capability of rapidly acquiring high data density describing the surface topology of structural members at millimeter accuracy. TLS has been used in various related civil engineering applications including biological crust monitoring [5], damage detection [6], structural analysis [7], excavation wall monitoring [10] and general deflection measurement under static loads [8, 9]. This paper proposes a method for post-processing TLS data to estimate deformation (vertical displacement and lateral distortion) and surface loss due to corrosion.

2. BACKGROUND

Since a systematic overview of the application of TLS in bridge engineering has recently been published elsewhere [10], this background section is restricted to laser based method for estimating deformation and surface loss. The first published vertical deflection measurements for bridges was done by Lichti et al. [11] in 2002, who measured displacements of stringers of a wood bridge in Perth, Australia. Vertical displacements were estimated by comparing fitting lines of each stringer cross-section under loaded and unloaded conditions. Results showed that stringer deflections based on TLS data were larger than ones from image-based methods. Zogg and Ingensand [12] monitored deformations of the Felsenau bridge when subjected to a static load of 54 tons performed at several sections of the viaduct. Third party software was then used to determine vertical displacements by comparing the 3D point cloud from the unloaded condition against the loaded condition. The TLS-based results were no more 3.5mm larger than ones based on precision levelling. Similarly, Paffenholz et al. [13] proposed a cell-based method to estimate vertical displacements. The scanned region was divided into sub-areas of 0.25m x 0.25m, and the median of the z-coordinates of each sub-area was used to determine the vertical displacements. The standard deviation of the z-component of the points in each patch was up to 3mm, while the standard deviation of the representative value was about 0.2mm. However, the accuracy of the proposed method was not reported.

Furthermore, TLS has also been used to detect surface deterioration based on principal curvatures or gradients derived from analysis of point-based coordinates, or point cloud based intensities and RGB values. One of those methods, Teza et al. [6] used a Gaussian curvature in sub-areas of the dataset to recognise damaged area. In that work, the sub-area was considered damage, if the standard deviation of the Gaussian curvature in the sub-area was greater than ones of the reference area. Alternately, Liu et al. [14] proposed the distance and gradient of data point in row and column grids as criteria for detecting defective areas of an extended pile cap of a concrete bridge. In contrast, Mizoguchi et al. [15] fit a primitive surface based on point clouds to an undamaged area by using a least square method. The total scaling depth was then calculated based on the distance from point clouds in scaling areas to the surface. Mosalam, et al. [16] also used TLS to acquire detailed information for damage assessment of a bridge located near Leogane, Haiti. The bridge was scanned from the North side of the bridge with fine and coarse sampling steps. Spalled concrete regions were detected by using color map of the point color. By using machine learning approaches involving K-means and Fuzzy C-means algorithms, González-Jorge et al. [5] detected biological crusts on concrete surface based point cloud intensity values. According to the extensive research above, TLS has demonstrated its potential usefulness. The next section demonstrates this in the documentation of a historic, metal bridge.

3. METHODOLOGY

This research proposes a method for post-processing TLS data for the documentation metal, truss bridges. The algorithm involves: (1) deformation determination and (2) surface loss estimation. The cell-based deformation algorithm was proposed to determine a relative deformation of the beam through data points of the beam's flange and can be applied to the beam's web data to predict a lateral deformation. Finally, an angle criterion and a cell grid were combined to calculate the area of surface loss.

The structure used for validation was the Guinness Bridge, also known as the Farmleigh Bridge, a Victorian metal bridge over the river Liffey built in 1880 [17]. This 4m wide and 4m high metal lattice truss bridge had a 52m clear span. No longer existing, the decking was a series of concrete arches spanning between the floor beams. The bridge was scanned with a TLS Leica ScanStation

P20 (technical specifications available in Truong-Hong et al. [18]). The overall bridge was scanned with a sampling step of 6.3mm at a distance of 10m. Notably, the bridge was accessible from only one side leading to incomplete data collection. Point clouds from different scan stations were registered together from all available vantage points. Irrelevant points (e.g. from the terrain) were removed manually within the scanner's proprietary software (Fig. 1). The remaining point cloud was exported in an ASCII format with x, y, and z coordinates for each data point as input data for the proposed method.

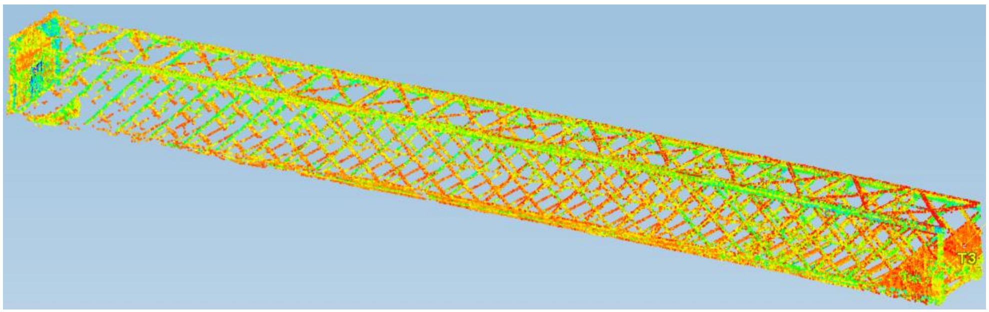


Fig. 1. Point cloud of the Guinness Bridge

4. PROPOSED METHODS

4.1 Deformation

The aim of the proposed work was to determine vertical deformation of the bridge's structural members. The workflow is shown in Fig. 2. The approach can also be used to determine lateral distortion. Under normal conditions, most elements are straight. The undeformed shapes of the members are, thus, treated as the reference lines.

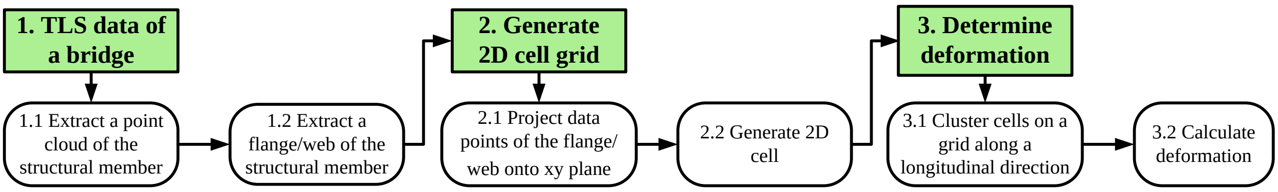
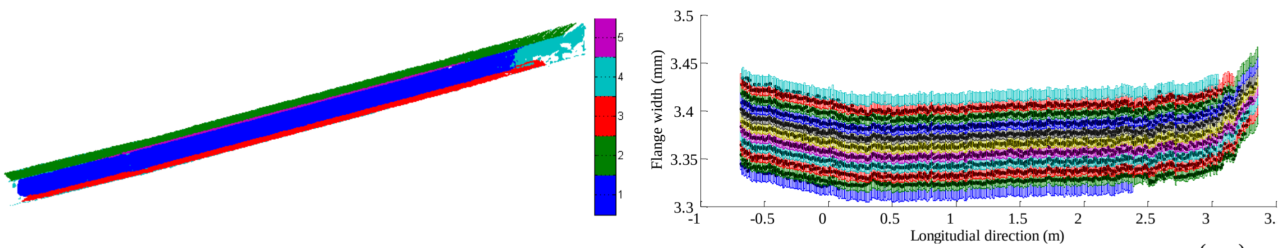


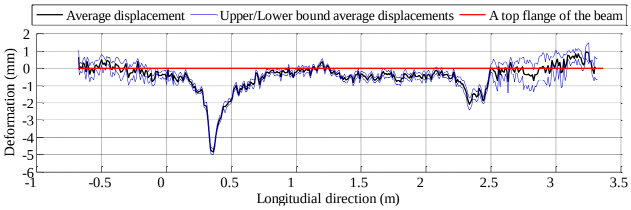
Figure 2. A workflow for determining vertical deformation

The data point of the lateral beam No. 4 was selected to illustrate the proposed method (Fig. 3a. After the data points of the structural members were separate from the larger data set (step 1.1), a region growing-based octree [19] was used to extract point clouds of the flange/web data of the structural member (step 1.2). The segmentation results are shown in Fig. 3a. Next, the data points of the top flange were projected onto the xy-plane in a global coordinate system (step 2.1), and 2D cell grids with a predefined cell size were generated (step 2.2). In this implementation, each cell containing data points has an elevation attribute, which is the average value of the z-coordinates of the data points.

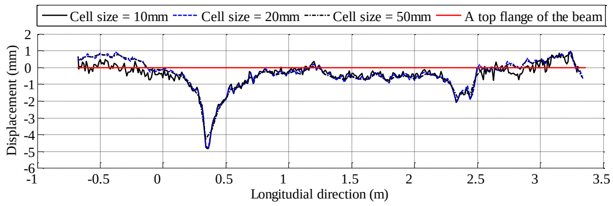


a) Resulted segmentation of a point cloud of the lateral beam No. 4 (*)

b) 2.5 cell of data points of the top flange(**)



c) Absolute vertical displacements



d) Absolute vertical displacements with various cell sizes

Note: (*) the colour shows the data points in the same segment and the segment No. 2, the data points of the top flange, used to compute vertical beam displacements; (**) the colour illustrates cells in the same longitudinal segments.

Figure 3. Determine vertical displacements of the lateral beam

Furthermore, the cluster algorithm was proposed to extract the 2D cells on the same pattern in the longitudinal direction of the beam (step 3.1) (Fig. 3b). In fact, due to mixed pixels that do not represent any physical surface during data collection [20], cell segments containing the edge points were not used for determining vertical displacement. Thus, in this example, only segment orders from 2-9 along the longitudinal direction of the beam were used (Fig. 3b). Based on the data point with the cell, a location of a cross-section (x_{sec}) and the vertical displacement (δ_{vert}) can be expressed in Eq.s 1-2, respectively.

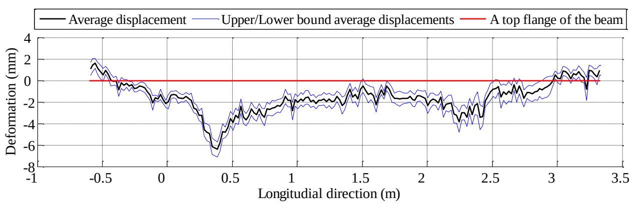
$$x_{sec} = \frac{\sum_{i=1}^{n} x_i}{n} \qquad \text{Equation 1}$$

$$\delta_{vert} = \frac{\sum_{i=1}^{n} z_i}{n} - z_{ref} \qquad \text{Equation 2}$$

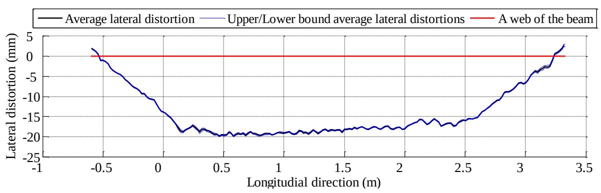
where x_i and z_i are x- and z-coordinates of the data points within the cell, while z_{ref} represents the undeformed state of the structure, is computed from the data points at two end points of the structural members, as given in Eq. 3.

$$z_{ref} = \frac{\sum_{j=1}^{m} z_j}{m} \qquad \text{Equation 3}$$

Furthermore, the average vertical displacement and estimated error bounds of the vertical displacement computed from data point based displacement in each segment are presented in Fig. 3c, where the required confidence level of 95% was imposed. The agreement limit of the maximum average vertical displacements was 4.83±0.15mm. Finally, to investigate cell size influence on estimated vertical displacements, 3 cell sizes were tested [10mm (C10), 20mm (C20), and 50mm (C50)]. The results are shown in Fig. 3d. The agreement limits of maximum average vertical displacements were 4.83±0.15mm, 4.81±0.11mm, and 4.26±0.17mm, respectively. When the cell size increased from 10mm to 20mm, the absolute difference was 0.02mm (C10 vs. C20). Thus, a cell size of less than 20mm is recommend. Figure 4 shows an example of the proposed method in determining vertical displacements and lateral distortion when a cell size of 20 mm was used.



a) Vertical displacements



b) Lateral deformations

Figure 4. Applied the proposed method for estimating vertical and lateral deformations of a bottom lateral beam No. 5

4.2 Surface loss

The proposed algorithm was to automatically determine the surface loss area. A surface of metal structure is considered as loss when no TLS data points achieved (Fig. 4). Surface loss area can be computed from data points along the hole's boundary. The damage at a connection between a lateral beam No. 3 and a bottom longitudinal chord was selected for illustration of this point (Fig. 5a).

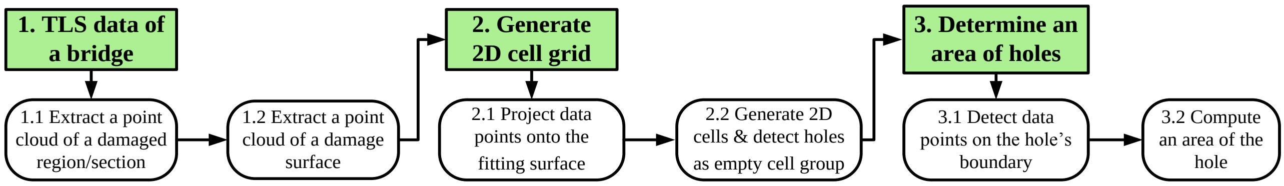


Figure 5. Workflow to compute area of surface loss due to corrosion

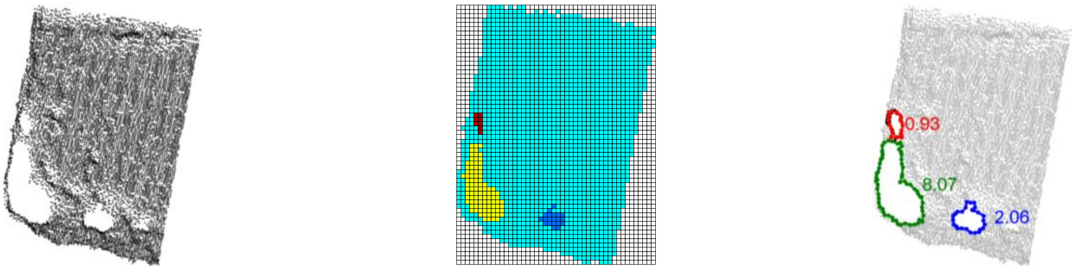
First, the data points of the damage region were isolated from the entire data set by using proprietary software of the scanner (step 1.1) (Fig. 5b). A region-growing based octree method [19] was employed to extract the surface containing surface loss or holes (step 1.2) (Fig. 5c). Next, to generate the 2D cell grid, the point of the surface was aligned to the xyplane in the global coordinate system (step 2.1). This was done by aligning eigenvectors of the fitting plane to the unit vectors of the global coordinate system, where the eigenvectors were computed according to the procedure proposed by Hope et al. [21] (Fig. 5d). Similar to work on detecting connection characteristics, a 2D cell grid was used to represent the data points of the surface after alignment to the xy-plane, where the cell size was set equal to 3 times of average sampling step – a distance between two adjacent data points (step 2.2) (Fig. 5d). The cell was classified as "full", if the cell contains at least one data point; otherwise, the cell was labelled as "empty". As the surface's hole is represented by empty cell groups within the data set, a clustering technique was employed to group the empty cells together [22]. The results are shown in Fig. 5d.

Additionally, to determine the area of a hole, data points on the hole's boundary, called boundary points were extracted by using the angle criterion [23, 24] (step 3.1). Unlike previous work, in this implementation, only data points within the full cell on the hole's boundary were considered as the candidate points. The candidate point was designated as a boundary point, if the maximum angle between two consecutive kNN points was larger than the angle threshold [24] for which 10 kNN points and the angle threshold of 90 degrees were adopted (Fig. 5f). Finally, the boundary points on the same real hole grouped to report the number of existing holes within the designated area. The real hole can be represented by multiple groups of empty cells. For example, there are 3 real holes shown in Fig. 5e. Next, the polygon of the hole's boundary was generated based on its boundary points, and then the area of the polygon (or of the hole) can be calculate (step 3.2). The results are shown in Fig. 5f.

a) Photo of the surface loss due to corrosion

b) Input data of the section of interest

c) Segments of the input data (*)



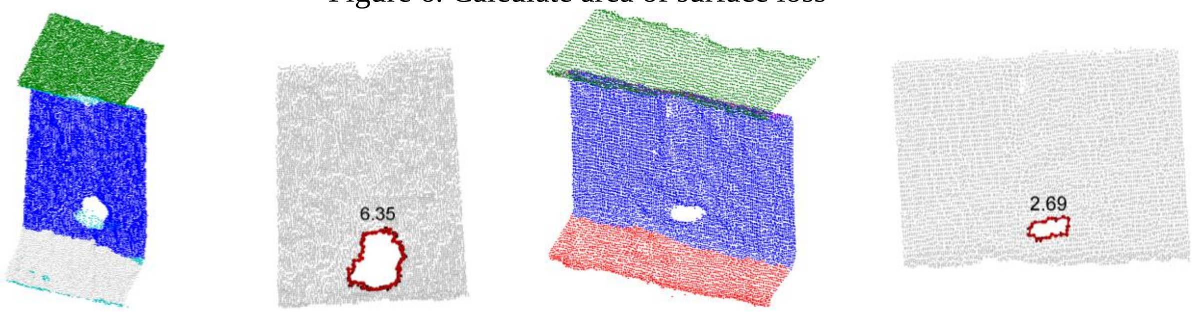
d) Data points of a surface loss projected on a xy plane

e) 2D cell grid and detected holes

f) Boundary points and hole areas(**)

Note: (*) blue points are the data points of the segment 1 containing surface loss; (**) unit in cm^2.

Figure 6. Calculate area of surface loss



a) Point cloud around a hole 1

b) Computed area of hole 1

c) Point cloud around hole 2

d) Computed area of hole 2

Figure 7. Illustration of the proposed method in determining areas of surface loss of Beam No. 3 (unit in cm^2)

Furthermore, other surface losses of Beam No. 3 were also documented (Fig. 6). The area of each hole was manually measured from the point cloud to evaluate the proposed method. Absolute errors were less than 0.6 cm^2 while relative errors were no more than 10%, except for the hole 5 with 18.8% (Table 1).

Table 1. Absolute and relative errors of surface loss areas of Beam No. 3

Hole	Hole's area (cm^2)		Absolute error	Relative error
	Manual	Proposed method	(cm^2)	(%)
1	1.98	2.06	-0.08	-4.0
2	8.67	8.07	0.6	6.9
3	1.02	0.93	0.09	8.8
4	6.38	6.35	0.03	0.5
5	3.29	2.67	0.62	18.8

5. DISCUSSION

As TLS can save up to 90% of the time required data acquisition [25], it has been widely used in civil engineering . One of TLS's advantages is its non-contact approach, where the topographic data

of a structure’s surface can be acquired at millimetre accuracy. Thus, TLS is emerging as a highly competitive method for data collection for documentation, particularly where access to the structure is limited. In this paper, cell-based methods were proposed for steel structures to automatically determine vertical and lateral deformations of a straight structural member and to estimate surface loss.
Since the data processing was cell-based, the approach depends on cell size selection. Changes in cell size from 10 mm (C10) to 50 mm (C50) caused a relative difference of the average vertical displacement of 11.8% (4.83 mm for C10 vs. 4.26 mm for C50). When observing the lateral deformations of Beam No. 5, the relative difference was 4.5% (20.61 mm for C10 vs. 19.92 mm for C50) (Fig. 8). The proposed method can also estimate a local deformation; however, it was fails when using the surface fitting based all data points of the structure’s surface [26]. Notably, howeve, noise in the scanned data caused by mixed pixels can affect the calculated deformations.

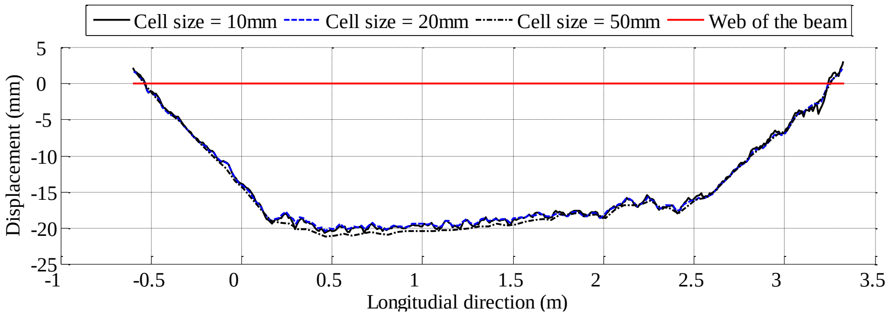


Figure 8. Lateral deformation of beam No. 5 subjected to various cell sizes

A combination of an angle criterion and a 2D cell grid worked properly in identifying surface loss of a steel structure. The proposed method determined the area of surface loss within 10% of what was detected manually. Although the method is appropriate for this case study, it may fail to detect a hole, if the structure surface is scanned with a sampling step equal to or greater than the equivalent hole span (width or length).

6. CONCLUSIONS

Rarely does original historic metal bridge documentation exist. As this complicates structural assessment, TLS is useful in acquiring topographic data points describing the visible surface of structures. This paper proposes a set of cell-based approaches for automatic measuring vertical and lateral deformations of straight structural members and area of surface loss for steel structures. The automated surface loss procedure was shown to differ less than 10% from manual extraction from the same point cloud. The proposed algorithms were successful in providing efficient tools for documentation of the Guinness Bridge built in 1880s in Dublin, Ireland.

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