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Authors(s)	Truong-Hong, Linh; Falter, Holger; Lennon, Donal; Laefer, Debra F.
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FRAMEWORK FOR BRIDGE INSPECTION WITH LASER SCANNING

Linh Truong-Hong¹, Holger Falter², Donal Lennon³ and Debra F. Laefer⁴

¹*Research Scientist, Urban Modelling Group (UMG), School of Civil, Structural and Environmental Engineering (CSEE), University College Dublin (UCD), Dublin, Ireland*

²*Professor, Coburg University of Applied Sciences and Arts, Coburg, Germany*

³*Technician, UCD Earth Institute, UCD, Dublin 4, Ireland*

⁴*Associate Professor, UMG, CSEE, UCD, Dublin, Ireland*

ABSTRACT

For the last two decades, a significant amount research has been developed for collecting data for bridge inspection. Yet, visual investigation with an on-site inspector remains the predominant method; however is the highly subjective and time consuming. Alternatively, terrestrial laser scanner (TLS) 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 framework of bridge inspection using TLS data, where a strategy of processing TLS data for deformation measurement, damage detection, and reconstruction of three dimension (3D) as-built models are explored. Demonstration of the application in bridge inspection is also provided.

Keywords: Terrestrial Laser Scanning, Bridge Inspection, Deflection, Damage Detection, As-Built

1. INTRODUCTION

A bridge's performance life is subjected to deterioration due to excessive usage, overloading, material aging and environmental impacts. The most recent American Society of Civil Engineers' (ASCE) Report Card on infrastructure categorized 24.9% of America's bridges as structurally deficient (American Society of Civil Engineers 2005). To counter this, knowledge of a bridge's performance level is required to schedule timely and appropriate maintenance; otherwise catastrophic damage may occur. In the last two decades, a significant effort has been devoted to developing non-destructive methods for bridge condition assessment. Yet, the predominant inspection method remains visual due to its simplicity (Yunovich et al. 2005). However, the process is subjective and highly dependent upon an inspectors' experience, especially when working in adverse conditions (poor weather and access difficulties). Visual inspection may also require rather significant logistics and bridge closure. Thus, the method is complex and time consuming when obtaining the relevant information for bridge assessment

Terrestrial laser scanner (TLS) is a non-contact method that has the capability of rapidly acquiring high data density describing the surface topology of structural member. Thus, many methods have been developed for processing TLS data for structural health monitoring and damage detection including biological crust identification (González-Jorge et al. 2012), damage detection (Teza et al. 2009; Truong-Hong and Laefer 2015a), deformation measurement (Truong-Hong and Laefer 2015a) and as-built metal member identification (Truong-Hong and Laefer 2015b). To date, such efforts remain as partial solutions. To have something more comprehensive, this paper proposes a framework for bridge inspection based TLS data, which includes deformation measurement, damage detection, and as-built 3D model generation of bridge members.

2. RELATED WORK

This section is restricted to TLS-based methods for bridge inspection involving deformation measurement, damage detection, and as-built 3D model. Further details of the application of TLS in

bridge engineering have recently been published elsewhere (Truong-Hong and Laefer 2014a).

The most common approaches in TLS deflection measurement is to compare areas of a structure under unloaded and loaded conditions, whereas the fitting line/surface or the data points of the scanned area is used to determine deflection. In one of those, Lichti et al. (2002) measured vertical displacements of a bridge's stringers through a difference of fitting lines of each stringer cross-section. Similarly, Zogg and Ingensand (2008) compared the 3D point cloud from the unloaded and loaded conditions to measure deformations of the Felsenau bridge under static load. Moreover, Paffenholz et al. (2008) proposed a cell-based method, in which the median of the z-coordinates of each cell was used to determine the vertical displacements.

TLS has also been used to detect surface deterioration based on principal curvatures or gradients derived from analysis of point-based coordinates, or intensity and red-green-blue (RGB) values of the point cloud. In one of those methods was developed by Teza et al. (2009), in which a Gaussian curvature was applied to sub-areas of the dataset to identify damage. In contrast, Liu et al. (2011) used criteria of the distance and gradient of data points in grids for detecting defective areas. More recently, Mizoguchi et al. (2013) determined scaling depth as the distance from the point cloud in the scaling areas to the surface of an undamaged area. In contrast, Mosalam, et al. (2014) used the point's colour to detect areas with spalled concrete. González-Jorge et al. (2012) used point cloud intensity values detected biological crusts on a concrete surface.

Even significant effort has been invested developed to generate 3D structure models in building information modelling (Anil et al. 2012; Cabaleiro et al. 2014), the application in as-built bridge models is still limited. Mailhot and Busuioc (2006) used commercial 3D modelling tools to manually create a 3D surface model of the steel portion of the Champlain Bridge from a TLS point cloud. For a concrete bridge, Walsh et al. (2013) proposed to fit a face of a simple surface (planes, cylinders, spheres, cones, etc.) from a TLS point cloud of individual segments. According to the extensive research above, TLS has demonstrated its potential usefulness in capturing the current condition of structures for bridge inspection. What remains to be done is a means to integrate the various needs into a larger framework, as proposed below.

3. A PROPOSED FRAMEWORK

The proposed framework consists of five main parts: (I) preprocessing, (II) database system, (III) inspection (IV) management system and (V) bridge assessment (Figure 1), this paper mainly focuses on parts I and III. Parts II and IV are a database system to store a point cloud and images for inspection, and results of bridge inspection based TLS data. Meanwhile, a part V is developed an automatic tool to assess bridge rating and track damage change.

In preprocessing, the point clouds from multiple scan stations are registered and merged into a single coordinate system, and then irrelevant points (such as from the terrain) are manually eliminated. The point clouds from different inspection time are geo-referenced, which allows tracking of any change in a structure over a period of time based. These steps may most easily be done by using the scanner's proprietary software. Even though TLS can acquire dense topographic data points of a structure, a point cloud's attribution (3D coordinates and intensity value) may not be sufficient to define material deficiencies. RGB values of the point cloud generated from images would be done. To facilitate the preprocessing, the segmentation is applied to extract equivalent surface patches and/or structure components.

Inspection should be done in a way to include deformation measurement, damage detection and 3D, as-built model generation, as described below.

Deformation measurement involves overall displacements of the bridge and local deformations/distortions of each member; however, in some case, vertical clearance may also be an

issue. Under normal conditions, the shape of the member is assumed as a smooth surface representing by grid cells/patches. The deformation is the distance from the data points of the member's surface under loaded condition to a corresponding cell/patch. Moreover, for a case of moving load, since the time at which each data point was captured was included, the deformation over time the domain can be derived.

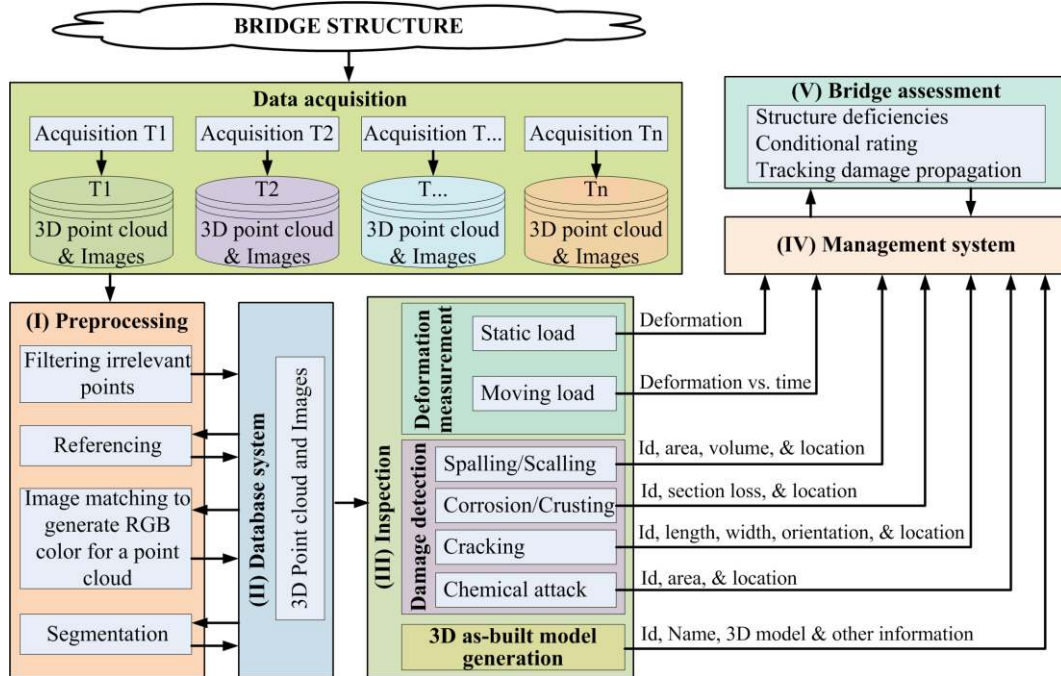


Figure 1: A framework for bridge inspection based TLS

Damage detection has four aspects: (i) spalling/scaling, (ii) cracking, (iii) corrosion/crusting, and (iv) chemical attack. At a location of spalling/scaling, geometry of this region differs significantly compared to an undamaged one. As such, the point cloud of the detected regions can be extracted from ones of entire member's surface by using the data points' features (i.e. a normal vector or a curvature). Then the area and location of the spalling/scaling can be determined directly from the point cloud; however, the volume of the damage is calculated by comparing a fitting surface of the damage area to the surface of an undamaged area.

For cracking, data points close to the crack edge can be recognized based the data points' features. In the presence of either noisy data or mixed pixels, the local surface variances may not provide sufficient information when the crack is small, particularly. In such cases, intensity values or RGB values of the point cloud can be used as additional attribute, in which the appropriate threshold strategy must be developed (Guldur et al. 2015). Either automatic or semi-automatic methods can be developed to estimate the crack features (length, width, orientation and location) from the point cloud of the crack edges.

In terms of corrosion, in reinforced/prestressed concrete structure, corrosion often occurs following spalling/scaling and will then generate further concrete cover loss. The approaches to detect spalling/scaling can be used to compute material loss. Intensity and RGB values of the point cloud can be used to extract the point cloud of the exposed reinforcement and/or prestressing strands. Subsequently, clustering and pattern recognition techniques can be employed to estimate strand's orientation and condition (i.e. the number and spacing). Intensity and RGB values are also useful for corrosion detection on steel structures. However, under severe corrosion section loss may occur. The area and location of the hole can be generated from data points on a hole's boundary by a cell-based angle criterion method (Truong-Hong and Laefer 2015a).

For chemical attack, similar to most corrosion in steel structure, the geometry of the damaged area has small variance. A possible means to detect this area involves supervised learning (i.e. González-Jorge et al. 2012) based on intensity and RGB values of the point cloud. However, these values vary to exposed surfaces subjected to different types of chemical erosion. Therefore, the method must be developed on a case-by-case basis.

3D as-built model generation is a non-trivial task due to the complexity of bridge structures, particularly those in steel. As-built models can be used in structural analysis for bridge assessment and for general management. From a point cloud of the entire bridge, segmentation is applied to extract the point cloud of each member separately. The surface fitting or sweeping spline fitting of a cross-section along a trajectory can generate 3D models of the members (Walsh et al. 2013; Tang et al. 2010). For a steel bridge, Truong-Hong and Laefer (2015b) adopted kernel density estimation to detect primary sides (web and flanges) of a real section for determining a standard steel cross-section. A matching strategy was then developed to map the extracted standard section to a point cloud of the cross-section. Finally, a 3D model of the steel member can be extruded from multiple cross-sections along a longitudinal direction.

4. TEST-BED BRIDGES

In order to test developed algorithms for automatic processing TLS data for bridge inspection, three test-bed bridges were scanned. Details of these bridges and the scanning information are given below.

Guinness Bridge built across the River Liffey in the 1880s is a 4m wide and 4m high metal truss bridge with a 52m clear span. The decking was a series of concrete arches spanning between the floor beams; these no longer exist. The bridge was scanned with a TLS Leica ScanStation P20. The structure was scanned with a sampling step of 1.6mm@10m and 6.3mm@10m for damage detection and as-built, and deformation measurement, respectively (Figure 2).

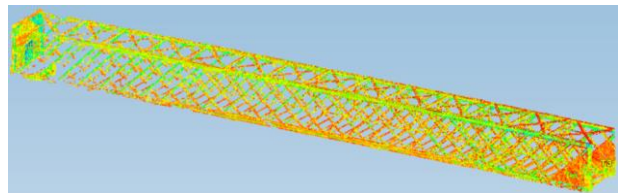
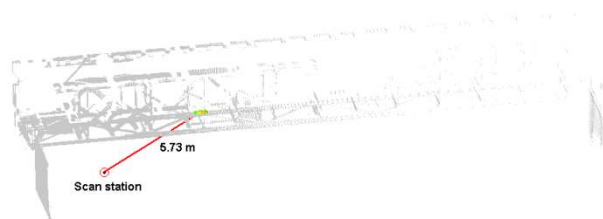


Figure 2: Point cloud of the Guinness Bridge

The Arteshofen and Lungsdorf Bridges are metal railway bridges built in the 1920s and located in the Pegnitz valley in the Bayreuth district of Bavaria, Germany. Both bridges are comprised of two trusses supporting by masonry abutments. The Arteshofen and Lungsdorf Bridges have a span of 31m and 37m, respectively. The first bridge was selected to measure vertical displacements of the bridge under dynamic loading from heavy equipment. The region of interest was approximately 65.5mm wide by 581m long at the bottom of the lower chord, located 8.9m from the bearing. The selected area was scanned with a sampling step of 1.6mm@10m corresponding to the angle spacing of $0.16e^{-3}$ degree from a distance approximate 6.73m (Figure 3). The expectation was to obtain a sampling step of 1.1 mm. The scanning time per scan is approximate 6.6 seconds.



a) Photo of the bridge



b) Data acquisition

Figure 3: Configuration of Arteshofen Bridge and data collection

The Lungsdorf Bridge was selected to demonstrate the ability of TLS for crack detection. The crack was scanned with a sampling step by 0.8mm@10m from a distance of 15.48m (Figure 7). The

vertical and horizontal angles from the scanner to the crack were respectively around 7 and 11 degrees. Moreover, an image of the crack was also taken by Nikon D7000.

5. TERRESTRIAL LASER SCANNING-BASED FOR BRIDGE INSPECTION

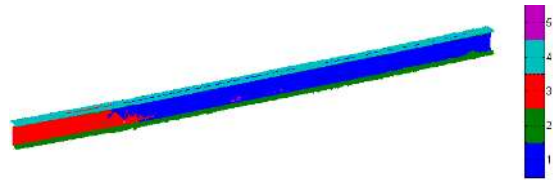
To demonstrate suitability of TLS data in bridge inspection, the point cloud collected from three bridges above was used as input data for the authors' previously published algorithms in deflection measurement, section loss due to corrosion, and 3D metal member reconstruction (Truong-Hong and Laefer 2014b; 2015a; 2015b). Moreover, this section also presents a crack detection approach from TLS data points where RGB values of the point cloud were derived from external images.

5.1 Deformation measurement subjected to static load

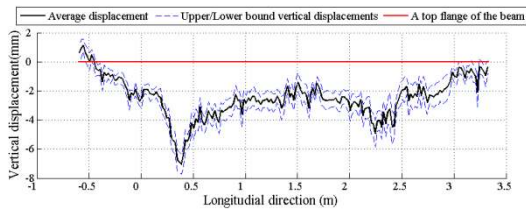
A point cloud of the floor beam No. 5 was selected to illustrate the use of TLS data to determine a local deformation of the member (Figure 4a and b). A point cloud to surface method presented in Truong-Hong and Laefer (2015a) was used to determine vertical deformation and lateral distortion based on the point clouds of the top flange and web, respectively (Figure 4c and d). Results showed a maximum vertical displacement of 7.05mm and maximum lateral distortion of 22.02mm. Since the data processing was cell-based, the accuracy of the approach was subject to cell size selection.



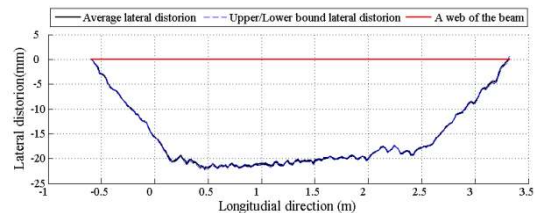
a) Photo of the floor beam No.5



b) A point cloud of the floor beam No.5(*)



c) Vertical displacements with a cell size of 20mm



d) Lateral distortion with a cell size of 20mm

Note: (*) the colour shows the data points in the same segment

Figure 4: Determine vertical displacements and lateral distortion of the floor beam No.5

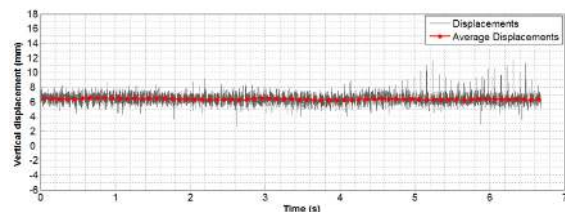
5.2 Deformation measurement subjected to moving load



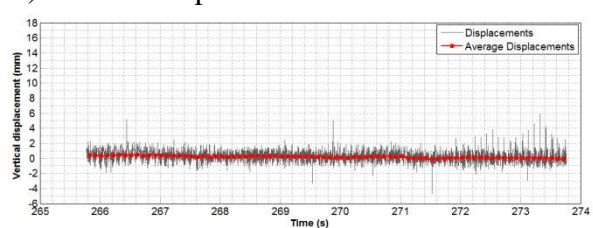
a) Track construction machinery on bridge



c) Empty bridge



b) Vertical displacements from 1-6.6 seconds



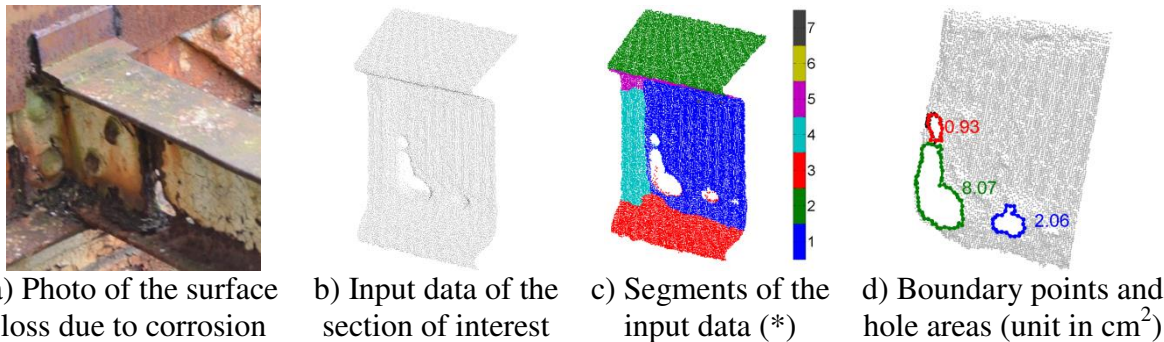
d) Vertical displacements from 265.7-273.7 seconds

Figure 5: Illustration of vertical displacement over time at Arteshofen Bridge

A point to surface based method presented in Truong-Hong and Laefer (2014b) was employed to determine vertical displacements under the German railway track construction machine at Arteshofen Bridge (Figure. 5a). Data points of each scan line and their order in the scan line can be extracted by using the known scan angle. The scanning time of each point can be then determined from the input start time and scanning duration of each scan. A point to surface based method was used to determine a vertical displacement at a specific time. The direct and smoothing vertical displacements from the two scans are shown in Figure 5, where a time step by 0.1s is used. The measurement shows that data noise mostly varied $\pm 1\text{mm}$. Since an elapsed time between two consecutive scans is 8.5 seconds, the monitoring process may not be continuous.

5.3 Section loss due to corrosion

A point cloud of the surface containing a visible section loss can be separated from the entire data set. A cell-based angle criterion method (Truong-Hong and Laefer 2015a) was used to detect points on the boundary of the hole, and subsequently generated the boundary line from these boundary points. The area and location of the section loss could be computed based on the boundary line.



Note: (*) blue points are the data points of the segment 1 containing surface loss

Figure 6: Calculation of area of section loss due to corrosion for the Guinness Bridge

The damage at a connection between lateral beam No. 3 and a bottom longitudinal chord of Guinness Bridge was selected for illustration of the algorithm (Figure 6). The method determined the area of surface loss within 10% of what was detected manually. Although the method worked properly in 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 hole (Truong-Hong and Laefer 2015a).

5.4 Crack detection

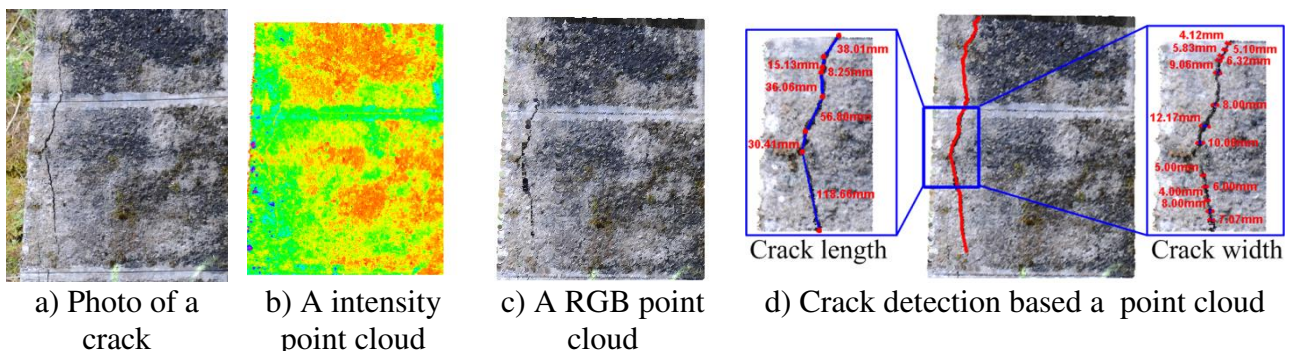


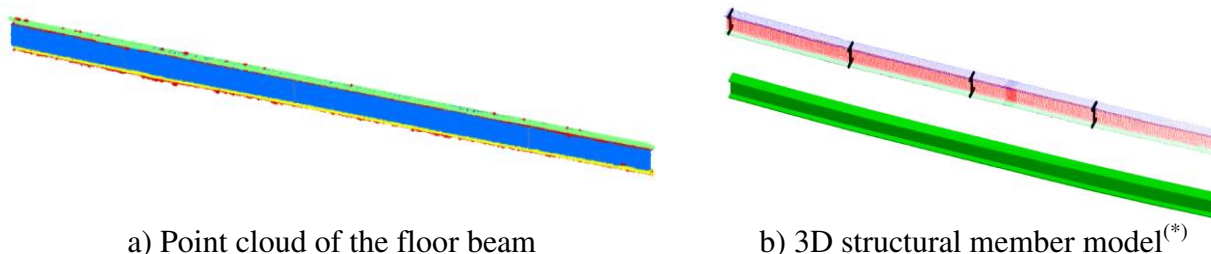
Figure 7: Crack detection at an abutment of Lungsdorf Bridge

Image clearly show crack patterns (Figure 7a), and image-based methods can detect cracks accurately but require supplementary information (Laefer et al. 2014). In reality, topographic data points associated with intensity values may not provide sufficient information to distinguish data points on the crack edge (Figure 7b). As such, the RGB colours generated from an image taken by

an external camera were used in identifying the crack pattern. A tool has been developed to measure length and width of the crack by picking points on the crack edge (Figure 7c). This demonstrates that crack identification from TLS data remains a big challenge. This is particularly true when the length and width of the crack are small, and intensity and RGB values of the point cloud of the surface around the crack is small variance.

5.5 3D as-built models

A point cloud of a structure of interest (herein floor beam No. 4) was manually extracted from the entire point cloud of Guinness Bridge (Figure 8a). A semi-automatic method (Truong-Hong and Laefer 2015b) was employed to determine the best match from standard steel sections and to map the standard section onto the point cloud of the section (Figure 8b). Finally, the complete 3D model was extruded from multiple mapping of standard sections. The method can detect the steel standard section properly. Since the matching standard sections were generated along a longitudinal axis of the member, a reconstructed 3D model can reflect the realistic form of the member, where deformations may exist.



a) Point cloud of the floor beam

b) 3D structural member model^(*)

Note: ^(*) the standard cross-section and the point cloud on a top; the 3D member model on a bottom

Figure 8: Generating a 3D model of the bottom floor beam No. 4 of Guinness Bridge

6. CONCLUSIONS

Although visual inspection is still the predominant method in bridge inspection, the capability of TLS in rapidly acquiring high dense topographic data points of structural surfaces has been emerging as an alternative solution. The paper presents a framework for TLS based bridge inspection, where a strategy of processing TLS data for deformation measurement, damage detection, and 3D as-built model generation are the main focuses. Furthermore, application of TLS data in deformation measurement, computation of surface loss, crack detection, and identification of metal members has been demonstrated as possible. A demonstration proves TLS-based methods can provide sufficient information for assessing condition of the structures.

In future work, the research will be extended to develop methods on measuring vertical clearance and the flatness of the bridge surface/structure. Furthermore, supervised methods will be investigated to detect a point cloud in damaged areas, which will implement into surface damage detection. Finally, database and bridge management system will be developed to store results from bridge inspection. Moreover, a tool for automatically tracking damage propagation and accessing bridge rating will also be developed.

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