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<b>Authors(s)</b>	Truong-Hong, Linh, Laefer, Debra F.
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# APPLICATION OF TERRESTRIAL LASER SCANNER IN BRIDGE INSPECTION: REVIEW AND AN OPPORTUNITY

## Abstract:

Heavy traffic and aggressive environmental conditions can cause unexpected bridge deterioration. Traditional condition evaluation is expensive. An alternative is Terrestrial laser scanning (TLS) which is a non-contact approach that safe, fast, and applicable to a range of weather conditions. This paper reviews applications of TLS on bridge measurement involving geometric documentation, surface defect determination, and corrosion evaluation, and crack identification. Currently, most post-processing of TLS is manual or within third party software. This paper discusses potential approaches to automatic post-processing.

**Keywords:** LiDAR; Terrestrial laser scanning; point cloud; bridge inspection; bridge clearance; bridge deflection; surface defects

## 1. Introduction

Knowledge of a bridge's condition is needed to establish a maintenance and replacement schedule. This requires surveying the physical condition to assess any deterioration, which can be time consuming [25] and typically requires at least partial bridge closure. A non-contact alternative that is gaining popularity is terrestrial Light Detection and Ranging (LiDAR), also known as terrestrial laser scanning (TLS), which enables data acquisition about an object's surfaces at a rate of a million points per second and with a millimetre level accuracy. This paper reviews recent applications of TLS in bridge engineering involving collection of a bridge's geometry to reconstruct models and to compute beam deflection, vertical clearance, and surface defections. In addition, two additional TLS workflows for crack detection and dynamic deflection measurement were also proposed.

## 2. Principal of Terrestrial laser Scanner

TLS uses either ranging or triangulation scanners [5]. With ranging, the distance between the transmitter and reflecting surface is computed either as the time of travel between signal transmission and reception called the time of flight (ToF) of a laser pulse or the phase difference between the transmitted and received wave, which is referred to as the phase comparison method. The latter one uses a transmitting device and a charge-coupled device sensor to detect the laser spot on an object. Then the three dimensional (3D) position of the reflecting surface element can be derived from the resulting triangle. For bridges and other large structures, ToF scanners are preferred because of their longer range [27].

The ToF scanner generates scanned points through a series of range measurements with uniform angular increments in both horizontal and vertical planes. This is controlled by rotating and nodding mirrors and rotating head mechanisms [12]. Thus, each sampled point is defined by spherical coordinates with the range measurement,  $R$ , horizontal direction,  $\theta$ , and vertical angle,  $\alpha$  (Figure 1).

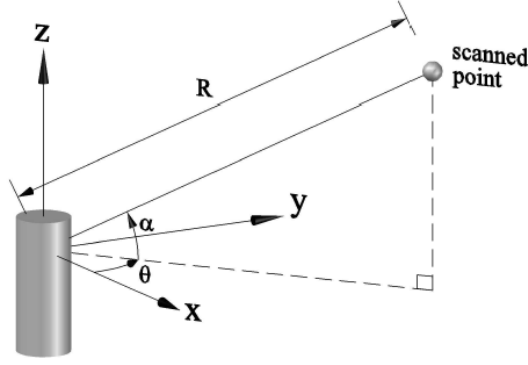


Figure 1. The principal of laser beam scanning

A range measurement is the distance from the transmitter to a reflecting surface,  $R$ , as expressed in Equation 1:

$$R = \frac{1}{2}ct \quad (1)$$

where  $t$  is the time interval between the emission and the pulse and its reception of the backscattered portion, and  $c$  is the velocity of light through air ( $3 \times 10^8$  m/s). A scanner's accuracy is largely based on the accuracy of the time measurement of the electronics integrated into the circuit (Equation 2). Furthermore, the ranging accuracy is inversely proportional to the ratio of signal to noise, which depends on various factors such as the power of the received signal, input bandwidth, background radiation, and amplifier noise [4,28].

$$\Delta R = \frac{1}{2}c\Delta t \quad (2)$$

Each raw scanned point ( $R, \theta, \alpha$ ) is automatically converted into a set of three-dimensional Cartesian coordinates ( $x, y, z$ ) by the scanner software, where the origin coordinate is at the scanner. Beyond the 3D coordinates of the scanned points, the scanner also acquires intensity values, which is a measure of the electronic signal strength obtained by converting and amplifying the backscattered optical power [21]. Pfeifer et al. [21] proposed the relationship between the emitted power,  $P_E$  and the received power,  $P_R$  as expressed in Equation 3 when the temporal variations of the pulse power are neglected.

$$P_R = P_E \frac{\cos \alpha}{4R^2} \pi \rho \eta_{\text{Atm}} \eta_{\text{Sys}} \quad (3)$$

where  $\rho$  is the reflectance of material,  $R$  is the range measurement, and  $\eta_{\text{Atm}}$  and  $\eta_{\text{Sys}}$  are respectively the atmospheric and system losses. Equation 3 implies that the intensity values strongly depend on the reflectance of the material, the incidence angle underlying a constant of atmosphere, and the range measurement [13,27].

Furthermore, by integrating a camera within the scanner, photographs of the scene can be taken simultaneously. From these images red, green, and blue (RGB) values can then be mapped onto each positional data point. Thus, information with each point cloud provided by TLS involves 3D coordinates, intensity values, and RGB values. To understand the capabilities of TLS in surveying bridge structures for inspection, the next section investigates recent work on TLS data processing in that field.

### 3. Bridge Inspection

TLS acquires 3D geometric data of a structure's surfaces as discrete data points. That information can be used to either reconstruct 3D models of the structures or to detect surface changes over time.

#### 3.1 3D Geometric reconstructions

Some of the earliest applications of TLS to bridges have been for the acquisition of historical arch bridges geometries [22]. In some cases, the surfaces were then derived by mesh triangulation to generate solid models and create a permanent record. In some instances, such as the work by Riveiro et al. [24], TLS was combined with close range photogrammetry. Similarly, Lubowiecka et al. [17] combined TLS with ground penetrating radar for a medieval bridge models to provide insight into the internal structure (fill material, arch stones and air water interface) of the bridge. Typically, these efforts rely on third party software or researcher driven algorithms such as that by Armesto et al. [2] who proposed fitting a non-parametric regression method based on a local bivariate kernel smoothing approach from the point clouds (Figure 2) for Spain's Segura Roma bridge.

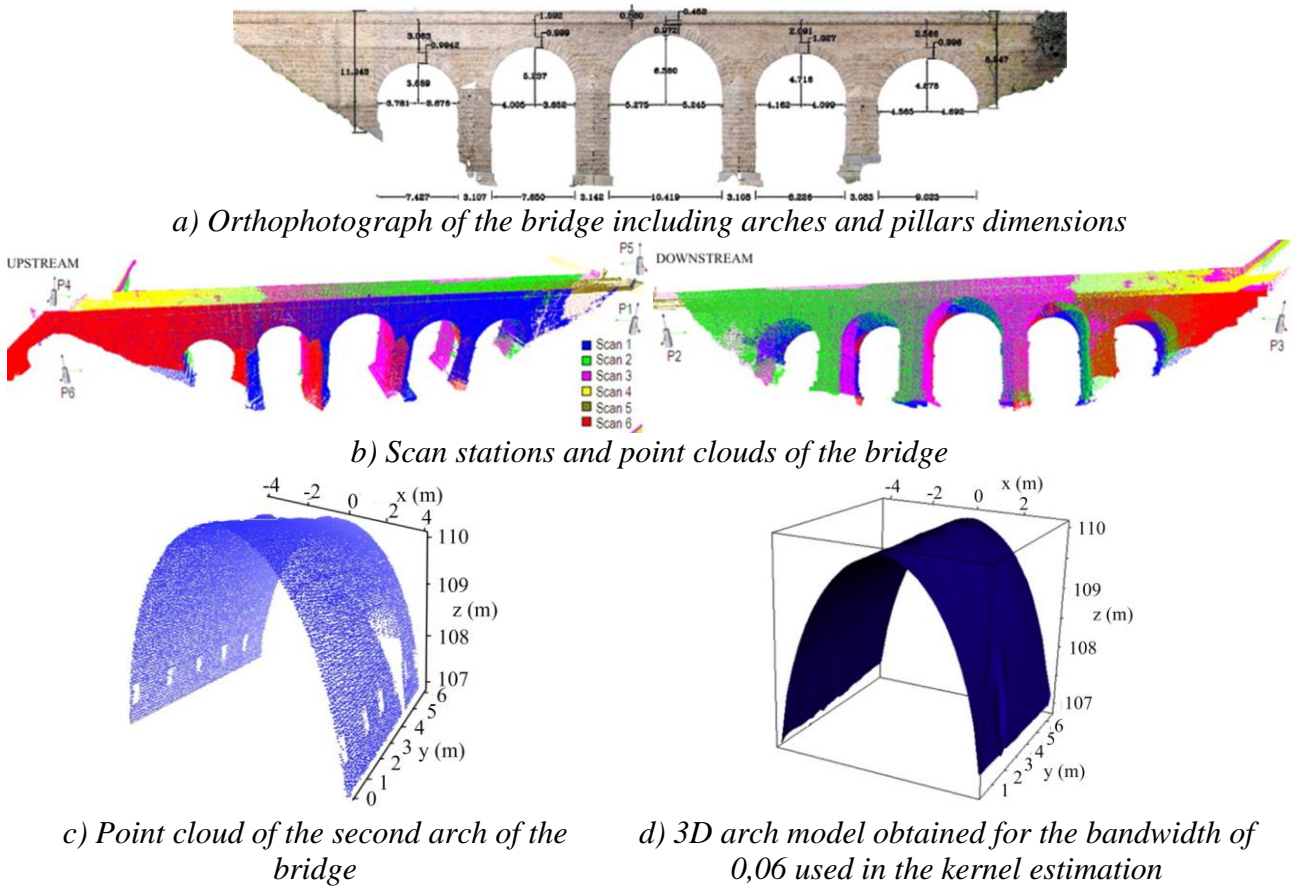


Figure 2. Reconstructing bridge models from TLS data by a non-parametric estimation algorithm (after [2])

### 3.2 Vertical bridge displacement

TLS has often been used to measure vertical deflections and vertical clearances, as summarized in Table 1.

*Table 1. Examples of TLS applied in measuring vertical clearances and bridge deflections*

Reference	Products	Sampling step	Application types	Verify method	Errors
Lichti et al. (2002)	I-SiTE (Riegl LMS-Z210)		Vertical deflection	Image taken by Olympus E20	9,1mm and 4,9mm (RMS)
Zogg and Ingensand (2008)	Z+F Imager 5006	12.5mm	Vertical deflection	Levelling	< 3,5mm
Paffenholz et al. (2008)	Z+F Imager 5006	~ 4mm	Vertical deflection	N/A	
Lovas et al. (2008)	Riegl LMS Z420i		Vertical deflection & 3D model	Levelling & total station	> levelling & < a total station
Kretschmer et al. (2002)	IMAGER 5003		Vertical clearance & 3D model	Traditional method	<±3cm
Riveiro et al. (2013)	Riegl LMS Z390i	~ 14mm	Vertical clearance & beam deflection	Total station and photogrammetry	(*) 9mm (>a total station) & 11mm (>photogrammetry) (**) -10mm - 0 mm;

(\*) Vertical clearance; (\*\*) beam deflection.

The first published vertical deflection measurements for bridges was done by Lichti et al. [6] in 2002, who measured displacements of stringers of a wood bridge in Perth, Australia. Vertical displacements were estimated by comparing fitting lines of the bottom and top of each stringer cross-section under loaded and unloaded conditions. Results showed that stringers deflections based on TLS data were larger than ones from image-based methods. Subsequently, Zogg and Ingensand [29] monitored deformations of the Felsenau bridge subjected to a static load of 54 tons performed at several sections of the viaduct. Third party software was 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. When measuring deflections of the Pentele bridge under the static load, Lovas et al. [16] reported that vertical displacements from TLS data gave strong correlations with traditional methods, although it over predicted the high-precision levelling and underpredicted the total stations. Paffenholz et al. [20] 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 z coordinates of each sub-area was used to determine the vertical displacements. Deflections up to 3mm were reported, but the accuracy was not. Finally, Berenyi et al. [3] noted that TLS can be used to measure the movements of the pylons and cables, whereas the traditional method cannot be done or unaffordable.

For measuring vertical clearance, Kretschmer et al. [10] monitored the v distance between the section of the road and its projection onto the bottom beam. The work showed vertical displacements-based TLS differing no more 3cm compared to ones-based from conventional

measurements. Furthermore, based on a 3D curve-fitting of a pavement surface and a beam camber from data points, the vertical clearance of an underpass bridge on the AP-9 in Northwest region of the Iberian Peninsula, Spain was estimated [23]. The work reported the vertical clearance-based TLS was slightly larger than ones-based total station by 9mm and ones-based photogrammetry by 11mm (for Canon 1000D). Liu et al. [14] measured the vertical clearance as the difference of z coordinates of the point clouds of the ground and the bridge deck in the same vertical scan line. In a study of four bridges in North Carolina, the maximum reported difference of vertical clearance based on TLS against the minimum inventory was 0.23m. Moreover, sub-millimetre accuracy has been reported by Kim et al. [9] when using mobile laser scanners (Geo-3D and Terrametric) along multiple paths under a bridge.

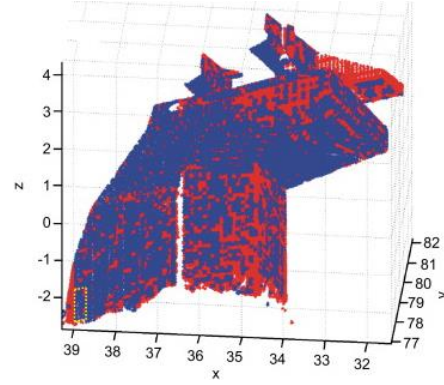
### 3.3 Surface defects

TLS has also been used to detect surface deterioration (e.g. biological crust, cracking, spalling or volume loss). Degenerated surfaces can be recognized based principal curvatures or gradients derived from analysis of point-based coordinates, or intensity and RGB values of point clouds. Observation of existing works on detecting surface damage of the bridge structures is summarized in Table 2.

*Table 2. Summary of the TLS application in detecting surface damage*

Reference	Products	Sampling step	Application types	Verify method	Errors
Teza et al. (2009)	Riegl LMS Z-420i	15mm for a column 7mm for a beam	Damage area		Correctly recognized damage area up to 87%
Liu et al. (2011)	LS 880HE		Damage area	No	No
Mizoguchi et al. (2013)	RIEGL VZ-400		Area & volume loss	Manual measurement	2.28mm (std = 3.60mm)
González-Jorge et al. (2012)	Riegl LMS Z-390i & Trimble GX200	5mm	Damage area	Photogrammetry based RGB	< 20%

As an example Figure 3 shows work by Teza et al. [26] using a Gaussian curvature in sub-areas of the dataset to recognise damaged area. In this work, the sub-area is considered damage if the standard deviation of the Gaussian curvature in this sub-area was greater than ones of the reference area. Alternately, Liu et al. [15] 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. As an alternative, Mizoguchi et al. [18] fitted 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.



a) Photo of the pier

b) Damage detection with sub-area size equal to 10 cm<sup>(\*)</sup>

Figure 3. Damage detection of the concrete column (after [26])

(\*)Blue is undamaged sub-areas with standard deviation (std) of Gaussian curvature less than 16;  
Red: damaged sub-areas with other values of std of Gaussian curvature; black: non classification  
since undefined curvature.

Differing from the methods above, González-Jorge et al. [8] proposed an unsupervised classification method to detect biological crusts on concrete surface based point cloud intensity values. Both K-means and Fuzzy C-means algorithms were to classify the intensity ortho-image into biological crusts, water, and concrete classes. The study showed very similar results for the two algorithms.

#### 4. Discussion

As TLS can save up to 90% of the time required data acquisition, it has been widely used in civil engineering [7,19] mapping cracks, delaminations, scaling, spalls and steel loss in both decks and girders [1]. However, existing algorithms for post-processing data remain either semi-automatic or entirely manual require significant user experience. Further automation in bridge inspection, requires that additional efficient, reliable algorithms be developed

As an example, according to a recent study by Laefer et al. [11], TLS can detect a crack as little as twice its sampling step (confirming the values of 1.6mm to 4.8mm proposed by Ahlborn et al. [1]). Based on this, a TLS-based crack detection workflow is proposed in (Figure 4). As the area within the crack width is subjected to a different light source and has different surface characteristics from the exteriors ones, the intensity values of point clouds in this area are distinguishable with the point cloud of the surface structure Point clouds within the crack lie on a different plane from the structure ones. From this, both intensity and depth thresholds are proposed to detect the point clouds of crack edges. Subsequently, a crack's width and length can be estimated.

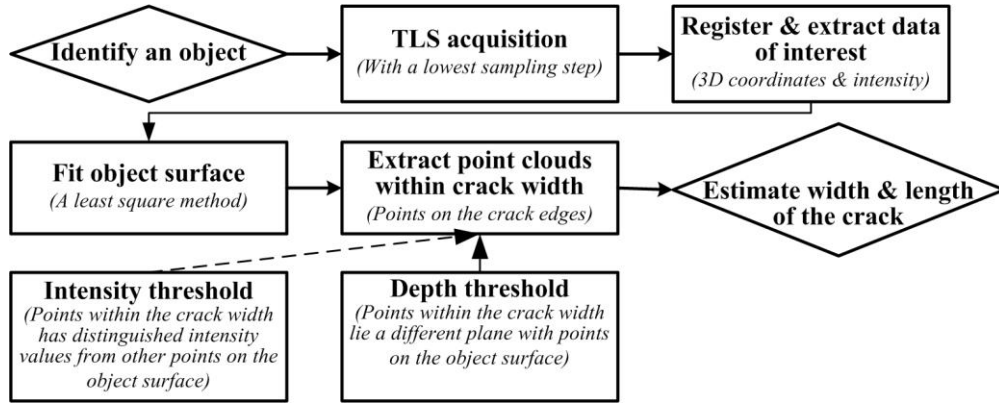


Figure 4. Workflow for detecting crack characteristics

Furthermore, since the scan rate of a commercial TLS generates up to a million points per second, vertical deflection monitoring of a bridge girder over time domain is possible. To pursue this task, the workflow in Figure 5 is proposed. This is based on the hypothesis that the vertical displacement of a bridge beam is nearly constant over a small section (e.g. 50mm length along the longitudinal direction). In such a case, the z-coordinate of each point cloud within time domain is the relative elevation of the beam section. In addition, multiple scan windows can be defined to acquire point clouds of the section of interest over a period time. Then, by comparing the beam elevation under self-weight to the loaded conditions, the vertical deflection in the time domain can be obtained. However, one drawback of the scanner is that the time that elapses between two consecutive scans (often less than 10 second), can cause data to be missed. The consequence is that the maximum deflection may not necessarily be captured.

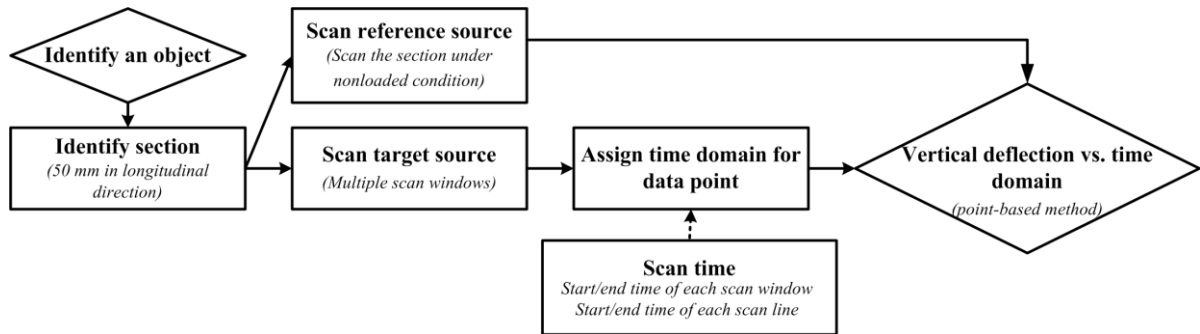


Figure 5. Workflow for capturing vertical deflection due to a dynamic vehicle

## 5. Conclusion

Throughout the rapid development of laser scanning technology over the past decade, TLS has been widely used in acquiring geometric data for various applications. To make engineers and bridge inspectors aware of the feasibility and affordability of TLS in bridge inspection, this paper reviews recent applications to TLS in this field. The majority of TLS applications remain focussed on geometric data collection for reconstructing bridge models, computing beam deflection and vertical clearance, detecting surface deflections, and overall documentation. Current workflows of post-processing data are either manually or semi-automatically, which required significant experience of users, and results are also sensitivity to predefined, user-selected criteria. Further automation is needed. To assist in this, a detect crack and a vertical displacement measure workflow are proposed.

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