Non-Contact Bridge Deflection Measurement: Application of Laser Technology

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Abstract

Structural deflections represent a critical response parameter often measured for structural health monitoring. Traditional measurement sensor technologies such as DCDTs, LVDTs, etc., require attaching the device between the point of measurement and a reference point. Generally, this requires connecting the sensor to the ground or a temporary structure such as scaffolding. Use of the traditional sensors for highway bridge deflection measurement poses many challenges as most of them are over either a road or a waterway. Because of these challenges, they are not often used and deflection is calculated either from indirect data such as girder end rotation or the structural parameters that contribute to deflection which is derived from measurements such as strain and curvature. Strictly speaking, measured displacements provide the best means for understanding structural behavior. Aiming at addressing the challenges of direct measurements of bridge deflections, this article will address the capabilities of two state-of-the-art non-contact measurement technologies. These technologies are: Laser Tracker and Laser Scanner. Laser Tracker records position coordinates at few discrete points while the laser scanner captures point clouds representing deformed and undeformed shapes of a structure. These two remote technologies present distinctive advantages, capabilities, limitations, and several challenges for field applications. The article will present a case study where laser tracker and laser scanner was collaboratively used to measure the deflection of a highway bridge under static truck loads. Further, the capabilities, limitations, and several challenges for field applications of these technologies will be summarized.

Keywords: Bridge, Deflection, Laser Scan, Laser Tracker, Non-contact

1. Introduction

Bridge deflection, which is influenced by many factors including skew, bearing type and configuration, and structural stiffness distribution, is an indicator of the structural soundness (Sugisaki et al. 2010). Traditionally, static bridge deflection is measured using cable extension transducers (potentiometers), linear variable differential transducers (LVDTs), or direct current differential transformers (DCDTs) (Aktan et al. 2003). The major drawback in this approach is that it measures displacements relative to a fixed reference (Sugisaki et al. 2010). The most common approach is to tie the cable to the ground or to a temporary structure such as scaffolding. Hence, it is impractical to use such instrumentation on bridges over waterways, highways, railways, or with high clearances (Hou et al. 2005). Because of these challenges, they are not often used and deflection is calculated either from indirect data such as girder end rotation or the structural parameters that contribute to deflection which is derived from measurements such as strain and curvature. Strictly speaking, measured displacements provide the best means for understanding structural behavior.

In order to avert using above stated measurement technologies that require fixed references, several other technologies and procedures have been developed and utilized in the field and laboratories. Hou et al. (2005) used inclinometers to measure angular changes in bridge sections and to calculate rotation and deflection. Chang et al. (2010) deployed a sensor network that consists of fiber optic bragg-grating (FBG) strain sensors. The FBG sensors record strains due to dynamic loads; hence, mode decomposition technique is used to calculate the static displacement of a bridge. Use of both inclinometer and FBG strain sensor data to calculate bridge deflection requires several assumptions making it impractical to deploy in complicated structural systems such as bridges. Other technologies that have been evaluated are digital speckle photography (DSP) by Chiang and Yu (2010), digital image correlation (DIC) by Yoneyama et al. (2010), Digital Close-Range Terrestrial Photogrammetry (DCRTP) by (2003), photo total station system (PTSS) by Zhang et al. (2006); a combined system of a psuedolite, dual frequancy GPS recievers, and a triaxial accelerometer by Meng et al. (2003); a 3-D laser scanner by Chang et al. (2008); the Laser Doppler Vibrometer (LDV) by Nassif et al. (2005) and Miyashita et al. (2010); CCD laser displacement sensor by Umemoto et al. (2010); and a total positioning station (TPS) by Westgate et al. (2010). Majority of the listed technologies have been evaluated under laboratory conditions while a few of them have been deployed on simple structures under outdoor conditions. Measurement accuracy of digital systems depends on the intensity of the light sources. Accuracy of calculated displacements is governed by the complexity of the structural system, assumptions, and exposure conditions.

The paper presents bridge deflection measurement using two technologies, a *laser tracker* and a *laser scanner*, equipment specifications, and capabilities and limitations of the technologies with respect to the specific application.

2. Laser Tracker

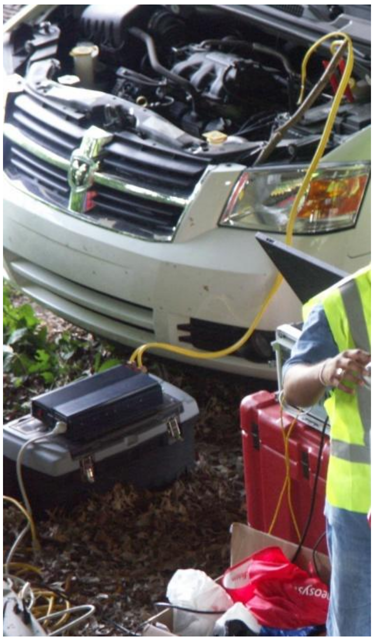
Laser tracker (Figure 1a) measures the coordinates (x,y,z) of targets with high accuracy (Table 1). Laser tracker has two main components: laser interferometer and optical encoder. The Interferometer is used to measure the distance to a target by counting the fringes of the two interfered laser beams: beam reflected from a target and the reference beam. The optical encoders are for measuring the azimuth and elevation of the laser beam after it strikes the mirror.

An inverter is used to power the control unit and laptop (Figure 1b). The entire operation is controlled using a laptop and a control unit (Figure 1c). Two types of reflectors are used with the Laser Tracker. One of them is a 0.5-in. diameter glass prism reflector (Figure 1d). The 0.5-in. reflector has an acceptance angle of $\leq \pm 50^0$. The other is a 1.5-in. diameter Red-Ring-Reflector (RRR) that is made of surface-hardened magnetic stainless steel with an acceptance angle of $\leq \pm 30^0$ (Figure 1e). Having at least one of these red-ring reflectors is required with the equipment. A meteorological station (Figure 1f) with temperature, humidity and pressure sensors is attached to the tracker for measuring ambient conditions as well as the structure temperature.

Table 1: Laser Tracker Specifications (Leica Geosystems 2010)

Ambient conditions	
Working temperature	*+0°C to +40°C (32°F to 104°F)*
Storage temperature	*-10°C to +60°C (14°F to 140°F)*
Relative humidity	*10 – 90%, non-condensing*
Absolute Interferometer (AIFM)	
Principle technology	*Single Beam Heterodyne Interferometer with Polarization Modulation Absolute Reference*
Wavelength	*633 nm / 795 nm (visible / IR)*
Largest Beam diameter	*4 mm*
Interferometer Distance Resolution	*0.32 µm (0.000013”)*
Interferometer Distance Accuracy	*± 0.5 µm/m (± 0.000006”/ft)*
Dynamic Lock-On Accuracy	*± 10 µm (± 0.00039”)*
Typical Lock-On working range	*1.0 – 80.0 m (3.3 – 262 ft)*
Accuracy information	
Angular resolution	*0.14 arc sec*
Angular repeatability, full range	*± 7.5 µm + 3 µm/m (±0.0003” + 0.00004”/ft)*
Angle accuracy, full range	*± 15 µm + 6 µm/m (±0.0006” + 0.00007”/ft)*

(a) Laser Tracker



(b) Powersupply (an inverter)

(c) Control unit and laptop

(d) 0.5-in. glass prism reflector

(e) 1.5-in. red-ring reflector (RRR)

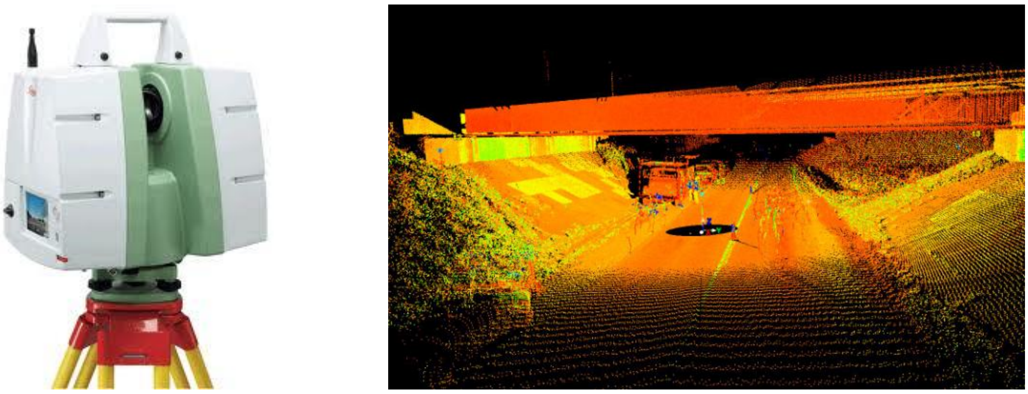
(f) AT MeteoStation

Figure 1: Equipment and accessories

3. Laser Scanner

The laser scanner used in this research (Figure 2a) has three components working together to sample 3D points on surfaces surrounding the laser scanner: the laser source, mechanical system, and timing system. During the data collection (scanning), the laser source continuously shoots out laser pulses with a frequency of 50,000 HZ; the mechanical system rotate the laser source horizontally and vertically, and record the azimuth and elevation angle of the laser source while shooting out each laser pulse; the timing system record the time different between sending out and receiving a laser pulse, and derive the distance from a measured point to the laser source. With the distance information reported by the timing system, and the azimuth and elevation angle reported by the mechanical system, coordinates of a 3D point can be determined for each emitted laser pulse. As a result, a 50,000 HZ scanner can theoretically collect 50,000 3D points per second. This data collection rate, however, can only be actually achieved when the user choose to complete a very dense scan (high-resolution scan) fully utilizing all laser pulses emitted. For sparse scans, the data collection rate is lower than 50,000 HZ.

This scanner is capable of capturing geometric details of the studied bridge with mm-level accuracy and detailed spatial resolution without attaching targets to the bridge. Configured with a data density of 1 cm at 10 m (sampling a surface 10 away from the scanner with a step size of 1 cm), this scanner can sample 3D measurements on surfaces visible from the laser source without using any reflective targets or prisms. Within the working range (0 to 300 m), most 3D points can be positioned within 6mm. With thousands of points of mm-level accuracy, meshing algorithm can construct 3D surfaces with accuracy of 2 mm. In this study, we put the scanner right below the center of the skewed bridge's superstructure (the black circle in Figure 2b was caused by the fact that the scanner cannot see the road right below it, signifying the scanning location), capturing most part of the bridge with point clouds denser than 2.5cm.



(a) (b)

Figure 2: (a) Laser scanner and (b) a scan of a bridge site

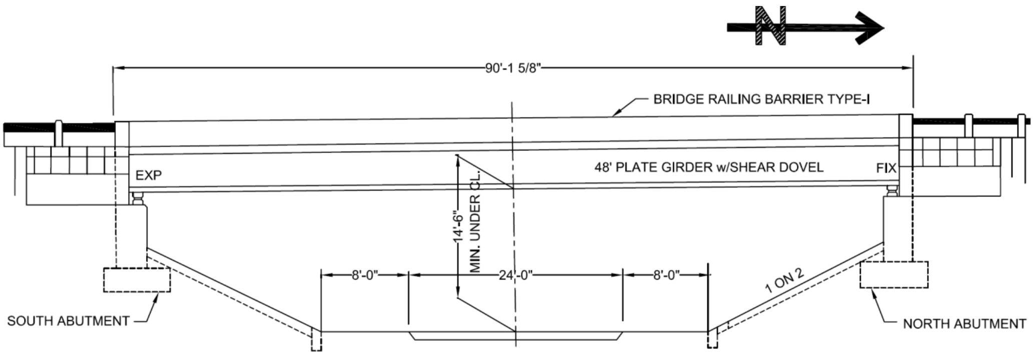
4. Bridge Deflection Measurement

A 120 ft long, 44 ft wide, 42-degree skew, single span simply supported bridge with two lanes of traffic was selected. The bridge consists of seven steel plate girders with cast-in-place concrete deck as depicted in Figure 3. The seven steel plate girders, intermediate diaphragm, and end diaphragm locations are depicted in Figure 3b. The girders are supported on fixed bearing at north abutment (abutment B) and on expansion bearings at south abutment (abutment A), respectively. Fixed bearings at the north abutment are in good condition except the ones underneath the exterior girders. Steel on bronze plate bearings are used over the south abutment and 1.875 in. space is provided to accommodate bridge movement due to thermal expansion and contraction. Majority of expansion bearing anchor bolts are bent inward or outward indicating frozen bearing conditions.

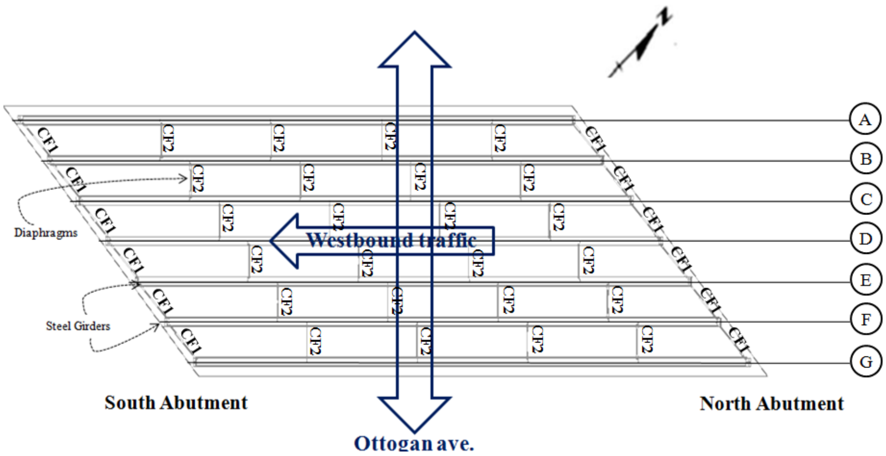
The bridge was loaded in four mutually exclusive configurations by using two trucks (Truck 04-4009 and Truck 04-1659) as shown in Figure 3c. A detailed finite element model of the bridge was developed and analyzed under the loading configurations. As designed boundary conditions (fixed - expansion) and frozen bearing conditions (fixed – fixed) were considered. Deflection along girder centreline was calculated under each loading configuration.

Laser tracker recorded position coordinates at discrete points along the girders where reflectors were attached. Laser tracker default coordinate system of which the vertical axis is aligned in the gravity direction was used. Position coordinates of the reflectors were documented before and after each loading configuration and the difference was documented as the deflection. One out of two lanes of the bridge was opened to traffic during load testing; hence, ten measurements were recorded at every instance and the statistical average was used to calculate girder deflection.

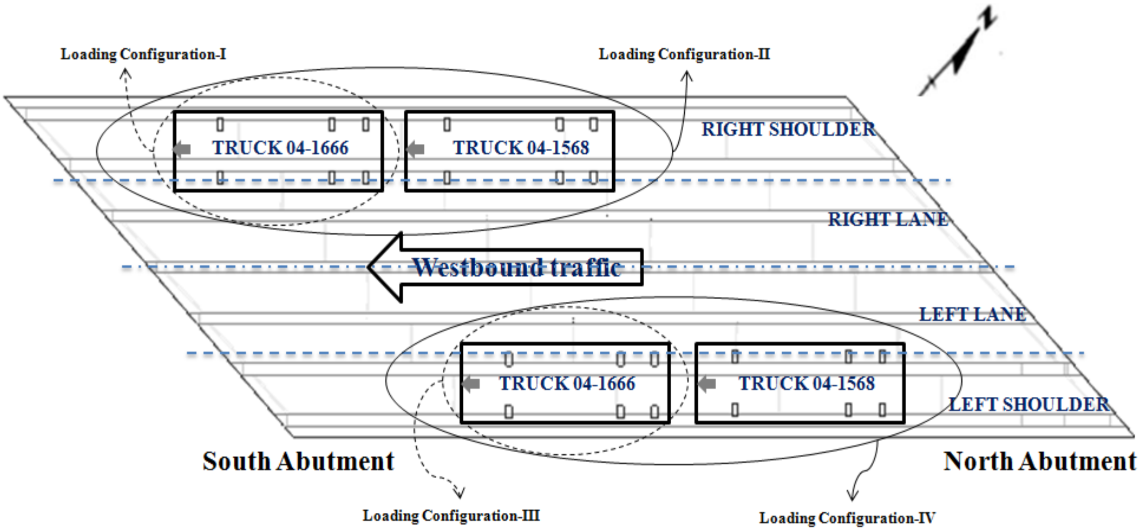
To have most part of the bottom surface of the bridge superstructure visible from the scanner, we set up the scanner right below the center of the superstructure. At the same time, with equal distances to the four corners of the bridge superstructure, this scanning location can achieve balanced data densities for the whole bottom surface of the superstructure. Before and after each loading configuration, a scan was taken with data densities of 1 cm at 10 m, covering the whole superstructure's bottom surface with data densities of at least 2.5cm. Every scan took about 6 minutes. The empty condition of the bridge was used as the reference geometry for deriving the deflections: all other scans will subtract this reference geometry along the vertical direction for obtaining vertical deformations on the bottom surface of the superstructure.



(a) Elevation



(b) Girder and diaphragm layout



(c) Loading configurations

Figure 3: Isometric and elevation views, girder and diaphragm layout, and loading configurations

4.1 Bridge Deflection

Girder A and G deflection calculated from laser tracker and laser scan data and finite element model with frozen bearing conditions (fixed – fixed) under loading configuration II and IV are depicted in

Figure 4 and 5. Girder A and G are the exterior girders and represent maximum deflection of the deck under the configuration II and IV, respectively. It is worth stating here that the girder deflection is calculated along centreline of girder bottom flange. Because of skew and eccentric loading, girders are subjected to significant twist and plotting deflection along girder centreline is not capable of representing torsional deformation. To verify the twists of girders, Girder G bottom flange deformation under loading configuration IV was developed from laser-scanned data and depicted in Figure 6. As this flange is colour-coded with deflection values (legend in Figure 6b), we can see that even though the major trend is that the deflections are larger in the middle, the decreasing trend of deflections from the middle to two sides is not uniform along the lateral direction of the bridge. For example, the bottom part of Figure 6 has slightly wider region of larger deviations than the upper part, indicating that cutting at different lateral locations will result in slightly different deflection profiles of this girder. Such variations of deflection profiles along the lateral direction indicate the existence of torsions.

There are many reasons for the differences in laser tracker measurements with respect to what is predicted from FE model: 1) offset of reflectors in the vertical direction from girder bottom flange; 2) offset of reflectors in transverse direction from girder centreline; 3) bridge vibration (note that one of the two lanes was opened to traffic during load testing); and 4) deviation of bridge behaviour from its ideal conditions represented by the finite element model.

In addition to the reasons mentioned above, some possible reasons causing the differences between the deflections generated from laser-scanned data and the deflections predicted from FE model include: 1) the deflections are generated from linearly interpolated locations on triangulated surfaces reconstructed from scans, occlusions and missing data may causing difficulties of linear interpolation and distort the deflection profiles; 2) torsional deformations of girders are out-of-plane, and vertical cross-sections of a girder from different scans under different loading conditions might not be the same physical cross-sections of the girder, and using them to derive the deflections might cause distortions.

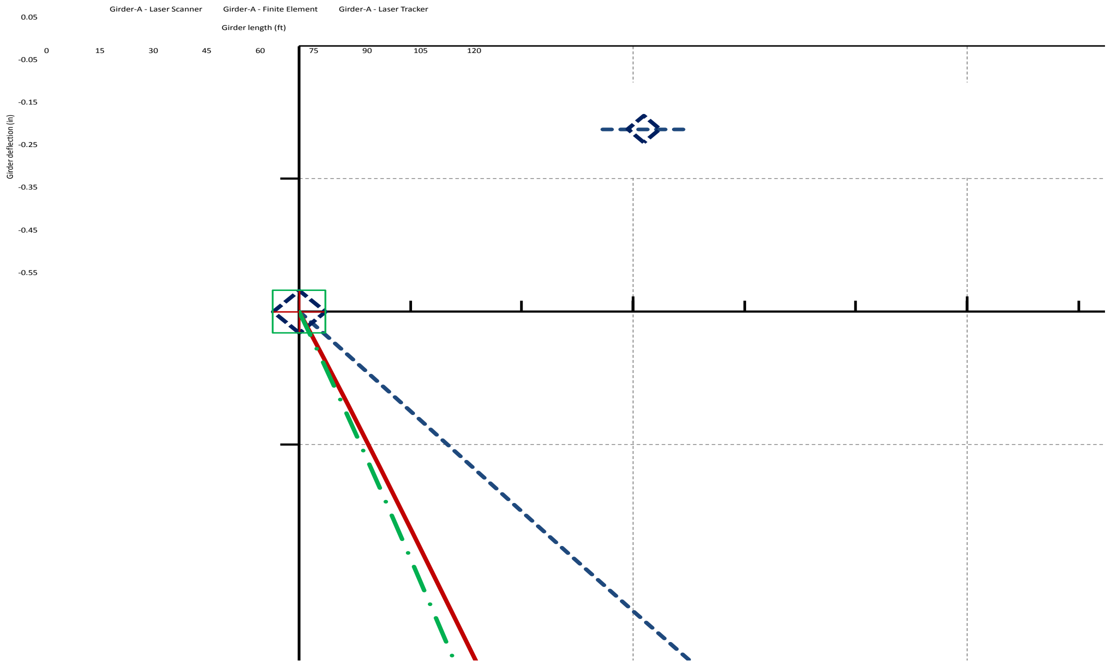


Figure 4: Girder A deflection – loading configuration II

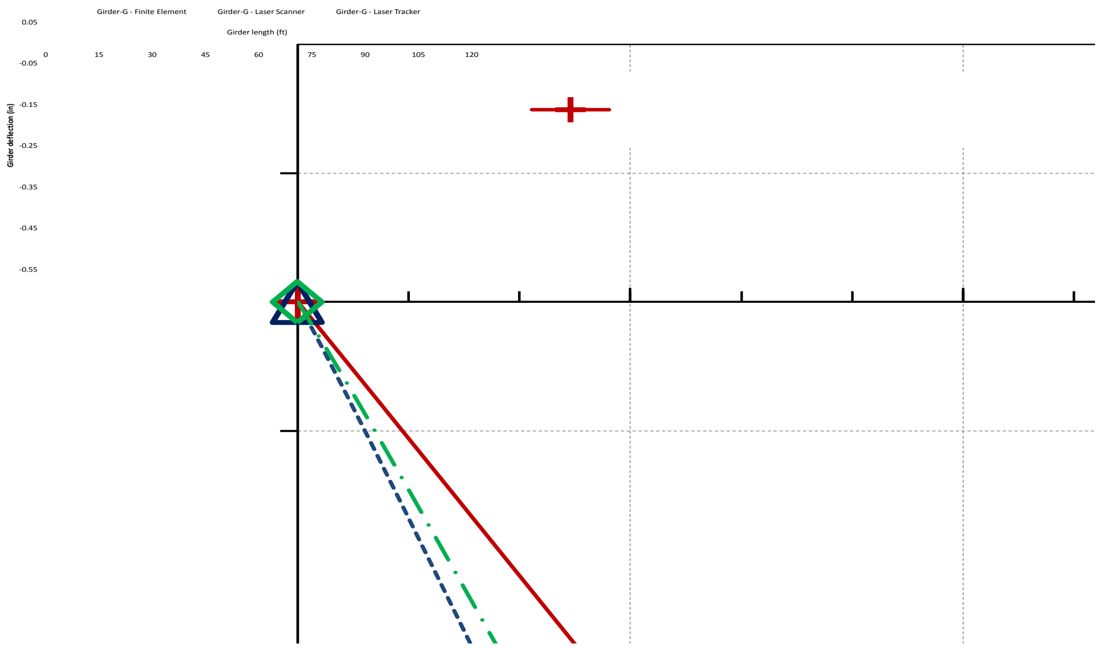
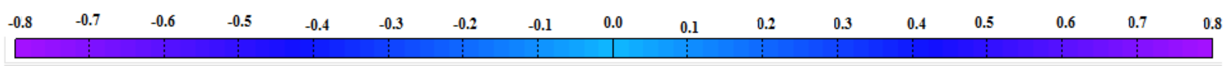


Figure 5: Girder G deflection – loading configuration IV

(a) Girder G bottom flange deformation



(b) Legend

Figure 6: Girder G bottom flange deformation – loading configuration IV

5. Summary and Conclusions

Two non-contact technologies for bridge deflection measurement are presented: *Laser Tracker* and *Laser Scanner*. Both technologies present distinctive advantages and limitations in field applications.

The *Laser Tracker* capabilities and limitations for deflection measurement under indoor and outdoor exposure conditions were evaluated. The specific application presented in this paper demonstrated that the deflection measurement of a typical bridge span using *Laser Tracker* takes about two hours from reflector installation to wrapping up of a static load testing. This study yields the following conclusions related to *Laser Tracker* application,

1) The *Laser Tracker* provides a fast, accurate, and economical non-contact means of measuring bridge deflection.
2) The *Laser Tracker* can be used in the field for monitoring structural deflection/deformation at multiple locations under static loads. There is no limitation to number of measurement locations on a structure. Generally, the decision is governed by the objective, scope, and the project budget.
3) Reflectors should be mounted along the girder centreline and the offsets should be minimized as practically as possible.
4) Laser is very sensitive to exposure conditions and the quality of air it travels through. System is capable of performing few basic adjustments based on measured in-situ weather conditions (temperature, humidity, and pressure). However, adequate measures are needed to avoid interference of heat waves. Performing measurements at night helps avoiding heat waves and minimizing impact to the public.

In this study, the used laser scanner shows potential of field applications with the capabilities of capturing dense point clouds in minutes with mm-level accuracy. Some major pros and cons of using a laser scanner for field applications are listed below:

1) The *Laser Scanner* provides a fast and non-contact means of deriving bridge deflections with mm-level accuracy and cm-level surface sampling rates.
2) The *Laser scanner* can be used in the field for monitoring detailed structural deflection/deformation. The densities of point clouds control the densities of deflection measurements, and in this study 6-min scans were able to capture all geometric features larger than 2.5cm across the bridge superstructure.
3) Deriving deflections from dense 3D points requires the users to go through a 3D model construction process (meshing) requiring substantial knowledge, experiences and skills of laser-scanned data processing and computer graphics. Improper data processing (e.g., linear interpolations on occluded parts of laser-scanned data) may distort the generated deflection profiles. Further explorations are needed for identifying proper data processing pipelines for generating accurate deflection profiles from dense laser-scanned point clouds.

4) Compared with the laser tracker, a laser scanner can measure much denser 3D measurements with lower accuracies, hence these two sensors having complementary technical capabilities. An integrated processing of data sets from these two sensors may produce more accurate deflection measurements. Future research will explore such integrated data processing methods.

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Research Publication Liability Disclaimer

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