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APPLICATION OF LONG RANGE 3D LASER SCANNING FOR REMOTE SENSING AND MONITORING OF COMPLEX BRIDGE STRUCTURES

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Abstract
Feasibility of applying non-contact long range 3D laser scanning as a practical tool for the modeling and monitoring of complex medium to long span steel bridges is examined. The effectiveness of this technology is demonstrated via a field application to evaluate global thermal movements along the cantilever type main span and portions of the approach trusses of the Champlain Bridge, Montreal, Canada, representing a surveyed length of more than 450 metres.

Three-dimensional (3D) laser scanning technology is described in general as are the specific technological platform, equipment, set-up, methodology and data processing techniques used to achieve the level of precision required to construct a detailed model of the main span superstructure and portions of the substructure. Moreover, the paper shows how geometric changes due to temperature variations can be detected and quantified.

The paper includes a discussion of the potential benefits of 3D laser scanning technology for bridge management, surveying and monitoring purposes. Potential uses include bathymetric laser scanning of submerged structures, constructing or enhancing as-built drawings, performing field measurements to produce shop drawings, reducing risks associated with hands-on site exposure and establishing a bench mark of pre-existing conditions in order to detect changes in geometry resulting from extreme loadings.

1. Introduction and background

Three-dimensional (3D) laser scanning has been available on a commercial basis since the late 90's [1]. Like several other new technologies currently used in civil engineering, 3D long range (3DLR) scanning has evolved rapidly with the ever increasing computer data processing and graphic capabilities.

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The Jacques Cartier and Champlain Bridges Incorporated (JCCBI) obtained its first exposure to this innovative technology following a quick but highly detailed 3D survey of one of the massive tie-down piers of the Jacques Cartier Bridge (Fig. 1).

Figure 1: 3D laser scan of Jacques Cartier Bridge tie-down pier

The demonstration survey conducted by SCDS-PRO Inc., which required less than 3 hours of field work and about 2 hours of data processing time, was sufficient to convince JCCBI that a closer examination of this technology for bridge surveying, 3D modelling and monitoring was merited.

JCCBI chose to pursue investigations into the feasibility and effectiveness of this technology for applications to large civil engineering structures via a demonstration project aimed at evaluating global thermal movements of the cantilever type through-truss main span of the Champlain Bridge, Montreal, Quebec.

The main span of the bridge which measures 450.4 m makes this project one of the largest 3D laser scans ever conducted worldwide. The Champlain Bridge was targeted for this survey because conventional manual measurements over the years were indicating an abnormal global thermal response, particularly along the approach trusses. It was believed that the abnormal thermal response of the bridge was occurring as a result of unintended restraints at expansion bearings which were replaced in the early 80’s.

The main objectives of the 3DLR survey were to: i) evaluate the level of precision which could be achieved by this technology; ii) evaluate the effectiveness of the technology when applied to a large, complex and difficult to access structure such as the Champlain Bridge; iii) determine if 3DLR laser scanning could be used to provide a more comprehensive understanding of overall global thermal movements iv) compare data obtained from 3DLR to similar information gathered from conventional means such as shop drawings and field measurements and v) explore other potential uses of this tool for structural monitoring and bridge management in general.

2. Long range 3D scanning (principle and technological platform)

To fully record a complex object, the scanner (HDS 2500) is moved around the object to measure points from many different angles and hence achieve complete coverage. A time-of-flight scanner such as the one used for this project shoots a laser pulse at the object and measures the time taken for the pulse to return to the scanner. Knowing the speed of light, the distance from the scanner to the surface of the object can be calculated. While a laser pulse is sent out at regular time intervals, motors which pivot two separate mirrors inside the scanner allow the laser to sweep over the entire surface of the object. The 3D points are calculated as a combination of the horizontal and vertical angles of the mirrors plus the measured distance. This method has a long range, up to about 200 m under ideal conditions.

CYCLONE is the software interface used to operate the scanner. Features such as user specified scan area and density, data filtering, scan scripting and automatic target recognition and extraction and other tools are provided that help to ensure the accuracy and reliability of the collected data. The versatile and powerful modeling module of CYCLONE enables operators to use point clouds directly and process them into objects for robust export into CAD or other applications and also to allow robust import of data from CAD.

3. Bridge description and survey zone

3.1 Bridge description

The steel portion of the Champlain Bridge as shown in Figure 2 has a total length of 763.5 m measured from piers 4E to 4W. This length includes the 450.4 m cantilever type main span which is composed of two 117.5 m anchor arms, two 49.0 m cantilever arms and a central suspended span of 117.5 m thus providing a maximum clear span of 215.4 m between piers 1E and 1W. The main span is flanked by two deck-truss approach spans on both sides of the cantilever span, namely between piers 4E to 2E along the east side and 2W to 4W along the west. Locations of expansion and fixed bearings are identified in the same figure.

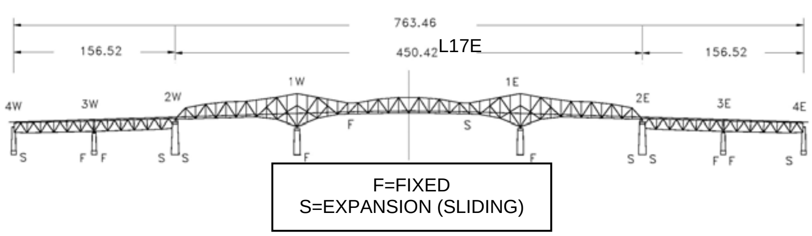

Figure 2: General layout of main span and approach spans

Maximum bridge expansion/contraction occurs at panel point L17E where a modular expansion joint consisting of 3 modules is provided in the orthotropic steel deck which was installed in 1992 and 1993 replacing the original reinforced concrete deck. Due to the configuration of the bridge and the location of expansion bearings, maximum bridge movement takes place at expansion joint L17E, where this joint accommodates thermal movements generated over a theoretical tributary length of 215.4 m.

3.2 Survey/target zone and site access

The zone surveyed under the demonstration project extends from about 9 m west of Pier 2W to about 10 m east of pier 2E. This survey length permitted the acquisition and extraction of expansion/contraction measurements occurring at the main span anchor piers which also support approach deck-trusses. Both the upstream (North) and downstream (South) faces of the superstructure were scanned. Magnetic sighting targets were placed in advance of the survey at various locations along the superstructure. Reference marks were also placed along the lower portion of piers. The locations of these targets are also identified in Figure 5. A zone at the base of the main post at pier locations 1E and 1W was targeted for a detailed high-resolution laser scan as shown in Figure 9a. At this location, a large steel assembly connects the concrete pier to five heavy built-up truss compression members via gusset plates and five large diameter articulation pins.

4. Field work and data acquisition

Measurements were performed under two different temperature conditions as follows:
1. Winter Phase, Ambient Temperature: -15 ºC ± 1 ºC
2. Summer Phase, Ambient Temperature: 25 ºC ± 2 ºC

Data acquisition was similar for both phases and the same technical principals were used in each case. The accuracy requirement imposed the necessity of a tightly controlled alignment of data sets coming from different setup positions of the scanner. To achieve this, the field crew installed special reference objects referred to as “fixed targets” that could be captured accurately during the survey by the integrated control unit. Floating (artificial) targets consisting of precise geometrical features of the bridge were also used. Hence, the targets consisted of two distinct sets as follows:

- <u>Floating (artificial) targets:</u> to ensure whole model space accuracy through sequential alignment wherein pairs of individual scans were “bundled” together to form an optimized chain of data. This approach allowed for a quasi-complete collection of the steel portion of the superstructure as shown in Figure 8a.
- <u>Fixed targets:</u> to provide the model operability via accurate distance determination and displacement quantification wherein the exact same targets were placed in the exact same position from one phase to the other in order to ensure the measurement consistency and desired accuracy. Target locations had to be precisely identified and carefully conserved over the project duration and in many cases the fixed targets played a double role as they were considered in the alignment process too.

Although the vectorial error in alignment was below 1 mm in 90% of the cases, error compensation was performed in two ways: i) by closing the loop of the inter-aligned pairs of scans and ii) by connecting the North and South bridge sides via a grounded control triplet (set of 3 grounded targets) that was stable, easy to site and capture in the scan process.

Complete bridge point cloud data acquisition during the winter phase was conducted from 13 different scanner positions around the bridge. A proper layout and optimum planning which minimized the total number of positions was possible due to the particular advantage of setting up and scanning directly on the iced channel of the St. Lawrence Seaway. However, the field team was confronted with several challenges and some severe environmental conditions which necessitated a very complex planning of the field work. Reliable solutions were developed to accommodate the natural obstacles and target visibility problems (see for example vegetation obstructions in Fig. 3).

In several instances, additional scans taken from complementary positions were needed in order to enable digital filtering (removal) of obstructions such as trees and to fill-in in the missing pieces of information (see Fig. 3 and 4).

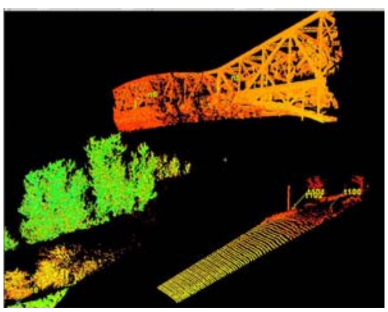

Figure 3: Natural obstacles requiring complementary scans

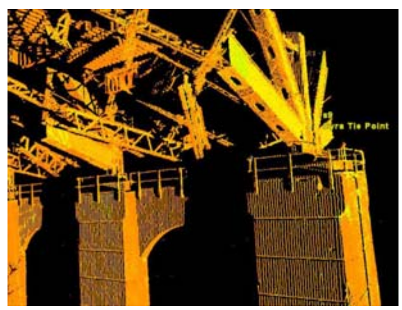

Figure 4: Collecting data from difficult to access areas

Total man-hour requirements for both winter and summer survey phases are reported in Table 1.

Table 1: Man-hours for complete survey and model creation

Operation	Winter phase	Summer phase
Target installation	6 hours	6 hours
Field scanning	28 hours	26 hours
Office work	56 hours	40 hours
Preparations,planning,sitevisit/revisit	70 hours	40 hours
Total	160 hours	112 hours

The scanning platform used was very efficient and was able to produce accurate details for difficult to access areas such as the underside of the cantilever truss span as illustrated in Figure 4. In this figure, blacked-out zones are indicative of areas where, from the given scanner position, the line of site of the laser was blocked.

In the course of the summer scanning phase, 18 scanner sensing positions dispersed around the bridge were necessary. For this phase, the target distribution as illustrated in Figure 5, was almost the same. Despite a greater number of scanning positions (18 .vs. 13), the total man-hours required were less as indicated in Table 1. This was achieved due to the knowledge of the site gained during the first phase and through optimization of the overall process.

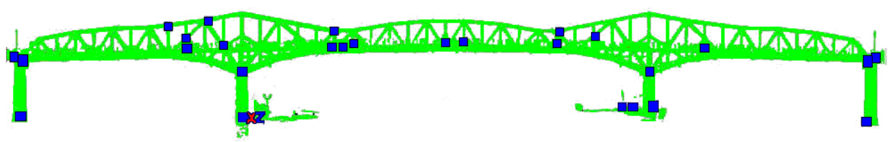

Figure 5: Target distribution example

5. Data processing and 3D model creation

Essential aspects in data processing and model generation process include common feature determination and identification via registration labels, integrating appropriate computational tools for filtering, averaging, target re-setting and referencing. Once these processes are completed, 2D and 3D modelling can be initiated as discussed below.

Registration is the process of integrating a project's scans into a single coordinate system, as a single registered set of points. This integration is derived using a system of constraints, which are pairs of equivalent objects, usually targets that exist in two different data sets. There are many instances when a “Fixed target” cannot be used for various reasons, such as very difficult or even impossible target installation conditions or failure to acquire target readings during a scan. In such situations, the fall-back solution used was to identify common geometrical features of the structure then lump them to single points via averaging algorithms and associate the lumped points to registration labels that would then become accurate substitutes for installed physical targets. Such points would thus serve as registration constraints in the model’s control space.

Another good technique used was to identify recognizable points as intersections of elementary geometries such as lines, planar patches, cylinders, spheres, etc. that were created through best-fit into common features. Those points were associated to registration labels as well. The registration label concept is illustrated in Figure 6. Averaging and filtering algorithms were implemented via the scripting and computational capabilities of MATLAB (a mathematical analysis and data processing software).

The integration of the MATLAB custom utilities with the point cloud editing and processing modules available in CYCLONE was possible due to the ASCII-type export of any point cloud section.

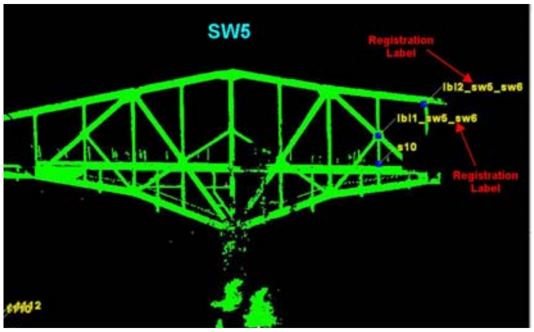

Fig. 6 - Registration labels

Economical 2D as-built drawings can be easily produced directly from point clouds once the bridge data points have been geo-referenced. This possibility is demonstrated in Figure 5 for the whole section of the steel superstructure and in Figure 6 for a portion of the bridge.

These images are but standard views in CYCLONE that can be directly or indirectly imported into commercial CAD packages. Prior to importing the 2D as-built data, a model cleanup may be required to remove non-pertinent information. Dimensioning is usually conducted within the CAD environment.

In 3D Modeling, data is delivered in a variety of forms and formats; several 3D geometries are available including *Cloud of Points* such as that shown in Figure 9a, polygon-mesh (Figure 7a), contours, and solid model (Figure 7b). Commercial 3D modeling tools allow for both 3D surface/solid model creation and standard parts/steel profiles definition by using the best-fit techniques.

Figure 7a: 3D polygon-mesh

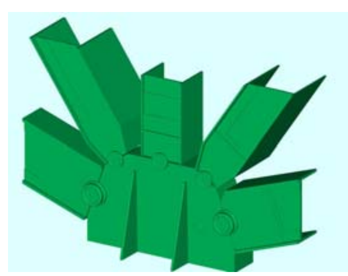

Figure 7b: Solid model

The 3D laser scan model provides the means to study and analyze the site or structure without having to visit it. It further provides a “digital copy” of the subject that can be revisited as the site or object changes over time.

6. Model creation (3D) and survey results

6.1 Overall 3D model

Figure 8a illustrates the overall 3D point cloud model which was created via the laser scanning and data processing procedure described in the previous section. The 3D image shown in this figure contains approximately 8.7 million separate data points. Production of this model required approximately 112 man-hours of work including field work, installation of targets, planning and data processing as summarized in Table 1.

In comparison, Figure 8b provides a similar overall 3D view of a portion of the bridge which was produced by conventional CAD modeling procedures involving careful review, transcription and assembly of information contained on shop-drawings. The 3D CAD model identified in Figure 8b required some 2,200 man-hours for document review, drafting time and validation of work. Table 2 compares overall bridge measurements.

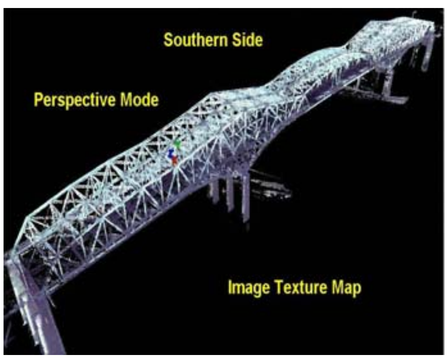

Figure 8a: 3D Laser scan whole model

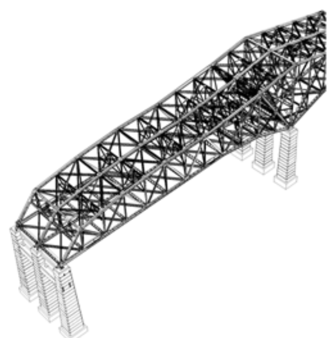

Figure 8b:- 3D CAD model (portion)

Table 2 : Comparison of 3DLR laser scan to ACAD 3D model

Description of principal dimension	Dimension obtained from 3DLR scan / summer readings	Corresponding dimension as per 3D ACAD and shop drawings
Central span dimension: Pin at 1E to pin at 1W	215,436 mm (upstream) 215,405 mm (downstream)	215,419 mm
Centre-line upstream truss to centre-line downstream truss	26,518 mm (at 1E) 26,518 mm (at 1W)	26,518 mm
Main post pins: Top chord to bottom chord	30,898 mm (at 1E upstr.) 30,919 mm (at 1W upstr)	30,937 mm

6.2 Results for high-resolution zone

Figure 9a illustrates the high-resolution laser scan point cloud model generated for the main post to lower chord gusset plate assembly and articulation pins located at Pier 1E. Figure 9b illustrates similar information produced from original Dominion Bridge shop-drawings and Table 3 provides a comparison of the principal dimensions obtained from these two sources. As indicated in this table, the two results are in very close agreement, not withstanding the fact that the measurements obtained from the remote laser scan were collected at a distance of some 107 metres from the surveyed detail.

Table 3: Comparison of survey results for high resolution scan zone

Description of principal dimension	Dimensions obtained from 3DLR scan (summer reading)	Corresponding dimension as per 3D ACAD & shop drawing
Overall width of gusset	2,901 mm	2,896 mm
Overall height of gusset	1,779 mm	1,780 mm
Largest pin cap diameter	453 mm	451 mm

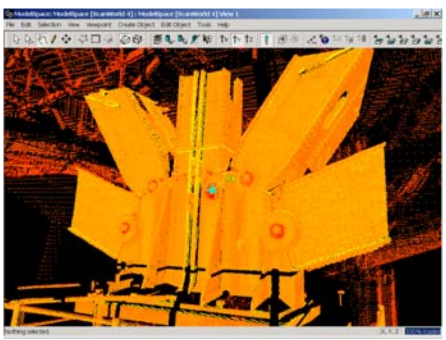

Fig. 9a - Point cloud high resolution zone

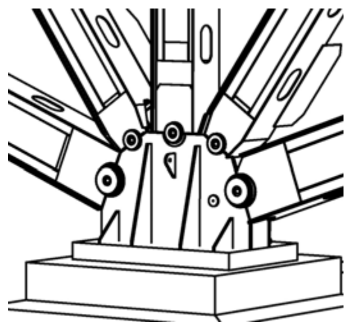

Fig. 9b - CAD Detail of assembly

6.3 Global thermal movements

Theoretical calculations indicate that the overall thermal movement which should occur at expansion joint L17E for a temperature variation of 40^o C is 101 mm assuming frictionless expansion bearings and a uniform temperature variation throughout the steel

Table 4: Overall thermal movements at L17E expansion joint

Target location	Distance between targets	Thermal movement
Upstream side (South) target S7 to S8	6231 mm (Summer) 6324 mm (Winter)	93 mm
Downstream side (North) target N7 to N8	11465 mm (Summer) 11531 mm (Winter)	67 mm
Average	-----------------	80 mm
Theoretical (+ 25^o C to -15^o C)		101 mm

superstructure (i.e. 40^{o}C x 11.7E-06 x 215,420 mm). 3DLR laser scan survey results of the movement detected across the corresponding expansion joint L17E as measured from the change in distance between targets S7 to S8 (south/upstream) and N7 to N8 (north/downstream) are tabulated in Table 4.

7. Other potential applications

Other beneficial applications of the 3D laser scanning technology described above for bridge management, inspection and documentation include:

- Production of as-built 2D/3D drawings of existing structures either via 2D/3D tracing or directly by using point clouds. A major argument in favour of 3D laser scanning for documenting bridge structures is that risks associated with hands-on site exposure are considerably reduced.
- Verification/production of shop-drawings for steel repairs where site access is extremely difficult or impractical.
- Establishing a bench mark of pre-existing shape/state in order to detect structural changes resulting from exposure to extreme loadings such as earthquake, vessel/truck impact or fire.
- Bathymetric scanning of submerged structures.
- Creating intelligent GIS (Geographic information system) maps, to query, analyze and display data on the fly, thus providing users with accurate and easy to interpret real time information concerning spatial location, size, terrain and site access.

8. Conclusions

Long range 3D laser scanning technology to survey, monitor and to construct a full 3D model of a complex, difficult to access and large bridge such as the Champlain Bridge was investigated and proved successful as demonstrated in this paper. The precision of the equipment and set-up used and the overall efficiency of the data collection and processing techniques implemented for this particular application produced sufficiently accurate measurements that could be repeated over time so as to quantify geometrical changes such as those resulting from thermal movements.

Comparison of conventional 3D models developed using existing shop drawings to 3D models constructed entirely from a laser scan indicates that comparable results can be obtained. Furthermore, data collected from a 3D laser scan can be very rich in information and used in practical ways to accurately document a bridge structure.

9. References

1. Wunderlich, Thomas, “Operational and economic prospects of terrestrial laser scanning”, Proceeding. of the 5th International conference on optical 3D measurement techniques, pp. 18-25, Vienna, 2001.