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RESEARCH PAPER

Development of new system for detection of bridges construction defects using terrestrial laser remote sensing technology

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Registration;
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DXF;
Visual Basic

Abstract There are probable damages and defects happening throughout structure execution or transport and consignment. Defect experience in construction is precious and remarkable. This research work is a trial to develop an easy system to accomplish the most common tasks in the process of detection and monitoring of the as-built structure. However, assessment programmes involved cannot sufficiently detect and deal with defects that happen at construction process, as they are based on measurements at particular positions and periods, and are not included into full electronic techniques. Therefore there is an important requirement to always observe the construction developments to keep away from major rework prices and interruptions. This research represents an automated advance to register laser remote sensing data of as-built model, with BrIM (Bridge Information Model) for a constructed bridge. An experimental work is carried out to confirm the planned method for monitoring the structural defects through a case study was implemented in the design and inspection data in the Jacques Cartier Bridge in Canada. The outcomes demonstrate that the existing technique can be employed to sense the defected elements or structure imprecision fast and accurately.

1. Introduction and review

Automation in remote sensing systems is a challenging field of research work due to the need of reducing cost (Serwa et al., 2010). There is still a significant rate of damages and defects occurring during transportation and shipment. Typically, an extra 10–20% of structural material is used to brace and support modules during shipment. However, most defects and damage still occur during transportation, which leads to rework after arrival on site as an unfavourable secondary

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effect. Additionally, errors and inaccuracies, which are mostly due to human interaction and challenging materials behaviours in the different stages, are other issues that cause rework and cost as a consequence. It has been estimated that approximately 10% of the construction rework cost is caused due to delays in defect detection (Nahangi et al., 2014; Akinci et al., 2006; Arditi and Gunaydin, 1997). Engineering constructions (e.g. bridges, buildings, roads, etc.) are subjected to defects, deformations and failures due to natural factors such as natural cold and hot cycles, problematic soil, changes in ground water level, etc. Therefore, there are many simple consequences that could result from the failure of a large structure. For these reasons, early detection of possible structural damage is critical. This stimulates the need for a reliable methodology for routine structural defect monitoring. Monitoring and analyzing deformations of these structures constitutes a special branch of Geodesy. There are several techniques for measuring the defects and deformations (Ismaiel et al., 2013; Gairns, 2008). These can be grouped mainly into two as geodetic and non-geodetic techniques. Laser scanning technique is the most recent and accurate technology for object geometry recovery. Laser scanners capture a huge amount of points for objects in a very short time in order to deliver what is called "point cloud" (Abdelhafiz, 2014). Multiple scans from different positions have to be taken in order to achieve all object faces and details in a 3D environment. Laser scanners are being utilized to collect 3D geometric as-built information for renovation, retrofit, and expansion projects in industrial, commercial, and heavy-civil sectors of construction, and a set of these studies suggests some cost benefits of using scanners for quality control purposes (Akinci et al., 2006; Cyra, 2004). The interest in terrestrial laser scanning has rapidly increased. However, to date, most research using laser scanners in structural assessment has focused on measuring structural deformation, estimating material loss, or finding surface defects, which can be used in structural engineering to complete drawings for an as-built structure or to test the actual dimensions of the as-built structure against its design (Abdelhafiz, 2009). The National Building Information Model Standard (NBIMS) defines BIM as "a digital representation of physical and functional characteristics of a facility and it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle from inception onward" (Smith and Edgar, 2006). BIM represents real world elements such as walls, doors, and windows as 3D objects. In addition to geometry details, other information can be attached to these objects including manufacturers, fire rating, schedule, and cost estimates (Goedert and Meadati, 2008). Fig. 1 depicts the distribution of introduced technologies for data acquisition from real-life processes and integration between virtual models and physical building. There are eight types of technologies in total, among which laser scanning, radio frequency identification (RFID), and camera are the most popular technologies proposed for BBB (Bridging BIM and Building) (Chen et al., 2015). Other related technologies include Augmented Reality (AR), Geographic Information System (GIS), Global Positioning System (GPS), and sensor.

Chen et al. (2015) mentioned that the laser scanning which is adopted in 28 studies digitally captures geometric data and spatial relationships through laser light (Shih and Huang, 2006). It is mainly used for process tracking (e.g. Turkan et al., 2012) and 'generation of 'as-built' models' (e.g. Arayici, 2007; Jung et al., 2014; Tang et al., 2010). Deviations between the 'as-built' and 'as-designed' models are used to assess the quality of construction work (Akinci et al., 2006). Besides, the spatial data of specific objects support site monitoring (Su et al., 2006), resources tracking (Teizer et al., 2007), and safety management (Cheng and Teizer, 2013). According to the studies, current BBB practice using laser scanning is heavily reliant on manual effort (Anil et al., 2011; Brilakis et al., 2011). Some researchers present approaches and algorithms that can achieve automatic object identification (Bosché et al., 2013; Xiong et al., 2013) and improve object recognition quality (Bosché et al., 2009), and flash LADAR technology enables rapid scanning for highly active situations (Randall, 2011). The objective of this research is enhancement of the building defect inspection by the simplification of the method of information visualization, by registration and comparison between the "as-built" model from 3D range sensors and the "designed" model from BrIM to detect the geometric discrepancies and defects with different accuracies. In previous cases studies, the researchers used laser scanners to scan building sites periodically and created "as-built" models of each site, and geometric discrepancies were detected as defects.

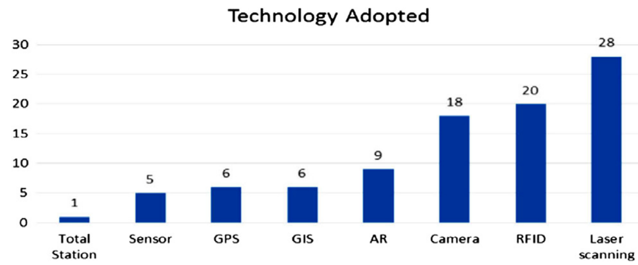


Figure 1 Technologies for BIM and building (after Chen et al., 2015).

2. Materials

The developed system is planned to carry out the research requirements using the techniques discussed in the previous sections to realize the case study purposes. Bisby and Briglio (2004) revealed the fact that 40% of in-service bridges in Canada are aged 50 years or more, so the importance of process improvement in Operation and Maintenance (O&M) becomes significant (Gagnon et al., 2008; Industry Canada, 2013), *Jacques Cartier Bridge* is chosen as the subject of the case study. Fig. 2 shows the layout of the scanning problem for the as-built bridge indicating the approximate dimensions of the studied part of the bridge. The length of the scanned part was 75 m while the approximate height was 50 m.

The laser scanner was put at a distance of 107 m apart from this part of the bridge. The bridge data were acquired from the bridge management authority (*The Jacques Cartier and Champlain Bridges Incorporated*) (PJCCI, 2004; Zaki and Mailhot, 2003). The data include CAD drawings, deck rehabilitation schedules and inspection and maintenance records. Further details about the system can be found elsewhere (Hu and Hammad, 2005); they proposed a location-based computing

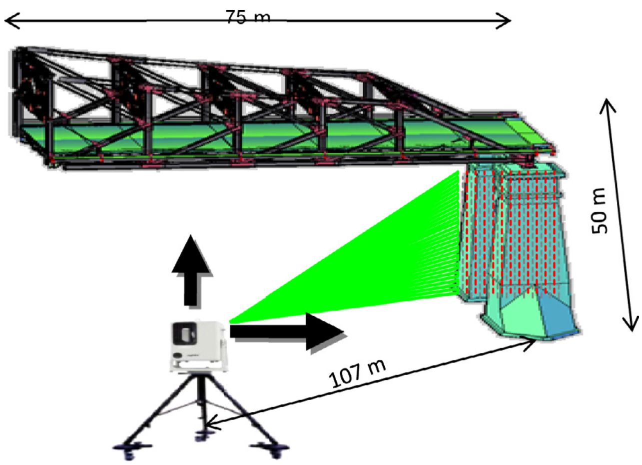


Figure 2 Layout of the scanning problem.

system to facilitate the data collection activities of the bridge inspection by registering defects on the 3D model of the bridge.

3. Methods

The proposed system was planned to cover most of the necessary tasks as shown in Fig. 3. The system started with bridge object through laser scanning process to produce point cloud model (e.g.: Data exchange File –DXF– or Drawing file –DWG–…etc.) at the same role, the predesigned CAD model was obtained in the form of BrIM. Both tiers were injected to the commercial modelling software to apply the pre-processing, preparing and comparison. Both models were extracted to obtain the final ASCII point format of *xyz* coordinates. Registration operation was applied using both coarse and fine methods. At the final step, an accuracy assessment of the overall system was applied.

3.1. Scanning

The laser scanner that we utilized includes a commercially-available HDS2500 (shown in Fig. 4) that has a maximum 40° × 40° field-of-view and SmartScan Technology™ – for added scanning control. With a single-point range accuracy of ±4 mm, angular accuracies of ±60 micro-radians, and a beam spot size of only 6 mm from 0 to 50 m range, the HDS2500 delivers survey-grade accuracy while providing a versatile platform for data capture. Its 360° × 195° pan & tilt mount and dual internal rotating mirrors enable it to be deployed in virtually any orientation (http://hds.leica-geosystems.com, accessed 6/2015). The combination of high accuracy and field versatility makes the HDS2500 ideal for fixed or raised installation when levelled tripod mounting is not practical, or for applications with less stringent field-of-view requirements.

In terms of commercially available systems, we have used AutoCAD in creating the as-planned product model, for data collection to fully record a complex object, the scanner is moved around the object to measure points from many different angles and hence achieve a complete coverage. This method has a long range, up to about 200 m under ideal conditions. CYCLONE is the software interface was 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 (Mailhot and Busuioc, 2006). The versatile and powerful modelling module of CYCLONE enables operators to use point clouds directly and process them into objects for robust export

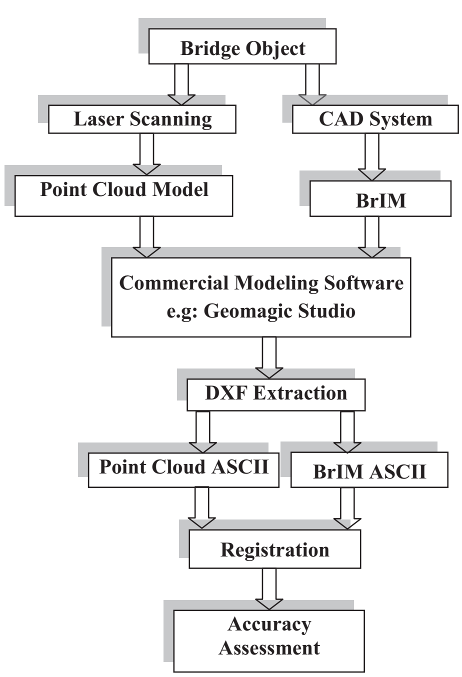


Figure 3 Overview of the proposed system.

Figure 4 Leica HDS2500 laser scanner.

into CAD or other applications and also to allow robust import of data from CAD. The entry of the planned dimensional scheme takes in a 3D scan point cloud and a 3D BrIM. The *first* action of the method consists in aligning (registering) the point cloud in the coordinate system of the model. For this, the approach based on plane matches and other approaches can be used (such as point or features matching) (Bosché, 2012). *After that*, each point of the point cloud is corresponded to a BrIM model (or none) using a metric join two criterion: (1) *closeness:* orthogonal distance of the point on the BrIM model objects surfaces; (2) *plane normal similarity:* similarity in orientation of the normals of the local surfaces around the scan point and around its matched point in the BrIM model, the matched point is the closest orthogonal projection of the scan point on the BrIM model objects (Bosché and Guenet, 2014). This step essentially achieves a full segmentation of the initial point clouds in a set of sub-point clouds matched to the different BIM model objects. Fig. 5 illustrates this Scan-BIM process. To show the viability of the proposed methodology, the system is developed and discussed in the next section.

This study proposes enhancement of the building defect inspection by the simplification of the method of information visualization by registration and comparison between the "as-built" model from 3D range sensors and the "designed" model from BrIM to detect the geometric discrepancies and defects with different accuracies. Standing on the method, the Defect Information Model (DIM) is in its real shape, which decreases the difficulty and saves the time of modelling the irregular shapes. The registration for laser scanned data and 3D BrIM include two main steps: (1) preprocessing, and (2) alignment. *Preprocessing* is a set of processes in order to acquire the appropriate point clouds to be used in the alignment step.

3.1.1. Preprocessing

These processes include:

Data acquisition as shown in Fig. 6.

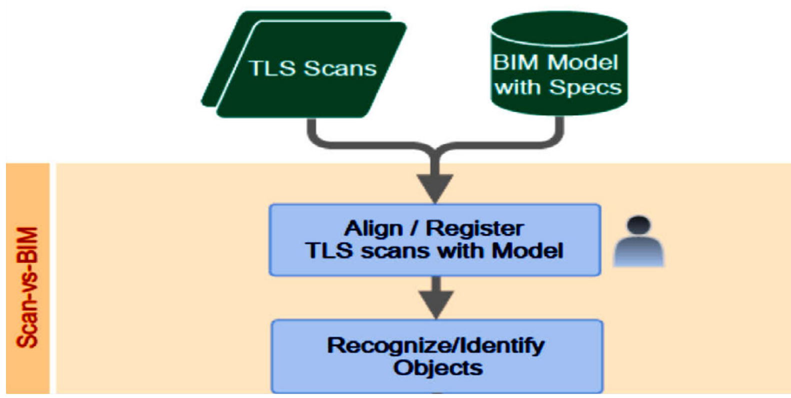


Figure 5 System procedures for scans and 3D BIM model (after Bosché and Guenet, 2014).

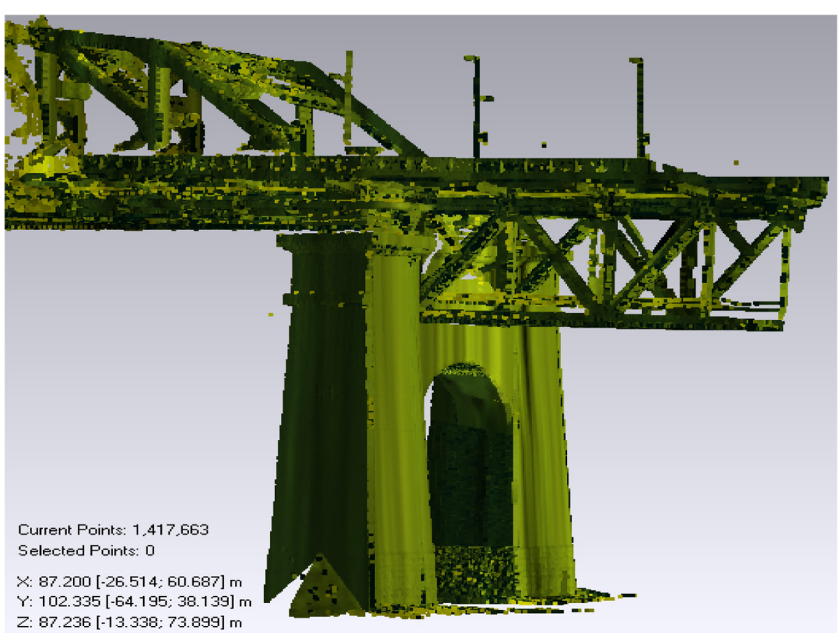


Figure 6 1,417,663 points of 3D laser scan of Jacques Cartier Bridge tie-down pier.

This stage starts with acquiring about 1,417,663 points of 3D laser scan of Jacques Cartier Bridge tie-down pier using HDS 2500 laser scanner.

Noise removal as shown in Fig. 7.

This stage is applied using commercial modelling software (Geomagic Studio) to reduce the noise of points in the studied sample of the bridge. NR (Noise Reduction) filter was used; this filter uses scanner error (noise) as an indication for noise, so the noise can be reduced by moving points to statistically correct locations. The result is a more uniform arrangement of points that can be wrapped more smoothly. The standard deviation of space vector of the points' movements was 0.00564 m. The Standard Deviation describes the variability of the distances that points were moved during noise reduction.

Format conversion to 3D points coordinates of the bridge extracted and converted from DXF format and imported to the *VB programming software*.

Basically, the included frame identified as BrIM has to be implemented by researchers. These researchers can be conceptual objects defined in BrIM software. Hence, it is essential to convert those objects into a dataset comparable to the captured data, for that purpose, we filled the designed column model with a form of 3D point clouds as shown in Fig. 8.

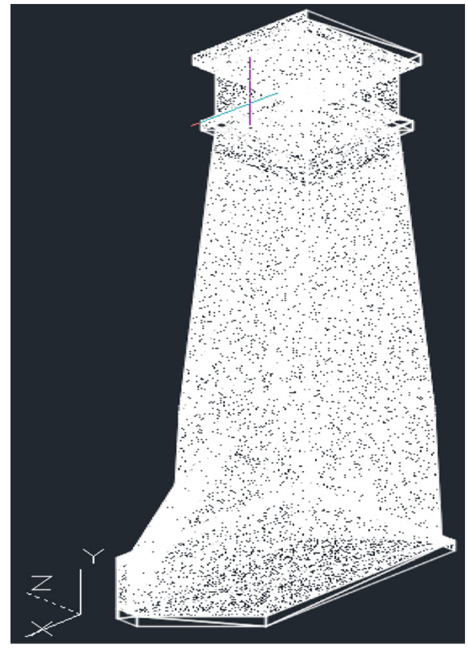


Figure 8 Designed column model in form of 3D point clouds.

3.1.2. Alignment stage

The comparisons between the designed and the as-built object stage results in quantifying and assuring the accuracy of the structure. An Iterative Closest Points (ICP)-based approach (Besl and McKay, 1992) is proposed here for the registration of the as-designed BrIM, and the as-built point cloud acquired by laser scanner. The registration process consists of two main steps:

(1) *Rough* registration that coarsely aligns the two sets together.

(2) *Fine* registration that accurately finds the best fit and orientation to register the point clouds.

Fig. 9 shows the algorithm for registration that commences with *PCA* (Principal Component Analysis) for coarse registration and follows ICP for fine registration. PCA and ICP are briefly described in Fig. 9.

Where the resulting point cloud that represents as-built data is called '*Scene* (*S*)' and the BrIM that represents as-designed data is called the *Model* (*M*). In order to have the

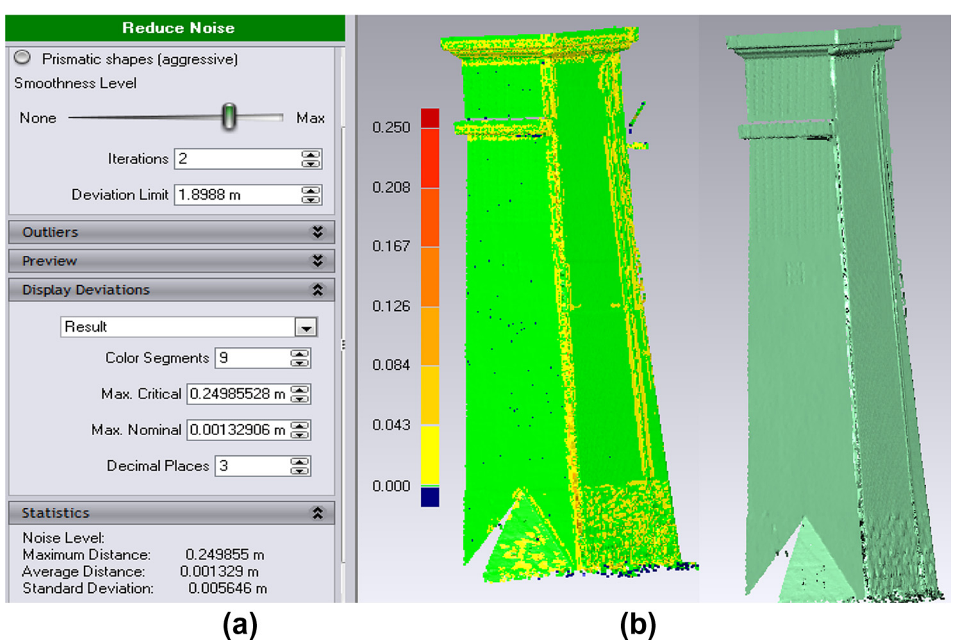


Figure 7 (a) Reducing the noise in the column with standard deviation = 0.00564 m, (b) after reducing the noise in the model.

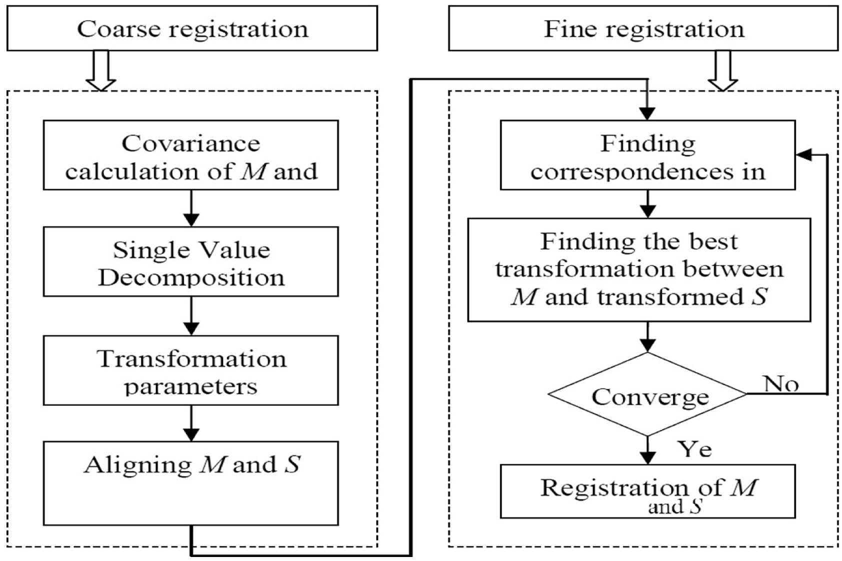


Figure 9 Recent registration algorithm (Nahangi et al., 2014).

3D BrIM Model (*M*) and the scanned as-built status (*S*) roughly aligned, coarse registration is performed with a standard deviation = 0.282 m, as shown in Fig. 10. Among all existing methods for coarse registration, Principal Component Analysis (*PCA*) is sufficiently quick and robust. The promptness and robustness of the method is due to its linear performance and simplicity of computation of the parameters involved. The accuracy provided by PCA is also adequate compared to the accuracy provided by iterative methods that were discussed by (Salvi et al., 2007). Serwa et al. (2010) indicates that PCA can be applied to obtain minimum and maximum correlations in data variables. Summarily, PCA finds the principal axis in the two databases and aligns the principal axes. The resulting registration is roughly aligned and expedites the fine registration step significantly. Having performed the coarse registration step (Fig. 10), the point clouds should be registered more accurately in order to be able to evaluate the scanned point cloud which represents the as-built status of assembly (Nahangi et al., 2014).

Additionally, it expedites the fine registration performance as a secondary result. Some results of registration for the column sample are shown in Fig. 11. In order to evaluate the performance of the registration another metric is defined; Root Mean Square (*RMS*) shows the accuracy of the registration.

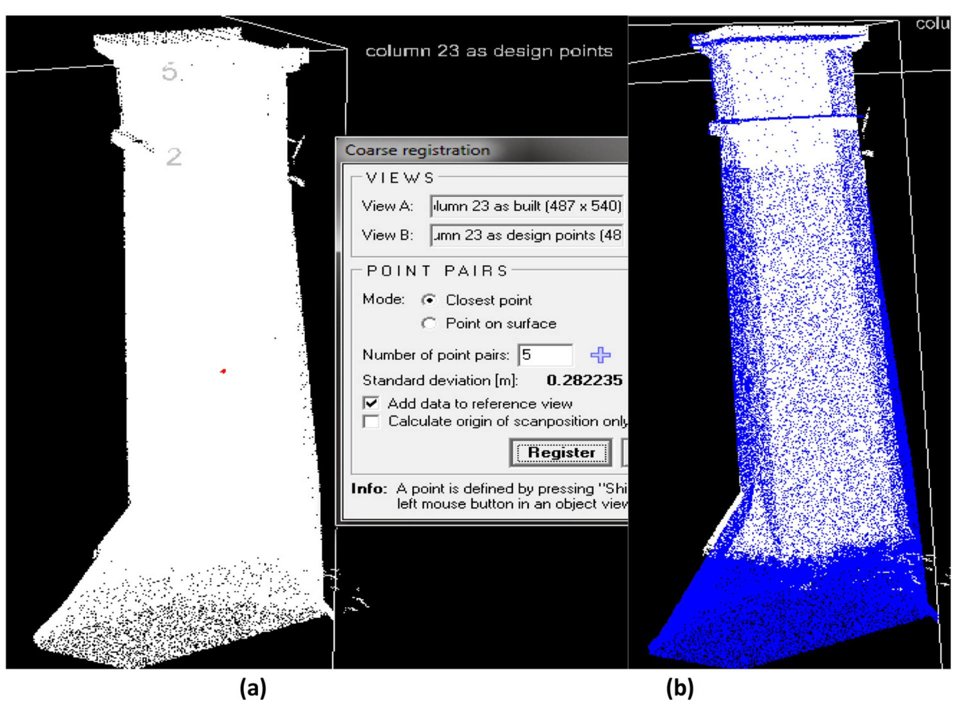


Figure 10 (a) Coarse registration of the column BrIM and point clouds, with standard deviation = 0.282 m. (b) Registration results (blue: BrIM model, white: scanned point cloud).

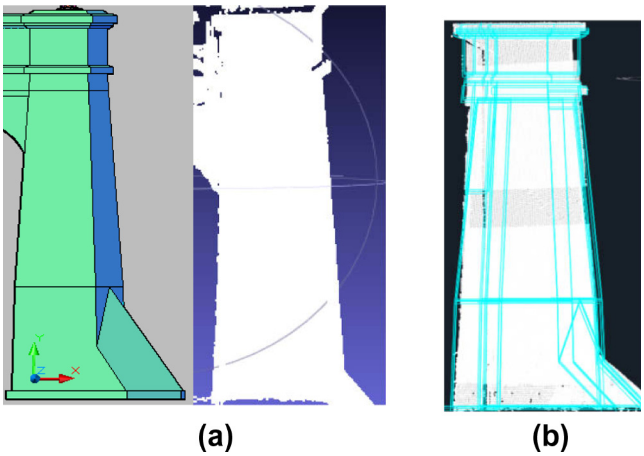


Figure 11 (a) Registration results, (green: BrIM model, white: scanned point cloud). (b) Initial position of the column BrIM and point clouds.

RMS is defined as follows:

$$\mathrm{RMS} = \frac{1}{n}\sum_{i=1}^{n}(di) \quad (1)$$

where n is the number of corresponding points, and d is the Euclidean distance between corresponding points in M and S.

3.2. Software development

Most of the selected papers do not provide information about 3D model or BrIM development software. In order to reinforce the connection between the database and 3D model or BIM, software is developed by *Application Programming Interface* (*API*) which is programmed by either *VB*.Net, C# or C++ (e.g. Goedert and Meadati, 2008; Riaz et al., 2014; Chen et al., 2015). The Comparative software must be developed to achieve the research objectives (Farghaly et al., 2012). The software is called LSAR (Laser Scanner Analyser and Reconstructor) which was developed. It was developed by Serwa using VB programming language and it is under enhancement to fulfil all laser scanning applications. This software was designed to automatically extract points from DXF file and convert them to ASCII file. In addition, it applies the closest point algorithm (fine registration). Also it evaluates the accuracy of the registration between the as built model and BrIM. The proposed software package was used to carry out the soft operations such as DXF extraction (Fig. 12).

The software was developed in Visual Basic language (VB) and then applied to studied assemblies based on the described implementation procedures. Fig. 13 depicts the task of DXF extraction of the specific coordinate's points from the given object of 3D BrIM.

Fig. 14 shows accuracy assessment module in the form of RMS and it indicates the results of accuracy of the original research data.

Where:

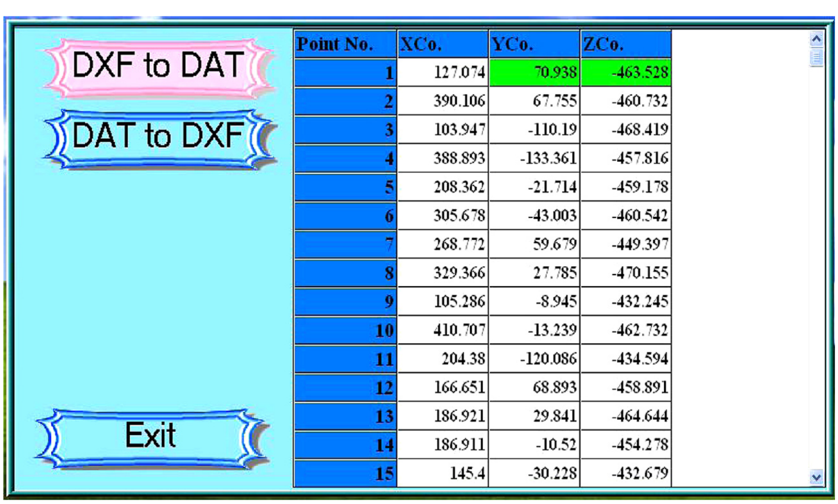
$$\mathrm{RMS-XY} = \sqrt{(\mathrm{RMS-X}^2 + \mathrm{RMS-Y}^2)}$$

$$\mathrm{RMS}-R = \sqrt{(\mathrm{RMS-X}^2 + \mathrm{RMS-Y}^2 + \mathrm{RMS-Z}^2)}$$

A modification is performed and the final value of *RMS* is calculated. It is noted that the desired accuracy for registration is achieved for the studied assembly.

Fig. 15 shows the output RMS file that contains DX, DY and DZ of each registered point sample to evaluate the whole developed system.

Using a computer that is facilitated to a 3.0 GHz processor and 20 GB RAM, the processing time for performing the iterations of the developed model takes about some seconds. Considering the required time for data acquisition and pre-processing. The achieved RMS value in addition to the visualized results shows that the proposed registration technique is correctly performed and is sufficiently reliable for making further decision with regards to the structure quality and construction process. The sources of error that affect in the registration accuracy are related to the scanning accuracy and the assembly shape. The scanning accuracy slightly relies on the other light source interference. Additionally, the assemblies that are (semi-) symmetric may be incorrectly registered due to the same registration results for the symmetrical orientations (Nahangi et al., 2014). Thus, the developed model may be limited to the described cases; however it reliably works in all studied as they are well scanned and not symmetric.



Point No.	XCo.	YCo.	ZCo.
1	127.074	70.938	-463.528
2	390.106	67.755	-460.732
3	103.947	-110.19	-468.419
4	388.893	-133.361	-457.816
5	208.362	-21.714	-459.178
6	305.678	-43.003	-460.542
7	268.772	59.679	-449.397
8	329.366	27.785	-470.155
9	105.286	-8.945	-432.245
10	410.707	-13.239	-462.732
11	204.38	-120.086	-434.594
12	166.651	68.893	-458.891
13	186.921	29.841	-464.644
14	186.911	-10.52	-454.278
15	145.4	-30.228	-432.679

Figure 12 Coordinates of the bridge extracted from DXF file.

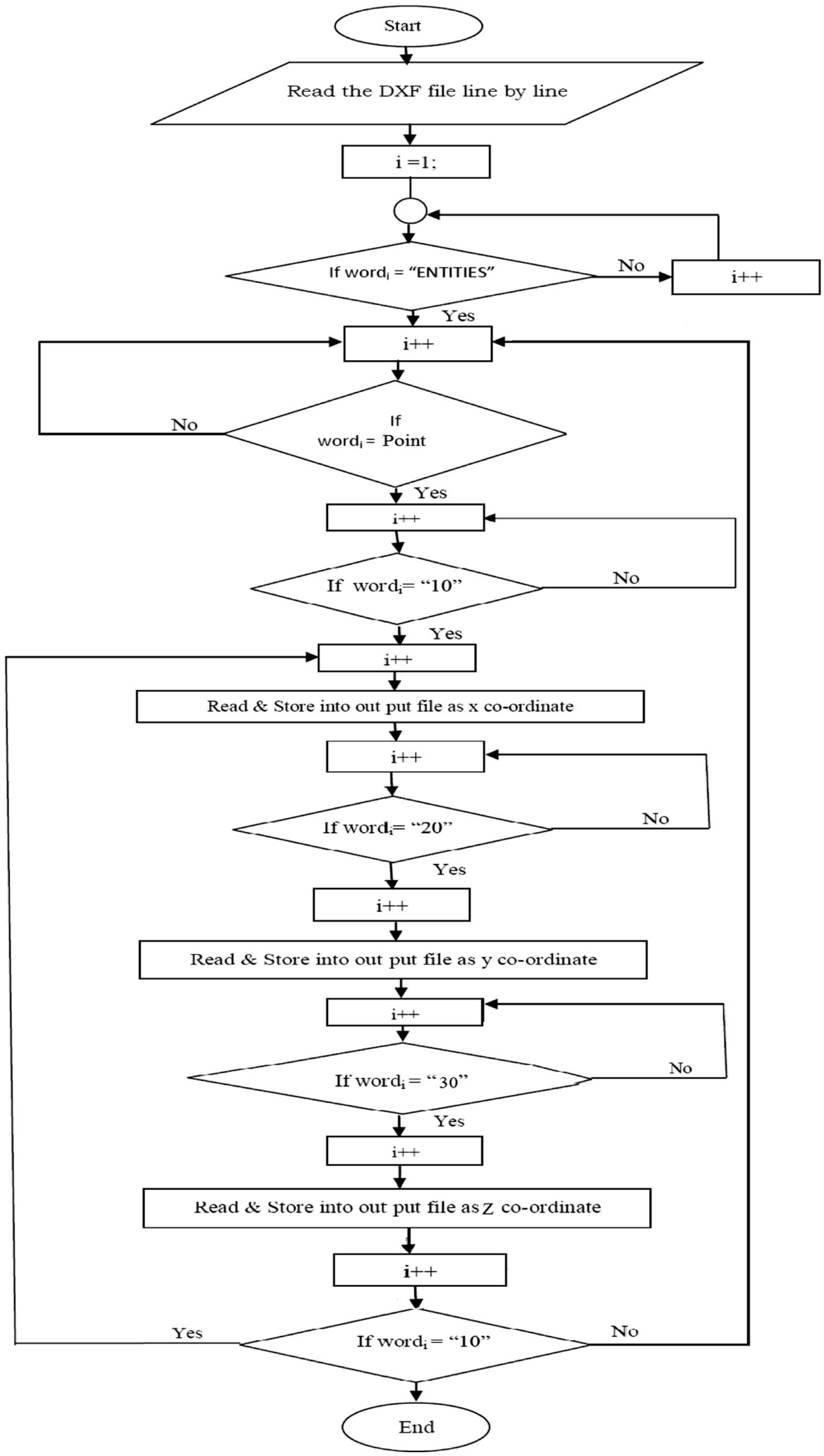


Figure 13 Flow chart of DXF file extraction of points' coordinates.

4. Results

4.1. Registration evaluation

RMS in X direction was 0.054 m, in Y direction was 0.056 and in Z direction was 0.101 m. RMS in the planemetric XY plane was 0.077 m and so the space RMS was 0.127 m as shown in Fig. 14, .One can note that each X and Y direction have approximately equal accuracy while Z direction is the worst. It is commonly in laser scanner application that Z direction has the lowest accuracy. The important remark is that the laser scanner point average spacing at the plane of the bridge was about 0.091 m. Comparing the results one can note that according to laser scanner specification of beam spot size of

Figure 14 (RMS) in X, Y and Z directions and the total R.

only 6 mm from 0 to 50 m range then beam spot size of 12.84 mm from 0 to 107 m range. Also for maximum range of 200 m gives beam spot size of 24 mm.

4.2. The deviation detection and the defect evaluation

The deviation detection has performed frequently throughout the construction process, it is expected that the as-built part of the integrated model will change over time and will achieve its highest level of completeness only when construction is finished. Thus, comparing design information to as-built information will not always be possible, since as-built information can be expected to be missing. The deviations found need to be further processed in relation to the construction specifications to assess whether a deviation is a defect.

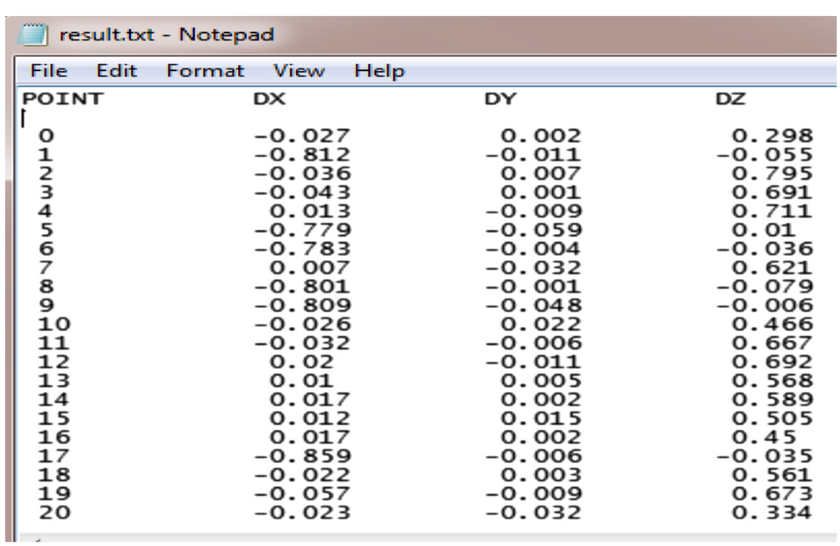
The evaluation of deviations is done by comparing them to the targeted quality standards, expressed in construction specifications, for the related components. This process utilizes the construction specification model developed for generating inspection goals and compares the amount of deviations to the corresponding allowable tolerances defined in specifications (Akinci et al., 2006). If a given deviation exceeds the allowable tolerance, then it constitutes a construction defect and thus further actions need to be taken to correct the defect or to incorporate it into the next version of the design.

Figure 16 As built model has wider base from the design model.

In the case study, we have successfully identified small scale deviations that would be harder to identify without using the method described in this paper; we have identified the type of deviation related to a design change that was not captured in the design documents. Fig. 16 shows the design model of the column foot registered on the as built model which has wider foot from the design model.

5. Conclusion

This research presented an approach that integrates TLS and BrIM technologies. TLS is used to acquire dense 3D point clouds of surfaces to be controlled. Data are then registered in the coordinate system of the project 3D BrIM. This paper represents an automated advance to register laser remote sensing data of as-built model, with BrIM for constructed bridge. An experimental work is carried out to monitor the structural defects through the design and inspection data in the Jacques Cartier Bridge in Canada. Based on the registration results presented in this research, the model is concluded to be accurate to monitor the construction processes. The coarse registration step in the presented model eliminates the incorrect registration of points cloud; the application of the model is limited to situations where an accurate point cloud is available. The outcomes demonstrate that the existing technique can be employed to sense the defected elements or structure imprecision fast and accurately. Development of specific purposes


result.txt - Notepad
File Edit Format View Help

POINT	DX	DY	DZ
0	-0.027	0.002	0.298
1	-0.812	-0.011	-0.055
2	-0.036	0.007	0.795
3	-0.043	0.001	0.691
4	0.013	-0.009	0.711
5	-0.779	-0.059	0.01
6	-0.783	-0.004	-0.036
7	0.007	-0.032	0.621
8	-0.801	-0.001	-0.079
9	-0.809	-0.048	-0.006
10	-0.026	0.022	0.466
11	-0.032	-0.006	0.667
12	0.02	-0.011	0.692
13	0.01	0.005	0.568
14	0.017	0.002	0.589
15	0.012	0.015	0.505
16	0.017	0.002	0.45
17	-0.859	-0.006	-0.035
18	-0.022	0.003	0.561
19	-0.057	-0.009	0.673
20	-0.023	-0.032	0.334

Figure 15 Results of (RMS) in X, Y and Z directions for the registered points.

software is more easy and reliable for the evaluation of overall system performance.

Research data responsibility

The first author Eng. M. Sedek bears all responsibility about data source licence.

Conflict of interest

There is no conflict of interest.

Acknowledgments

The first author would like to thank Prof. Dr. Amin Hammad for giving the chance to participate in PJCCI project. Also the authors would like to acknowledge Concordia University, Canada, for the research and data facilities.

Appendix A

The following visual basic code function called ReadDXF extracts specified code/value (e.g. *xyz* coordinates) from a DXF file. This function requires four string parameters, a valid DXF file name, a DXF section name, the name of an object in that section, and a comma delimited list of codes:

```
Function ReadDXF _ )
    ByVal dxfFile As String, ByVal strSection As String _ ,
    ByVal strObject As String, ByVal strCodeList As String (
  Dim tmpCode, lastObj As String
  Open dxfFile For Input As #1
  codes = ReadCodes
  While codes(1) <> "EOF "
    If codes(0) = "0" And codes(1) = "SECTION" Then
      codes = ReadCodes ()
      If codes(1) = strSection Then
        codes = ReadCodes
        While codes(1) <> "ENDSEC "
          If codes(0) = "0" Then lastObj = codes(1 (
    ' If this object is one you're interested in
          If lastObj = strObject Then
            '    Surround the code with commas
            tmpCode = "," & codes(0 "," & (
    '         If this code is in the list of codes ..
            If InStr(strCodeList, tmpCode) Then
    '           Append the return value .
              ReadDXF = ReadDXF _ &
                codes(0) & "=" & codes(1) & vbCrLf
            End If
          End If
    '       Read another code/value pair
          codes = ReadCodes
        Wend
      End If
      Else
      codes = ReadCodes
    End If
  Wend
  Close #1
  End Function
```

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