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THE EFFECT OF POINT CLOUD SCAN RESOLUTION ON THE ACCURACY OF A PEDESTRIAN BRIDGE CONDITION ASSESSMENT

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Abstract:
The structural integrity of infrastructure systems is important to ensure serviceability and safety. ISO 55000 recommends condition assessment as a key step in infrastructure management. Presently, infrastructure condition assessment has been performed by using manual methods. Three-dimensional (3D) scanning presents intriguing opportunities for monitoring structures, enabling engineers to rapidly gather structural information. Hence, scan-to-Building Information Modeling (BIM) has been identified as a promising method for structural health monitoring. It is therefore important crucial to investigate the use of different 3D scanning methods and procedures to improve its efficiency. The objective of this paper is to study the effect of point cloud data resolution on the accuracy of a pedestrian bridge condition assessment. The parking garage pedestrian bridge on the University of Windsor campus was scanned in 1/5 and 1/10 resolution by using a FARO Focus M70 3D scanner to capture two separate point clouds of the above bridge. The point cloud data was registered with respect to pre-established benchmarks. As-built drawings were used to create a BIM model of the above pedestrian bridge in Autodesk Revit and were registered with respect to the same benchmarks. The data from each point cloud was then compared with the as-built model in the Verity software to identify errors between the point cloud and BIM model to determine if decreasing the scan resolution affects the condition assessment results. This process will provide infrastructure engineers and facilities managers with effective and efficient information for structural health monitoring.

Keywords: condition assessment, 3D scanning, point clouds, Building Information Modeling

1. INTRODUCTION

Bridges form an integral part of infrastructure systems and for them to continue functioning properly, it is important that maintenance is regularly conducted on them. Currently, the most common method of inspecting bridges is through visual inspections conducted by engineers who determine the bridge's condition based on structural deformities that they can visually identify (Turkan, Laflamme and Tan 2016). However, due to human nature and subjectivity of visual inspections, there is a limitation to the accuracy one can achieve in conducting a visual condition assessment of a bridge (Kim, Sohn and Chang 2015). Although visual inspections can provide a good base for identifying general bridge characteristics, it cannot provide an adequate assessment of finer details that may not be immediately interpreted by the naked eye. Therefore, the visual inspection score is limited to what the inspector can visually identify and then interpret, which leaves visual inspections prone to subjectivity (Office of the Auditor General of Ontario 2021).

According to the Office of the Auditor General in Ontario, in their report on the Ministry of Transportation in Ontario (MTO), they found that technologies are not being used to improve efficiencies and cost-effectiveness, and that there are problems with bridge inspection accuracy that are yet to be resolved (Office of the Auditor General of Ontario 2021). Thus, to create a more accurate and objective method of conducting structural assessments of bridges, the use of imaging technologies can prove to be an effective tool at solving these problems. More specifically, the process that will be discussed in this paper is a type of "Scan-to-BIM" process, which involves the transferring of laser scan data into Building Information Modeling (BIM) applications, such as Autodesk Navisworks, for analysis. Three-dimensional (3D) laser scanning is an effective way to gather structural information due to its relatively high measurement accuracy, fast measurement speed, and its high interoperability with BIM-related applications (Wang, Guo and Kim 2019) which can then be used to draw conclusions from point cloud data.

Scan-to-BIM has been used in many civil engineering applications, from gathering data on historical structures (Napolitano, Hess and Glisic 2019), to creating structural maintenance systems (Shim et al. 2019), and construction quality control (Kalyan et al. 2016). Visual assessments of structures have long been used in the architectural, engineering, and construction industry, but despite their widespread use, they also have prominent limitations, such as subjectivity, high cost, and a higher safety risk (Kim, Sohn and Chang 2015) which can be improved upon using scan-to-BIM practices. However, to best utilise the capabilities of scan-to-BIM it is important that these practices are optimized for use to further improve and realize the efficiencies of this process. Therefore, it is crucial that different scanning methods or procedures are further investigated so that the best practices can be obtained and shared with those using scan-to-BIM in industry.

Since there has been a lack of investigation on the effect of terrestrial laser scanning (TLS) scan quality when conducting a structural condition assessment, the focus of this study is to investigate the effect of decreasing scan resolution on a software's ability to compare the as-built point cloud of a steel bridge to the 3D as-designed Revit model of that same bridge The objective of this study is to determine whether decreasing scan quality can result in a similar analysis output accuracy when comparing the as-built point cloud to the 3D bridge model. This study makes recommendation to improve the efficiency of digitalized maintenance procedures by analysing the effect of scan quality on BIM software analyses. Decreasing the output accuracy can decrease total scanning time and file size, increasing efficiency in the scanning process.

2. LITERATURE REVIEW

Although the scan-to-BIM process is relatively new, scan-to-BIM has been used in numerous infrastructure applications to gather as-built structural data. As-built structural data has often been used to gather information about historical structures, especially those that lack available structural drawings due to their age (Bernat et al. 2014). TLS was used to capture a 19th century structure in Gdansk, Poland, that was set for demolition. Using the TLS data, a 3D structural model was developed and used in the design process of its replacement structure, which was meant to be a replica of the original structure (Bernat et al. 2014). Moreover, a 3D point cloud of the spire of the Cathedral of Senlis in France was gathered, processed, and was used to create a digital geometric historical BIM model for use in structural analysis (Rolin et al. 2019). The use of scan-to-BIM processes in historical structures demonstrate the ability for accurate as-built 3D BIM models to be created from TLS scan data and used for subsequent analysis to draw conclusions, such as the creation of new structural drawings or a Finite Element Analysis model.

Not only has TLS been used as an effective tool to create BIM models, but TLS has also been found to be an effective tool for use in structural maintenance applications. Due to its high spatial accuracy, TLS can monitor structures with accuracy to the millimetre (Kregar, Marjetič and Savšek 2022). Thus, enabling it to pinpoint details like smaller cracks and deviations that would otherwise be less perceptible to the naked eye when conducting a visual inspection. TLS has been used to determine surface flatness defects on concrete surfaces (Tang, Huber and Akinci 2011), deflection and spalling on concrete beam test specimens (Olsen et al. 2010), and the cracking in road pavement (Kubota, Ho and Nishi 2019). Furthermore, a combination of structural deformation identification methods and scan-to-BIM processes were used to create a 3D deformation map of two towers that are a part of the Istanbul Land Walls. This process was able to effectively determine structural deformations by comparing the point cloud taken prior to the earthquake to the one taken after, with structural displacements found to be 15 mm and 20 mm respectively after a recent earthquake (Batur, Yilmaz and Ozener 2020). Therefore, not only is TLS effective at examining structural deformations, but it is also sufficiently accurate to depict deformation differences between multiple point cloud models.

The application of TLS as part of a scan-to-BIM process is not the only area where scan-to-BIM has been investigated, as the scan-to-BIM process is currently an area of active research. The use of TLS as a quantitative bridge maintenance tool has been investigated dating back to the early 2010s, with approximately 15 papers per year published on the subject in 2010 to 44 papers per year in 2018, demonstrating the growth of TLS usage in bridge engineering (Rashidi et al. 2020). Research has been conducted on the measurement and modeling of buildings by using both TLS and close-range photogrammetry on three different structures found in Poland (Skrzypczak et al. 2022). By analysing the geometrical measurements obtained from the structure itself, a 3D Revit model was developed and compared with the point cloud of the structure. This comparison yielded results that showed that the measurement accuracy between the point cloud and 3D Revit model was greater than ±1 cm (Skrzypczak et al. 2022). Furthermore, the impact between manual and automated scan-to-BIM processes was analysed. By analysing the three main phases of the scan-to-BIM process: scanning, registration, and modeling, the accuracy and precision of generated BIMs were evaluated (Esfahani et al. 2021). In all, the researchers determined that standardizing modeling practices, along with automating the modeling of primary building objects, provided improvements in the accuracy and precision of the scan-to-BIM process, and determined that automation is useful for improving time savings (Esfahani et al. 2021). TLS has proven to be an effective structural condition assessment tool, along with an effective tool for use in 3D modeling, point cloud analysis, and the creation of as-built BIMs.

3. METHODOLOGY

Figure 1 illustrates the full methodology adopted in this research and explains the main processes along with some sub-processes that are required to obtain and analyse scan data for analysis.

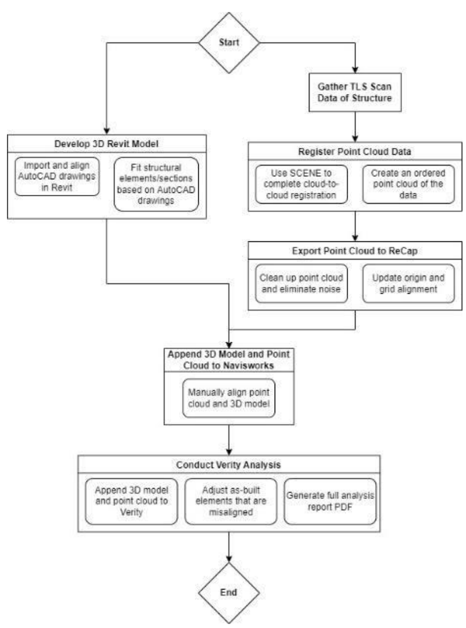


Figure 1: Scan-to-BIM Process Used in this Investigation

3.1 University of Windsor Parking Garage Bridge

The University of Windsor Parking Garage bridge is a short-span steel bridge constructed in 2013 that connects the 2nd floors of the adjacent parking garage and the Joyce Entrepreneurship Centre, shown in Figure 2. It is supported by two cross-braced W530x72 sections, which support the weight of the concrete floor slab and the covering structure made up of HSS steel. According to the design drawings, the clear span length of the bridge is 9 m, and the clearance height of the bridge is 4.2 m, with the height between the bridge deck and the interior ceiling reaching 2.7 m in height at its shortest point. This bridge was chosen due to its simple construction, accessibility, and availability of the required architectural and structural drawings.

Figure 2: University of Windsor Parking Garage Bridge

3.2 3D TLS Scanner and Software

The scanner that was used to gather the relevant point clouds for assessment was the Faro Focus M70. According to Cansel, the FARO Focus M70 scanner has a range of 6-70 m, with a ranging error of ±3 mm and a measurement speed of up to 488 000 points per second. It is described as a portable device that is effective for use in measuring small scale-facades and complex structures, not unlike the structure to be studied in this report (Afshar and Lachapelle 2022). FARO SCENE is a point cloud registration software and was used in this investigation. SCENE allows the user to easily register multiple scans based on common points to a high level of accuracy, which is an integral step in the creation of the 3D scanned model of a structure. The software used in this investigation is Verity (*Verity* 2017) and was developed by ClearEdge3D to conduct construction quality assessments. Verity can fit elements from a 3D model to the as-built point cloud of a structure and determine the installation or position error of each element based on point cloud geometry. Other programs such as Undet, Autodesk Point Layout and FARO As-Built were considered for this analysis, but all three were more effective at analysing the position of flat surfaces in relation to the point cloud instead of structural elements such as beams or columns.

3.3 Scan-to-BIM Procedure

Initially, a total of five scans were taken of the bridge, three were taken at ground level to capture the bridge's exterior, and two were taken on the bridge itself from either end to capture the bridge's interior. Each scan was captured at a resolution of 1/5, with a scan quality of 3X. A second set of five scans was then taken of the same bridge in identical locations, but this time at a resolution of 1/10 and with a scan quality of 3X. For the FARO Focus M70 scanner, a resolution of 1/5 means that the point distance 10 m from the scanner is 7.670 mm, whereas a resolution of 1/10 means that the point distance 10 m from the scanner is 15.340 mm (*SCENE 2021 FARO Focus Laser Scanners Training Workbook* 2021). Therefore, decreasing the scan resolution will decrease the number of points captured and increase the point distance. Scan quality is less variable than resolution and is generally determined based on environmental conditions. Scan quality should be increased if conditions are poorer or if error tolerances are smaller (*SCENE 2021 FARO Focus Laser Scanners Training Workbook* 2021). A more detailed overview of the two different scans can be shown in Table 1 and the scan plan for this procedure can be found in Figure 3. The scanner locations are identified by the five circles found on the plot.

Table 1: Laser Scan Settings

Scan Parameter (per scan)	Default Quality Scan	Lower Quality Scan
Resolution	1/5	1/10
Quality	3X	3X
Scan Time (min)	5:32	3:48
Scan Size (pts)	8192x3413	2560x1707
MPts	28 million	7 million

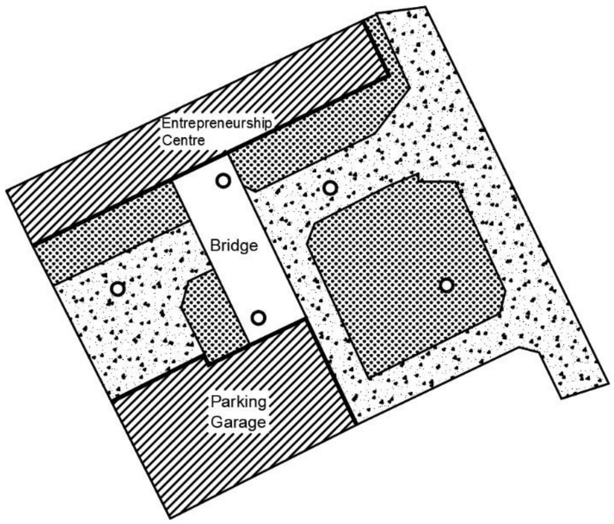
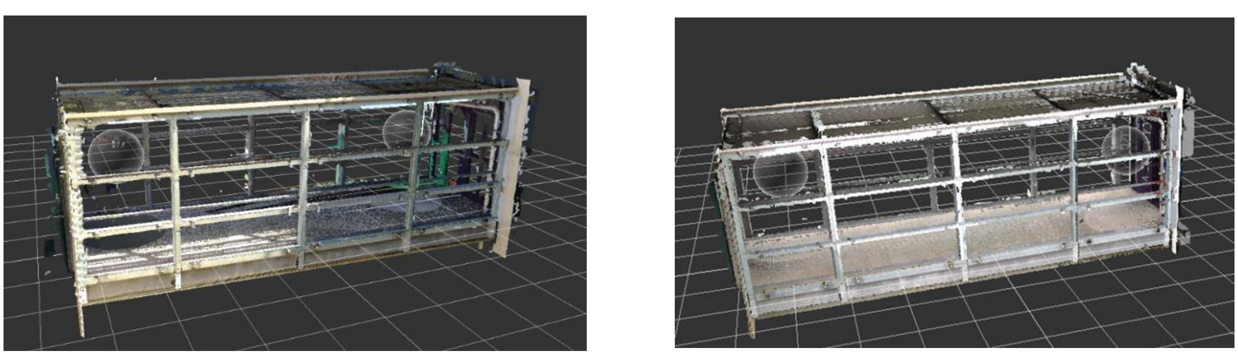


Figure 3: Scan Plan Used for this Investigation

Once scanned, the point clouds from all five scans were registered using SCENE to create a project point cloud, which combines the data from all the scans taken. The point cloud was registered by using the cloud-to-cloud registration method, where SCENE uses common reference points found in the separate point clouds in registration. This point cloud was then exported into ReCap, where the point cloud was cleaned of any irrelevant data and noise to obtain a point cloud that solely depicted the bridge to be analysed. Finally, after the completion of data cleaning, the point cloud was exported from ReCap into Revit where it was analysed. The final point clouds as imported to Revit are shown in Figure 4.



a) b)

Figure 4: As-Built Point Cloud in ReCap - a) 1/5 Resolution, b) 1/10 Resolution

3.4 Creation of the As-Built 3D Model

To create the as-built 3D model, AutoCAD design drawings of the parking garage and the Joyce Entrepreneurship Centre were obtained from the University of Windsor. These drawings depicted the plan view and two elevation views of the bridge, which were imported into Revit. Using common points, the plan and elevation drawings were aligned in the 3D view and were used as tools to assist in assembling the 3D model. The final 3D model that was used in the comparative analysis is shown in Figure 5.

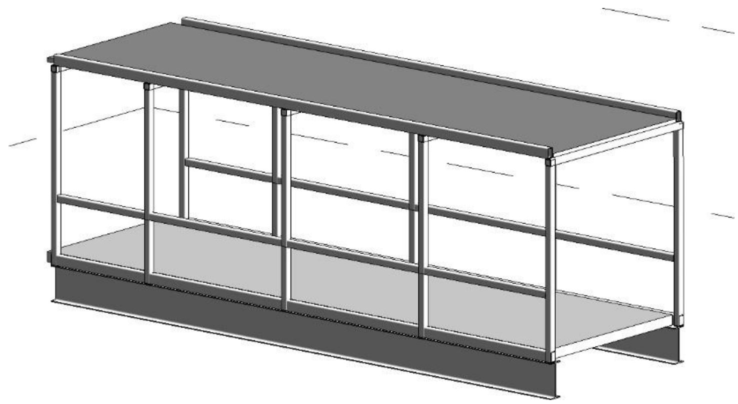


Figure 5: 3D As-Designed Model of Pedestrian Bridge in Revit

3.5 Analysis of Modeling Accuracy

To analyse the current state of the bridge, it was compared to the as-built point cloud by using Verity. Verity is an analysis tool that compares laser scans of as-built conditions to 3D Navisworks models and is used to generate quality assessment reports. Therefore, the 3D Revit model of the bridge was exported to Navisworks along with the ReCap point cloud, where the point cloud was manually aligned to the 3D model at gridline A4. Gridline A4 was chosen arbitrarily as there was no specified reference point, and that the overall displacement error as found in the analysis should not differ based on the chosen reference point. Manual alignment was completed using the “Units and Transform” tab in Navisworks along with the “Measure” function. Since Verity works in conjunction with Navisworks, these items were then added to Verity and analysed. In Verity, each element of the 3D model was analysed with respect to the point cloud and based on this relationship, the software attempts to fit the element to the point cloud to show the assumed location of the as-built element.

Verity also allows the user to generate a summary report on the analysis and can provide detailed information on the accuracy of the analysis conducted. Information found in this report includes the installation error of each element in the *x*, *y*, and *z* directions, along with images showing the difference in position between the modeled and as-built locations as shown in the software interface. Therefore, the analysis report can be an effective tool at discerning the accuracy of element positioning within a structure. In total, two analysis reports were generated, one for the default quality scan and the other for the lower quality scan.

4. RESULTS

First, the effect of scan resolution on the analysis of scan data through an automated process was assessed. For the 1/5 resolution scan data, 18 of the 27 total elements analysed were defined as “passing”, which means that Verity was able to clearly identify the as-built position of the element from the point cloud, with a further 5 defined as “uncertain”, which means that Verity could not fully verify that the position of the as-built element was accurate without manual intervention. This is compared to 14 of the 27 total elements defined as “passing” and a further 7 defined as “uncertain” for the 1/10 resolution scan data. This data can be shown in Figure 6. At first glance, this shows that the higher resolution scan data produced more accurate results, however Verity is a semi-automated system and requires the user to review all the elements for verification. The user can also reposition or align the predicted as-built positions manually and ask the software to refit the as-built element to the point cloud to achieve a more accurate as-built position. After verification, 22 elements passed for the 1/5 resolution data, while 20 elements passed for the 1/10 resolution data. In all, after verification, the decrease in scan quality resulted in a 10% decrease in the number of elements that passed the analysis.

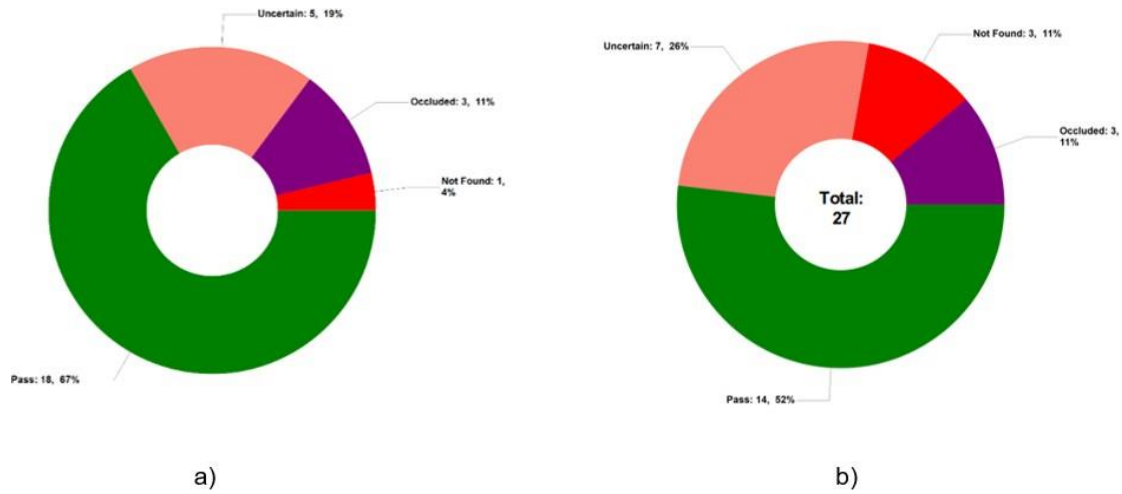


Figure 6: Initial Verity Analysis – a) 1/5 Resolution, b) 1/10 Resolution

In Table 2, the results of the analyses can be compared. Overall, the scan resolution when decreased from 1/5 to 1/10 had a negligible effect on the analysis results. Despite the 1/10 resolution scan taking less time, scanning less points, and contributing a smaller file size, both scans provided enough information to the software to determine each element’s as-built position precisely and determine the installation error between the as-built element and the modeled element. This can be seen in Table 2, where the installation errors between the 1/5 resolution scan data and the 1/10 resolution scan data are almost identical for the mean, median, smallest, and largest errors, and only differ due to alignment error which can be attributed to the point clouds’ manual alignment to the 3D models in Navisworks. The error value for each element is the average displacement between the 3D model element and the as-built location. As for the sum and the weighted average, the 1/10 resolution scan data is showing better results because this data only accounts for “passing” elements, of which there are more than in the 1/5 resolution scan data. Since the 1/5 resolution scan data includes members with a greater surface area and greater error, the weighted average is biased towards these elements, making weighted average of the 1/10 scan data appear smaller.

Table 2: Verity Analysis Results

Total Installation Error	1/5 Resolution Scan Data	1/10 Resolution Scan Data	Percent Difference
Sum	923.608 mm	876.182 mm	5.13 %
Mean	41.982 mm	43.809 mm	4.35 %
Median	36.887 mm	39.925 mm	8.24 %
Smallest	7.990 mm	8.697 mm	10.98 %
Largest	103.147 mm	103.119 mm	0.02 %
Weighted Average	42.357 mm	36.814 mm	13.09 %

5. DISCUSSION

In this investigation, the University of Windsor parking garage bridge was scanned from five different positions at two different resolutions, 1/5 and 1/10, using a Faro Focus-M70 3D scanner. This scan data was then used to conduct a condition assessment of the bridge through a comparison with the as-designed 3D bridge model generated in Revit. By varying the scan resolution, the condition assessment results could be compared to determine the impact of scanning at a lower resolution and as a result, whether the scanning process efficiency could be improved. The results verify that decreasing the scan resolution from 1/5 to 1/10 did not decrease the effectiveness of Verity's ability to analyse the displacement between as-built and as-designed conditions however further conclusions can be drawn from this investigation. The first observation made is that since scanning at a lower resolution takes a shorter amount of time, scanning the structure at this lower resolution for analysis in Verity would be beneficial. Decreasing the scanning time will allow for more scans to be taken over the same period, which can be an important time and cost-saving measure especially if multiple structures are to be scanned. Moreover, this allows the scanner operator the time to take more scans of the structure, if need be, from different positions or angles to better capture the structure in the same amount of time.

Building on these findings, scanning at a lower resolution requires less time since the scan data is smaller, as shown previously in Table 1. Scanning at 1/10 resolution captures 25% less points than scanning at 1/5 resolution, greatly reducing the file size of each captured scan. Lower file sizes can be correlated with increased ease of work since software like ReCap and Navisworks, which are used in the point cloud processing, have less data to handle. From a user perspective, using larger files results in increased loading times, which proved to be an additional challenge when manually aligning the point cloud to the 3D model in Navisworks. Furthermore, this can also be demonstrated in Verity where the processing time for the 1/5 resolution scan data took 4:20 minutes, while the processing time for the 1/10 resolution scan data instead took 2:56 minutes, which results in an approximate 32% reduction in processing time. File size can also be further reduced by scanning in grayscale instead of in colour or by narrowing the scan area to capture only the structure to be analysed. Thus, not only does scanning at lower resolution save time during field data collection, but it also saves time during the data processing procedure.

Despite the decrease in scan resolution resulting in similar analysis results, there exist some limitations in the scanning process itself that can also impact the results and can be improved upon. Currently, there is no automated or even semi-automated method of aligning the 3D model to the point cloud. For this investigation, the point cloud and 3D model were manually aligned at an arbitrary point using translation and rotation tools already found in Navisworks. Using this process will induce error as it is difficult to ensure that the chosen alignment point is the point of best fit between the point cloud and the 3D as-built model. The introduction of a semi-automated feature to best fit the point cloud to the 3D model would further improve the accuracy of this analysis and can also assist in reducing the time taken to conduct the manual point cloud alignment. Increasing automation would remove much of the human error currently found in the investigation and could even be extended further to be used for point cloud noise removal. In this investigation, noise was also removed manually in ReCap, however due to software and human limitations, it would be very time consuming and tedious to ensure it is all removed.

Another limitation found resulted from time constraints involved in completing this analysis. In this investigation, scan data of only two different resolutions were compared, however with more time, this investigation could have been extended further to investigate scan data in a greater range of resolutions. Therefore, with this increased resolution range of scan data, an investigation could be conducted to determine the resolution at which there is a significant decrease in analysis quality or determine the lowest resolution which can provide enough scan data to conduct a sufficient analysis. Moreover, resolution does not have to be the only independent variable used in an investigation; scan quality, number of scans, or scan distance can be other potential independent variables for use in an investigation. Thus, the optimal scan settings can be obtained, which can contribute the further optimizing the scanning process.

Lastly, using other point cloud analysis software or plug-ins to conduct a similar investigation on scan quality assessment could also provide further research developments in the field. Currently, to our knowledge, there is no other software that can conduct a point cloud and 3D model comparison analysis and provides an easy user interface to the degree that Verity does. Other software such as CloudCompare, Autodesk Point Layout, or Cintoo could be used to conduct this analysis in the future to compare the effect of scan quality between programs.

6. CONCLUSIONS

In conclusion, through the comparison of an as-built point cloud to the 3D as-designed Revit model in Verity, it can be determined that decreasing the scan resolution from 1/5 to 1/10 does not significantly affect the accuracy of the point cloud comparison analysis. Despite the decrease in scan resolution, the position of the as-built elements from the point cloud can be identified by Verity at almost the same effectiveness as the higher resolution point cloud. As a result, total scan time and scan processing time can be reduced, improving scan efficiency. Therefore, it is recommended that to increase the efficiency of the scan process for condition assessment, reducing the scan resolution is a viable option as it is able to reduce individual scan time and processing time by approximately 32% despite only a 10% decrease in elements passing the Verity analysis.

These findings can be beneficial to those conducting maintenance or quality assessments using TLS. Oftentimes firms conducting these procedures will be investigating more than one specific structure at a time, or structures much larger than the parking garage bridge investigated in this report. Thus, gathering scan data can already constitute a large portion of this process. By reducing the total scan time, this will provide the opportunity for the firm to scan a larger area or more structures than they would have if scanning with a higher resolution, while also achieving the same results. In continuation, scanning at a lower resolution also reduces file size, improving processing efficiency.

To further extend research in this field, different scan procedures could be investigated. Scanning different elements of a structure in different resolutions or qualities could be useful in improving point cloud data accuracy. Higher resolution could be used to scan more detailed or more important areas of a structure where precision is more important, while more generic elements could be scanned at a lower resolution. In theory, the point cloud will be able to provide more information where it is most needed, while also decreasing file size and scanning time without sacrificing analysis accuracy.

7. ACKNOWLEDGEMENTS

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