A comparison between laser scanning, photogrammetry and infrared scanning to create 3D digital models of existing concrete bridges

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SUMMARY

Routine bridge inspections usually consist of visual observations. These inspections are time-consuming and subjective. There is a need to identify new inspection techniques for infrastructure that reduce traffic disturbance, and improve the efficiency and reliability of the acquired data. This study compared the performance of three different imaging technologies for the three-dimensional (3D) geometric modelling of existing structures: terrestrial laser scanning, close-range photogrammetry, and infrared scanning. Each technology was used to assess six existing concrete railway bridges. The technologies were compared in terms of geometric deviations, visualization capabilities, the level of the inspector’s experience, and degree of automation. The results suggest that all methods investigated can be used to create 3D models, however, with different level of completeness.

**Keywords:** *Bridge Inspection, Optical Methods, Remote Sensing.*

# INTRODUCTION

Transport agencies must address maintenance issues to guarantee serviceability and safety of our infrastructure. This includes increased inspections and investing into structural health monitoring programs. Disruption to train services due to scheduled maintenance work, visual inspection etc. is increasing. Typically, a routine inspection consists of field measurements and visual observations made by a bridge inspector. The main purpose is to gather information such as geometry, concrete deterioration, corrosion, etc. [[1-3](#_ENREF_1)]. The way such data are documented is through field inspection notes, freehand sketches and photographs which are then used as input to the bridge management protocol of transportation agencies. The procedure is highly dependent on the inspector’s experience [[3](#_ENREF_3)], and knowledge of the structural behaviour and material properties of the system being investigated. The method has its limitations in the sense that only accessible parts are investigated due to the difficult terrain in which the structure is sometimes located. In addition, knowledge transfer from one inspection period to another becomes difficult when different inspectors carry out the investigation. [Graybeal et al. [4]](#_ENREF_4) noted that routine inspections have relatively poor accuracy, with the following factors affecting the reliability of these results: inspector fear of traffic, near visual acuity, colour vision, accessibility and complexity.

Emerging technologies are now becoming more and more common in the civil engineering field. One such example is the use of optical methods – arguably a more advanced visual inspection – where the imaging characteristics of an object are recorded using high precision, high sensitivity cameras. According to [Fathi and Brilakis [5]](#_ENREF_5) optical-based sensors are classified as active or passive sensors. Active sensors obtain depth information by emitting energy and recording the reflected signals Passive sensors make use of ambient light to capture the surrounding environment and, with the use of post-processing techniques, range data are obtained [e.g. close-range photogrammetry (CRP)]. Many studies have examined the use of unmanned aerial vehicles (UAV) for bridge inspection. The current status of UAVs for inspection purposes in infrastructure engineering was recently reviewed by [Duque et al. [6]](#_ENREF_6), who highlighted reports showing that UAVs have successfully been used to detect damage such as cracks and corrosion. However, many of the studies reported field tests performed on windless conditions, and reported unavoidable issues related to drone access to the bridges given the regulatory prohibitions on drone flights in proximity to traffic, loss of (or weak) GPS signal under the bridge, etc. Alternatively, with the expansion of the low-cost consumer cameras photogrammetry could play an important role in autonomous damage detection on existing bridges. There are even more studies regarding photogrammetry as alternative to traditional measurement. Since many of the previous studies were focused on somewhat idealistic conditions (laboratory settings, no natural vegetation around the studied object, small-scale objects, trained personnel and favourable weather conditions), this study makes a clear contribution to the body of knowledge, as it aimed to measure the performance of different optical methods, i.e. TLS, CRP and IS, in terms of accuracy, time-consumption, costs and automation. In addition, the photogrammetry was carried out by personnel with different levels of training. Team 1 consisted of two MSc students with no prior experience other than a few trials in a laboratory before the field trip, and Team 2 were two experienced surveyors who carried out the scanning.

# Tested bridges

The Swedish Transport Administration (Trafikverket) selected the bridges on which the technologies were to be tested. In total, six bridges located in northern Sweden along the Iron Ore Line were selected, all in service. These bridges were located in both urban and rural areas, spanning flowing waters as well as roads carrying traffic. Most of them were surrounded by vegetation. Traffic flow was not disrupted at all during the survey. Figure 1 shows the location of the selected bridges together with a general view of each one. Their locations are numbered in the order they were scanned. Details of the bridges scanned and particularities of the methods used are presented in Table 1.

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**Fig. 1.** Bridge location and photos of the bridges taken on the day of scanning. "Map by Maphill"

**Table 1.** Summary of data collected

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Bridge** | **TLS** |  | **CRP** | | | | |  | **IS** |
| Scanning positions |  | Camera stations | No. of photos | ISO | Aperture | Shutter speed (sec) |  | Scanning positions |
| Edbäcken bridge | 10a) |  | 12 | 90 | 160 | f/8 | 1/10 - 1/200 |  | N/Ac) |
| Påunakbäcken bridge | 11a) |  | 55 | 581 | 160 | f/10 | 1/6-1/125 |  | 13 |
| Kedkejokk bridge | 15b) |  | 25 | 621 | 160 | f/8 | 1/4 - 1/20 |  | 17 |
| Juovajokk bridge | 15b) |  | 45 | 737 | 160 | f/8 | 1/6 |  | 22 |
| Pahtajokk bridge | 11a) |  | 32 | 397 | 160 | f/8 | 1/13 |  | 21 |
| Kallkällevägen bridge | 11a) |  | 142 | 744 | 160 | f/8 | 1/8 – 1/25 |  | 67 |

a) Each scanning generating about 30 – 40 million points of data.

b) Each scanning generating about 20 million points of data.

c) Due to strong interference from ambient light none of the scans aligned correctly

# Techniques and equipment

## Terrestrial laser scanning - TLS

In TLS, the 3D geometry of the structure is obtained by using light detection and ranging technology (LiDAR). The system works by emitting light and detecting its reflection to determine the distance to the object. The equipment used in this study was a long-range, RIEGL VZ-400, 3D terrestrial laser scanner. Based on the time-of-flight principle, the 3D scanner is able to make measurements ranging from 1.5 m to 600 m with a nominal accuracy of 5 mm at 100 m range. It uses near-infrared laser wavelengths with a laser beam divergence of 0.3 mrad, corresponding to an increase of 30 mm of beam diameter per 100 m distance. The scan angle ranges from 100° vertical scan to 360° horizontal scan. The raw data i.e. point clouds captured from multiple scans were post-processed (registration and geo-referencing) using Leica Cyclone software. The software automatically aligns the scans and exports the point cloud in different formats for further processing.

## Close-range photogrammetry – CRP

In CRP, a series of images is recorded using digital cameras, and coordinates of points (targets), patterns, and features in the images are subsequently identified using image processing techniques [[7](#_ENREF_7)]. The process of estimating the 3D structure of a scene from a set of 2D images is known as structure from motion (SfM). The approach relies on pixel correspondence between images and, in contrast to older photogrammetry algorithms, no pre-calibration of the camera is necessary. To make the process easier, the surfaces of the imaging object have to have distinct features, either natural (sharp edges, discoloration, bolts, rails etc.) or artificial (targets). A minimum of 60% overlap between images is necessary, in both the longitudinal and transversal directions. A commercial SfM software, Agisoft PhotoScan Pro, was used to create the 3D model by estimating the interior orientation and defining the orientation of the camera position for each photo relative to the object scanned. When the processing of the data is finished, the software returns the camera positions and internal geometry of the camera from the calibration process. The equipment consisted of a DSLR camera, a Canon EOS 5D. This is equipped with a full-frame CMOS optical sensor giving 12.8 megapixels resolution. The camera was equipped with a Canon EF 35mm wide-angle prime (fixed zoom) lens. For one of the bridges scanned, another team carried out additional photogrammetry scanning using a better camera (Canon EOS 5D Mark II). The camera had 21.1 megapixels resolution and was equipped with a Canon EF 24 mm prime lens. The images taken by the Canon EOS 5D Mark II were supplemented with aerial photos taken with a 3DR Site Scan drone equipped with a Sony R10C camera with 16–50 mm zoom lens. The Sony camera gives 20.1 megapixels using an APS-C size sensor. The 3D model was generated using a commercial SfM software, Bentley ContextCapture.

## Infrared scanning – IS

Infrared scanning uses RGB-D cameras in combination with an infrared camera and infrared projector able to augment the still image with depth information (Miranda and Abreu 2016). The equipment used in this study was a Matterport Pro2 3D Camera. The Matterport camera uses three infrared sensors that capture depth data together with visual data (RGB) at 360° (left – right) and 300° (vertical). The images are taken at a resolution of 8092 × 4552 pixels. The camera is wirelessly connected to a tablet from which the scanning is carried out. The capture time for each scan is about 40 secs, including the transfer time from camera to the tablet and the time for the alignment process. The range of the camera is about 4.5 m in indoor environments. Although not supported by the developer, if scanning is carried out outdoors, more scan positions are required. To avoid alignment issues, the scanning must occur during civil twilight (30 minutes before sunrise and 30 minutes after sunset), or otherwise on a cloudy day to avoid infrared light from the sun. When completed, the scans are uploaded to Matterport’s cloud service for 3D data registration and the point cloud is obtained.

# Results and analysis

The analysis was carried out both quantitatively and qualitatively. The first step was to create a 3D model of each of the scanned bridges and compare the visual capabilities of each method. A qualitative process was also carried out to highlight the potential of each method investigated. Quantitatively, geometric deviations were calculated when comparing the span length and width of each bridge deck. Only selected results are given in the following sections; the complete details of the study can be found in [Popescu et al. [8]](#_ENREF_8), [[9](#_ENREF_9)].

## Documentation and visualization

The first part to investigate was the visualization of the digital models including the level of detail captured by each optical method. The 3D models of each bridge scanned, as created by TLS, CRP and IS, are shown in Figs. 2–6.

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***Fig. 2.*** *3D models of Påunakbäcken bridge—differences in level of detail between the tested methods.*

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***Fig. 3.*** *3D models of Kedkejokk bridge—differences in level of detail between the tested methods.*

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***Fig. 4.*** *3D models of Juovajokk bridge—differences in level of detail between the tested methods.*

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***Fig. 5.*** *3D models of Pahtajokk bridge—differences in level of detail between the tested methods.*

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***Fig. 6.*** *3D models of Kallkällevägen bridge—differences in level of detail between the tested methods.*

Due to insufficient overlap between the photos, the Edbäcken bridge, which was the first to be scanned, could not be reconstructed. Alignment issues also occurred for the Matterport camera due to strong ambient light. The only model for this bridge that could be created used laser scanning data. However, as the purpose here is to compare the potential of each method, the laser scanning-based 3D model is not shown. It can be seen that for all bridges, the TLS was able to construct the complete 3D model including not only the bridges’ structural elements but also secondary objects such as guardrails and vegetation around the bridges.

The point clouds obtained from TLS were grayscale, thus, no RGB information was available for the studied bridges. The photogrammetry-based models also captured enough information for other objects of interest, such as the structural elements (abutments, piers and bridge deck). Regarding the secondary elements within the scene to be captured, only guardrails could be modeled. It was not possible to capture the vegetation around the bridges entirely since only ground-based photogrammetry was carried out, thus limiting the size of the surrounding area captured. However, in contrast to TLS, the photogrammetry-based models contained RGB data, making the visualization model more natural. The 3D models generated by IS ranked the lowest in terms of amount of information captured. The abutments and the bridge decks were captured with enough data to be able to extract the general dimensions. Information about the bridge extremities, vegetation around the bridge, and guardrails was not captured for any of the bridges since they were out of the range of the Matterport camera. As with CRP, the IS provided RGB data. By highlighting the texture and materials, the RGB information provides a true-to-life experience which otherwise might be difficult to visualize with an intensity level scan provided by TLS.

For one of the bridges scanned, three different models were created in order to investigate aspects of the photogrammetry method such as the experience level of the team carrying out the scanning, the quality of image acquisition, photogrammetric software capabilities and post-processing skills. The Pahtajokk bridge was selected as a good candidate for this analysis mainly because it was near the end of the field trip and the inexperienced team (Team 1) had already gained confidence, although not to the same level as Team 2. In total, three photogrammetry-based models were created for Pahtajokk bridge:

* Model #1 – Processing carried out by Team 1 with photos taken by Team 1 (Agisoft PhotoScan Pro + Canon 5D)
* Model #2 – Processing carried out by Team 2 with photos taken by Team 1 (Bentley ContextCapture + Canon 5D)
* Model #3 – Processing carried out by Team 2 with photos taken by Team 2 (Bentley ContextCapture + Canon 5D Mark II + 3DR Site Scan drone)

In Model #2, Team 2 (experienced) constructed a 3D model based on photos taken by Team 1. The authors were trying to identify what could be weak points when creating 3D models. Such weak points could be e.g. the quality of the photos (resolution of the camera, amount of overlap, camera settings etc.) and/or the software and data processing capabilities of the analysts. Model #3 combined ground-based photogrammetry with aerial photogrammetry. In this way, a better model could be created by utilizing the strength of both approaches. With ground-based photogrammetry, one can have access to relatively narrow spaces where flying a drone might be problematic due to limited access, loss of (or weak) GPS signal etc. With aerial photogrammetry, the surroundings can also be captured as well as the railway and top side of the bridge. For Model #3, the whole process (data acquisition and processing) was carried out by Team 2. A comparison between Model #1, #2 and #3 is shown in Figure 7. All models are complete with no major differences other than slight differences in the image contrast. Model #3 incorporated photographs taken using a drone, which enabled the entire area surrounding the bridge to be photographed. Since no significant differences were found it can be concluded that the image quality and amount of overlap were sufficient to create the 3D models independently of the acquiring team’s experience. This is important because the ease with which a new method can be adopted by inexperienced users (i.e. the steepness of its learning curve) will significantly affect its rate of uptake.

Another aspect worth comparing is that of the resolution offered by each method, which is a function of the point cloud density. In this way, one can evaluate whether the resolution is high enough to observe damage on the structural members. The abutment of Pahtajokk bridge was selected because multiple joint dislocations were noticed during the field survey. Figure 8 highlights differences in the rendering capabilities of TLS, CRP and IS compared with the field photograph. A high level of detail can clearly be seen, though the IS was less detailed than the TLS and CRP-based models.

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***Fig. 7.*** *CRP models of Pahtajokk bridge: (a) Model #1, (b) Model #2 and (c) Model #3.*

This is demonstrated by plotting the local density of the point cloud of the same region. The highest estimated point cloud density was obtained for TLS with an average density of about 228×103 points/m2 (62935 points/m2 – standard deviation). A comparable value was also obtained for CRP (226×103 points/m2 with 25229 points/m2 – standard deviation) while the IS provided the lowest density (14×103 points/m2 with 1643 points/m2 – standard deviation). By highlighting the texture and materials, the RGB information provides a true-to-life experience which otherwise might be difficult to visualize with an intensity level scan provided by TLS. The point cloud analysis has been carried out using CloudCompare software.

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***Fig. 8.*** *Point cloud visualizations of the abutment of Pahtajokk bridge based on the TLS, CRP and IS models, with a field photograph for comparison.*

## Geometric deviations

The point clouds generated were imported into Autodesk ReCap for measurement extraction. The “ground truth” for geometric measurements in remote sensing is nearly impossible to establish using devices such as a total station, which itself may be prone to measurement error. Instead, the existing as-built drawings were used in this study to establish the ground truth. The geometric deviations were analyzed based on point-wise measurements; however, further studies would be helpful to compare the entire 3D model against a previously built model. In this way, global movements due to e.g. differential settlements that can introduce torsional effects on the superstructure could be identified. With a few exceptions, all methods provided good accuracy as can be seen from Table 1, however due to limited space the comparison is shown only for three bridges.

**Table 2.** TLS, CRP and IS accuracy comparison

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Bridge** | **As-built dimension** | **Terrestrial laser scanning** | |  | **Close-range Photogrammetry** | |  | **Infrared scanning** | |
|  | (mm) | (mm) | %L |  | (mm) | %L |  | (mm) | %L |
| **Påunakbäcken bridge** |  |  |  |  |  |  |  |  |  |
| Span | 2950 | 2930 | -0.68% |  | 2947 | -0.10% |  | 2985 | 1.19% |
| Width (deck) | 4500 | 4517 | 0.38% |  | 4525 | 0.56% |  | 4546 | 1.02% |
| **Juovajokk bridge** |  |  |  |  |  |  |  |  |  |
| Span | 5500 | 5434 | -1.20% |  | 5412 | -1.60% |  | 5458 | -0.76% |
| Width (deck) | 3800 | 3780 | -0.53% |  | 3735 | -1.71% |  | 3780 | -0.53% |
| **Kallkällevägen bridge** |  |  |  |  |  |  |  |  |  |
| Central span (interax) | 14500 | 14592 | 0.63% |  | 14468 | -0.22% |  | 14828 | 2.26% |
| Width (deck) | 4540 | 4526 | -0.31% |  | 4510 | -0.66% |  | 4628 | 1.94% |
| Diameter (pillar) | 1000 | 1000 | 0.00% |  | 977 | -2.30% |  | 1009 | 0.90% |

Figure 9 displays a qualitative comparison of imaging techniques used in this study in terms of cost, level of automation, accuracy/resolution, portability, range distance, and acquisition and processing time. Each method was given a grade of low, medium, or high for each item based on its performance, with the high grade corresponding to the best performance. For better interpretation a quantitative comparison in terms of actual equipment, data acquisition and processing time, will be provided in the following. The equipment costs can be approximated to about 50,000 € for TLS, 1400 € for CRP, and 4700 € for IS. Data acquisition varies based on the size and ease of movement around scanned bridges, from the authors’ experience with studied bridges the TLS would be completed in about 1–2 hours, CRP in about 1–4 hours, while IS in about 15 min–2 h. The postprocessing time could take up to 7 days for both TLS and CRP (including computational time/point cloud registration and final cleaning of irrelevant points), and 2 days for IS.

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**Fig. 9.** Performance of the 3D imaging methods

# Conclusions and future work

This study investigated the use of three optical methods for creation of digital models of bridges. It has been shown that the 3D models could serve as a tool for bridge inspectors from which measurements could be extracted. A complete off-site inspection is currently not feasible as some areas of the bridges were difficult to capture mainly due to restricted access and narrow spaces. The main conclusions of the study were as follows:

* All methods tested provided a digital model with different level of completeness, from which general measurements (span length, deck widths, pier diameters etc.) could be extracted with good accuracy.
* No special training is needed to create good quality 3D models using CRP or IS imaging. However, good skills in the processing phase as well as good software capabilities will help increase the accuracy of the models generated by CRP. The high level of automation of the IS method, although a positive aspect, gives limited control and flexibility for improving the end-model by the bridge inspector. The IS method shows good potential if further improvements can be made in the cloud computing solution and the range distance.
* The point clouds generated were denser for TLS and CRP while for IS, the density was several times lower. Denser point clouds enable better visualization, however, at the cost of increased computational time, storage space and difficulty in handling the models.

It is believed that these methods could help improve the accuracy and efficiency of bridge inspections by eliminating human error, as well as provide the opportunity of a historical record of the progress of deterioration. Future developments would focus on automated damage detection by employing artificial intelligence and enriching the 3D model by additional information such as material properties and inner geometry. In order to study the existing structures over time and provide objective information of visible changesa, additional scans would be necessary.

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